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A "Grammar" for assessing the performance of power-supply systems: Comparing nuclear energy to fossil energy

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ABSTRACT

This article illustrates an innovative approach for the characterization and comparison of the performance of power-supply systems. The concept of 'grammar' forces to declare the pre-analytical decisions about: (i) semantic and formal categories used for the accounting – primary energy sources (PES), energy carriers (EC), and production factors; (ii) the set of functional and structural elements of the power-supply system included in the analysis. After having tamed the systemic ambiguity associated with energy accounting, it becomes possible to generate a double assessment referring to: (i) external constraints – the consumption of PES and the generation of waste and pollution; and (ii) internal constraints – the requirements of production factors such as human labor, power capacity, internal consumption of EC for making EC. The case study provided compares the production of EC (electricity) with "nuclear energy" and "fossil energy". When considering internal constraints, nuclear energy requires about twice as much power capacity (5.9–9.5 kW/GWh vs. 2.6–2.9 kW/GWh) and 5–8 times more labor (570–640 h/GWh vs. 80–115 h/GWh). Things do not improve for nuclear energy when looking at external constraints – e.g. the relative scarcity of PES. This may explain the difficulties faced by nuclear energy to gain interest from investors.

1. Introduction

Since the Age of Enlightenment quantitative analysis is perceived by many as the "only" way to generate "true" and "useful" information. However, in recent decades, with the arrival of the Age of Complexity there has been growing concerns among scientists as regards to the usefulness and effectiveness of "crisp" quantitative analyses to be used in normative terms for the governance of sustainability, especially in relation to energy analysis [1–3]. In fact, when dealing with the process of decision making it is essential to be aware that any issue definition of a problem (a pre-analytical simplification of the representation required in order to be able to crunch numbers) requires a long series of delicate choices involving both normative and descriptive aspects [4]. For this reason, the usefulness of the resulting quantitative information depends on: (i) the quality of the choice made on the normative side – that is the relevance of the narratives about energy transformations used when choosing models and indicators; and (ii) the quality of the choices on the descriptive side – that is the pertinence of the resulting quantitative representation.

In relation to this second aspect the unavoidable existence of multiple relevant scales to be considered in quantitative analysis clearly indicates that it is not possible to deal with assessments of complex processes operating across different scales (e.g. energy systems) using the excessive simplifications of reductionism – i.e. protocols generating numbers based on the adoption of one scale and one dimension at the time [2]. As a matter of fact, the unavoidable co-existence of multiple relevant dimensions and multiple relevant scales in the discussion of sustainability implies that mono-scale analysis should not be used to define "the best course of action" [5–7].

The complexity of energy systems comes from the obvious fact that energy transformations of interest are governed by autocatalytic loops: energy systems must use energy carriers to generate energy carriers. For this reason: (i) their characteristics are unavoidably affected by non-linear relations; and (ii) they are operating simultaneously across different levels of organization and scales. To proper represent these processes we have to consider simultaneously different scales:

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(1) a local scale at which energy carriers are used to generate useful power – e.g. when the electricity of a power plant is used to power technical devices or liquid fuels are used for running engines. Using this scale we can assess information such as the value of power levels per hour of labor or the total consumption of energy carriers per year;
(2) a meso scale referring to the power capacity used by a plant – e.g. what type of converters are needed to generate the power output (e.g. measured in watts), that have to be maintained and reproduced. Using this scale we can assess the energy embodied in the technology used by the energy system discounted over its life span when considering the life-cycle assessment (LCA) of the energy embodied in technical capital;
(3) at a larger scale, we can assess the overhead for society associated with the labor requirements of an energy system – e.g. the hours of human activity required for the control of energy transformations. Using this scale we can establish a bridge with the socio-economic dimension of the process;
(4) expanding further the scale of analysis we can assess the compatibility between the requirement of Primary Energy Sources needed to produce the energy carriers and their availability in nature (feasibility in relation to boundary conditions).

As explained in previous books [1,2], mathematical models trying to collapse different types of quantitative information referring to different external referents observable only at different scales into a single system of inference must necessarily rely on a lot of assumptions and simplifications that unavoidably translate into quite unreliable results. This is the reason why the approach proposed in this paper does not offer a "mathematical protocol" for analysis and comparison of energy systems, but a semantically open 'grammars'.

A 'grammar' is a set of expected relations over semantic characteristics of analyzed energy systems – that can be formalized "a la carte" by tailoring the chosen protocols on specific questions and situations. So what we propose here is not a mathematical protocol to be applied "by default" to any situation independently from the particular system considered and its context. Indeed, we believe that the use of mathematical formalisms without an informed discussion about the implications of pre-analytical choices (the semantics of an analysis) may reduce the quality of the analysis. The method proposed here especially intends to avoid to the temptation of over-reductionism – what we call "formalism non-sense" – often found in energy analysis [1,2]. That is, the choice of "relevant criteria", "benchmarks for indicators used for each criterion" and the "weighting factors" cannot be done once and for all in a given protocol. Each choice requires a special tailoring depending on the context within which the integrated assessment takes place. For this reason, it is not recommended to apply or suggest a "substantive" method for weighting the importance of different criteria [3]. In fact, we believe that the quantitative results show that an informed discussion over sustainability and energy systems does not necessarily require mathematical formalisms: when dealing with complex systems it is more important "to do the right sums rather than to get the sum right" [8].

This explains why we are proposing here the concept of grammar in which the pre-analytical choices done by the analyst must remain clearly visible, especially when considering also the unavoidable existence of uncertainty on the integrated characterization. In this way, when the actual analytical step is carried out (after crunching numbers) the users of the quantitative result can track back the series of decisions leading to the final quantitative results. The idea of finding "optimal solutions" becomes a mission impossible once we accept the idea of multi-criteria analysis. In this framework, we believe that the analysts working in integrated assessment should not be the ones selecting the relevant criteria, the targets and benchmarks, as well as the weighting factors to be used in the analysis. Rather, the analysts working in integrated assessment should help their clients (social actors and stakeholders) to carry out an informed process of deliberation based on a set of criteria, indicators, targets and weighting factors suggested or at least agreed by the users of the analysis.

2. The need of a double energy accounting

According to thermodynamic principles we cannot "make" energy. We can only exploit primary energy sources which represent favorable physical gradients outside human control. This exploitation requires investing production factors such as: (i) available energy carriers; (ii) power capacity; and (iii) labor. These production factors must be used as inputs in the process generating a net supply of energy carriers. This simple statement clearly indicates that if we want to characterize the performance of energy systems we have to use more than a single quantitative variable [2]. That is, the quality of primary energy sources depends on several characteristics of the process adopted for their exploitation: (1) in relation to 'internal constraints' – we have to specify how much inputs – energy carriers, power capacity, human labor – we have to invest in a given set of energy transformations under human control to get a net supply of energy carriers [2,9–13]; (2) in relation to 'external constraints' – we have to specify what is the overall size of favorable physical gradients outside human control – the amount of primary energy sources – which must be available on the supply side (biophysical constraint) and how much sink capacity is required from the environment to absorb the waste or pollution generated by the process (environmental impact).

These different pieces of information can only be obtained by considering an integrated set of quantitative variables referring to different semantic categories of accounting. In spite of the plausibility of this statement, when looking at the literature in energy analysis we found that the quantitative analysis of the relationship between energy quality and economic performance is in general carried out using a variable at the time – e.g. individual ratios such as energy output per economic input (e.g. the price of energy carriers). In biophysical analysis, early works in this direction date from the 1980s and include attempts to use indices based on assessments of energy output per energy input (e.g. the index called EROI: Energy Return On the Investment) or thermodynamic concepts such as exergy analysis (Cleveland et al., 1984; 2000; Hall et al., 1986; Gever et al., 1991; Kaufmann, 1992; Hall, 2000; Ayres et al., 2003; and Ayres and Warr, 2005 – an overview in Ref. [2]). In general terms we can say that the use of mono-dimensional and mono-scale methods entails serious problems when the goal of the analysis is to deal with the issue of "energy quality". As explained more in details in [2,14] these methods cannot overcome the unavoidable ambiguity of the definition of the label "energy". That is, quantities of energy belonging to the category of Primary Energy Sources (e.g. tonnes of oil equivalent) are not "the same" as quantities of energy belonging to the category of Energy Carriers (e.g. kWh of electricity). Moreover, within the same semantic category – e.g. Energy Carriers – joules of a given energy form (mechanical energy or electricity) are not equivalent to joules of a different energy form (thermal energy).

The problem of equivalence between different energy forms calls back to the systemic ambiguity associated with the concept of energy, that can be trade to the origin of the science of "energetics" [2]. In relation to this ambiguity we can say that, the science of thermodynamics has been especially developed for dealing with the consequences of the fact that different energy forms even if measured in the same quantity of Joules do have different qualities. The focus of the pioneers of thermodynamics, however, was mainly restricted to the problem of how to convert thermal energy into mechanical energy and vice-versa. By introducing the concept of thermodynamic cycles they found a way to characterize, in an analytical way, a given set of energy transformations – e.g. the Rankine cycle. That is, classic thermodynamics posed the problem of the existence of non-reducible differences in quality of different energy forms: e.g. 1 J of mechanical energy is not the same as 1 J of thermal energy. Then the work of Carnot, Joules and others made it possible to solve this problem by generating "equivalence criteria" within well defined thermodynamic cycles (a conversion factor between Joules of thermal energy required to generate Joules of mechanical energy). Yet this solution based on the pre-analytical definition of a given set of thermodynamic cycles is not particularly useful for the analysis of the energetics of self-organizing systems, such as modern societies dealing with exosomatic energy (outside human bodies). Indeed, large complex systems operating across different scales can operate simultaneously using different technologies to carry out the same task (e.g. generating electricity using power plants operating with different efficiencies) and in different boundary conditions – e.g. the outside temperature for the processes going on inside the human body is stable and different from the temperature outside the human body. In such context, the use of equivalence criteria and quality factors (e.g. exergy) is limited (more information in Ref. [2]).

Moreover, the innovative concepts introduced in the field of non-linear thermodynamics made things even more difficult to handle. When dealing with complex metabolic systems that act as dissipative systems whose identity has been frozen in time. According to the metaphor proposed by Schrödinger these systems define, on their own, what should be considered as a set of favorable gradients (negative entropy). That is, the definition of both what is an "energy input" and "waste" – to be adopted in a quantitative analysis – depends on the identity of the metabolic system. Gasoline is an energy input for a car, but not for a mule. Hay is an energy input for a mule but not for a car. In the same way, a jumbo jet cannot run onto electricity, in the case it were supplied with a "thermal equivalent" amount of joules. For this reason it is essential to account Joules of energy only after having established a set of relevant categories of accounting, since the simple indication of unspecified "quantities of Joules" is not sufficient to carry out a useful description of energy systems. Complex autopoietic systems (=systems generating themselves) require a pre-analytical tailoring of the categories used for their quantitative analysis on their specific characteristics and features. For this reason the quantitative analysis proposed in this paper is not based on "quantities of energy" [i.e. a single number] but on vectors [i.e. an array of numbers] in which we specify using different categories: (i) the overall quantity of Joules of energy carriers; (ii) the fraction of thermal; and (iii) the fraction of mechanical energy (more details in Ref. [2]). This characterization can be used to check the compatibility of the supply of energy carriers with the characteristics of the requirement (end use). Using the metaphor of human metabolism, in order to develop knowledge about the physiology of a human being you have to observe first of all how the human body functions (what type of energy inputs are used to carry out which functions) and then to provide a more elaborated definition of the energetic intake (from carbohydrates, from proteins, from fats). The same applies to energy systems whose functions must be identified in order to discuss the energetic metabolism of society.

According to this rationale, when studying and comparing energy flows in different countries it is essential to perform (and keep separated!) two kinds of energy accountings [14] referring to:

(1) Primary Energy Sources (PES) expressed in physical units such as tonnes of coal, kilograms of uranium) – the use of PES makes it possible to bridge the assessments made using energy variables with assessment made with non-energy physical units. This analysis is useful for dealing with environmental impact and biophysical constraints;
(2) Energy Carriers (EC) expressed in energy units such as joules or watt-hours – the use of EC makes it possible to bridge the assessments made using energy variables with variables useful for socio-economic analysis (i.e. prices and technical coefficients). This makes it possible to develop a new method of bio-economic analysis (proposed here) defining "bio-economic costs" in terms of requirements of production factors (hours of paid work, power capacity, and inputs of energy carriers) per unit of net supply. This analysis is useful for dealing with the existence of internal constraints defining the viability of a given energy system.

The innovative approach called MuSIASEM (Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism) makes it possible the integrated handling of physical units, energy variables and other socio-economic variables [1,2]. Therefore, this approach makes it possible to differentiate the quantitative representation of "external constraints" – the biophysical constraints "and" environmental impact associated with the overall requirement of PES and generation of waste and pollution – from the quantitative representation of "internal constraints" – the viability of the proposed control over inputs of EC "and" of other production factors [1,2]. In more general terms we can say that the MuSIASEM approach has been developed to provide an integrated assessment structured on a multi-criteria analysis capable of dealing with the complexity of energy systems as well as the inherent ambiguity associated with the concept of "energy" [14].

3. The concept of grammar applied to the analysis of energy systems

3.1. The concept of grammar

In order to overcome the epistemological problems discussed in Section 1 "quantities of energy" considered as relevant for the assessment can only be measured and aggregated after having agreed on a pre-analytical definition of a 'grammar' which has to be tailored on a given and finite set of energy transformations. A grammar consists in a set of expected relations linking 'semantic categories' (the different energy forms used in the process) and 'formal categories' (their relative quantification) according to a given set of production rules (the technical coefficients determining "transformities" among different energy flows). For a more detailed description see Ref. [1], Chap. 6 and [2], Chap. 9 and 10. An illustration of this concept applied to the case of power-supply systems is given in Fig. 1.

After having defined a Power-Supply System as an integrated set of 'unit operations' (functions, corresponding to the production rules of the system) capable of generating a net supply of electricity (output) from a given amount of Primary Energy Sources (input), we can make a distinction between the different semantic and formal categories needed to analyze and characterize the chosen set of energy transformations. Primary Energy Sources (a semantic category of energy form requiring the existence of favorable gradients whose existence is outside human

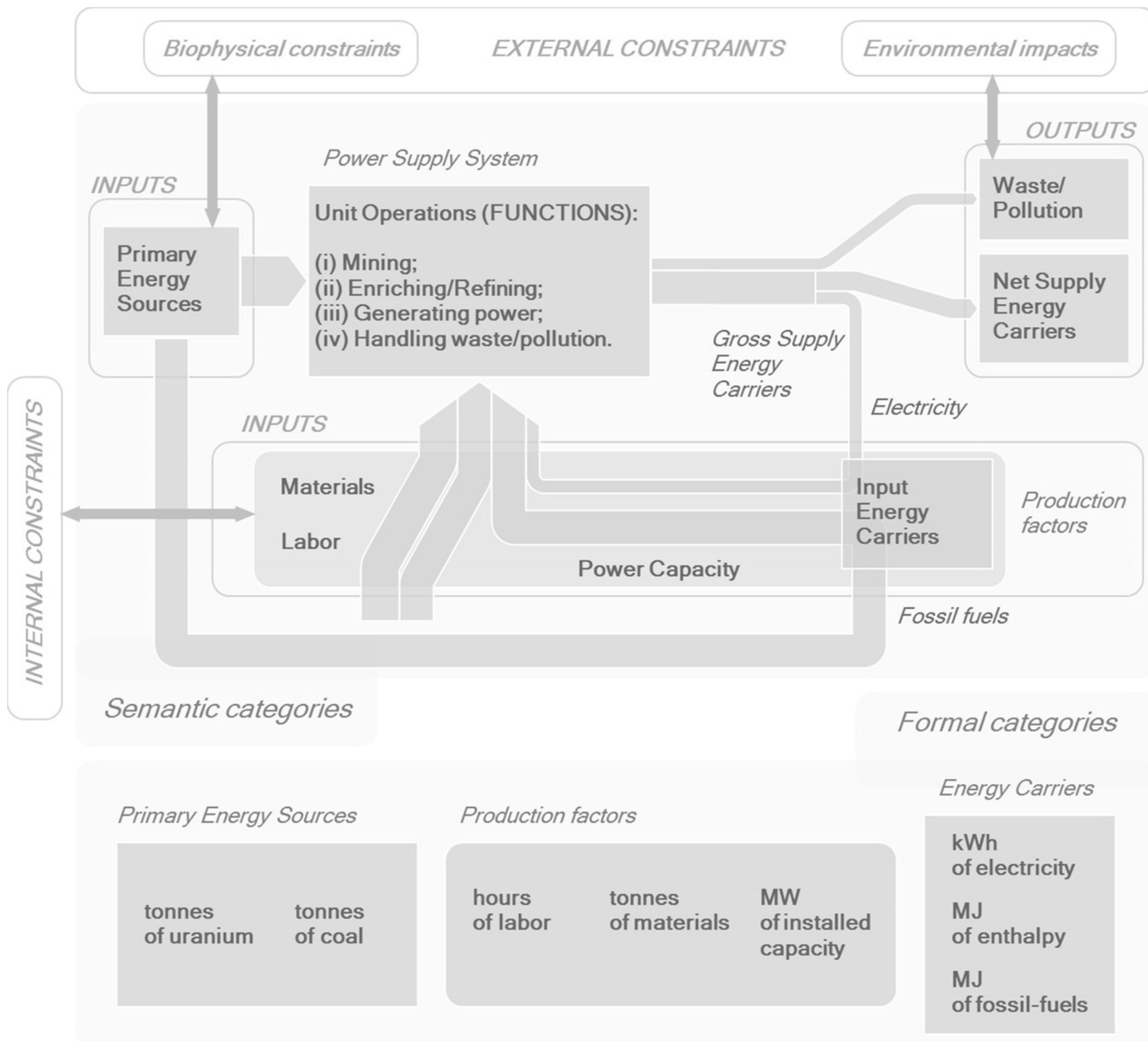

Fig. 1. Semantic and formal categories for characterizing the performance of a power-supply system.

control) can be quantified, using formal categories (proxy variable to which we can assign a value using a measurement scheme). For example, we can use kilograms of uranium (when assessing nuclear power plants) or tonnes of coal (when assessing coal-fired power plants) to assess the required quantity of Primary Energy Sources (PES) over a period of one year. The output and the inputs of "energy" associated with the process of exploitation have to be measured using another semantic category for energy accounting: Energy Carriers under human control (EC). In turn, these inputs and output have to be measured using different formal categories. Depending on the nature of the energy carrier considered we have to use different variables – e.g. kWh of electricity and MJ of enthalpy (or process heat) – when the quantitative accounting of these energy carriers refers to non-equivalent energy forms (e.g. thermal vs mechanical). Because of its ability to establish an agreed relation between the chosen semantics (perception of the issue) and the chosen formalization (representation of the issue) the pre-analytical definition of a grammar is essential. In fact, the grammar makes it possible to obtain a shared meaning about the numbers developed within the quantification process by identifying clearly the external referents – i.e. what is observed and what is described by the numbers. This is illustrated in Fig. 1 in the case of power-supply systems where inputs and outputs are identified in semantic terms and put in relation to their external referents (internal and external constraints).

In summary, a grammar requires a pre-analytical agreement among those that will use the quantitative results about the "relevance" of the semantic categories and the "pertinence" of the formal categories and the production rules used in the protocol. When characterizing the performance of a power-supply system, exploiting primary energy sources to generate a net supply of energy carriers (output), this agreement has to refer to the series of choices required to establish a relation between: (i) the requirements of biophysical gradients outside human control (Primary Energy Sources, as inputs) – an information relevant for the analysis of biophysical constraints (external constraints); (ii) the requirements of sink capacity from the environment to absorb the waste and pollution generated (e.g. radioactive waste, carbon dioxide emissions, as outputs) – an information relevant for assessing the environmental impact (external constraint); and (iii) the requirements of production factors (inputs of power capacity, energy carriers, human labor) – an information relevant for an analysis of internal constraints. In the resulting integrated characterization these requirements must be calculated per unit of net supply of energy carriers, when considering the whole set of energy transformations taking place across the different energy forms involved in the process.

3.2. Defining a frame for assessing the performance of power-supply systems

The first step of the analysis is to identify the process of production of a net supply of a unit of Energy Carrier (e.g. 1 kWh of electricity) starting from a given typology of Primary Energy Sources (e.g. nuclear, coal, hydro). This production requires a series of different unit operations (or functions). By specifying these unit operations, first in functional terms and then by assigning to each function an associated structural type capable of expressing such a function, we can finally describe "what the power-supply system is" – using the MuSIASEM jargon we define the 'fund-elements' [2] – and "what the power-supply system does" – using the MuSIASEM jargon we define the 'flow-elements' [2] – across different levels of organization (parts/whole). Put in another way, we can generate such a representation only after having agreed on the need for a set of typologies of functions (why you need the various elements of the power-supply system) and the definition of typologies of structural organization (how the various elements of the power plant and the overall system work and express their function within or outside it). Therefore, in order to be able to compare the performance of different processes of production of energy carriers – in this example, power-supply systems producing electricity – it is important to individuate and define in the pre-analytical phase the set of tasks and relative compartments in charge for these unit operations determining the emergent property of "the power-supply system" that are common to the different typologies of power-supply systems.

That is, the grammar requires also a protocol of accounting capable of quantifying the chosen semantic categories. For example, favorable gradients can be measured in "potential heat" that can be extracted by available uranium minerals or in "potential heat" that can be extracted by available coal. Quantitative assessments of PES should be expressed in non-energy physical units (e.g. tonnes). In the same way, power capacity can be the capability of processing energy carriers in the process of exploitation of nuclear energy or fossil energy during the production of electricity (i.e. the physical converters needed to generate the power output measured in watts). The grammar therefore has to provide a protocol of accounting capable of establishing a relation between:

(i) the requirements of PES and of sink capacity – a quantitative definition of required inputs and outputs measured in non-energy physical units, that are relevant to assess the severity of external constraints;
(ii) the net supply of EC – a quantitative definition of flow output relevant to assess the performance of the power plant; and
(iii) the requirements of production factors – a quantitative definition of the inputs required to stabilize the output, an information relevant to assess the severity of internal constraints (the biophysical viability of the process).

3.3. Standard grammar of energy transformations within power-supply systems

In Fig. 2, we provide four examples of grammars characterizing the set of energy conversions taking place within different power-supply systems. In particular, by looking at the different energy conversions ("what the power-supply system does"), the standard grammar of energy transformations helps guiding on what energy forms (semantic categories and subsequent formal categories) must be included within the main label "Energy Carriers" in order to compare two different power-supply systems that use PES (of different forms) to generate a Net Supply of EC (electricity).

For instance, in the case of nuclear energy used for the production of electricity, the following set of energy transformations (or conversions) can be identified (PES = Primary Energy Source; EC = Energy Carrier):

- Conversion #1: PES to EC_{HEAT} (EC_{HEAT} = Process Heat or Enthalpy)
- Conversion #2a: EC_{HEAT} to EC_{MECA} (EC_{MECA} = Mechanical Energy)
- Conversion #2b: EC_{MECA} to gross EC_{ELEC} (EC_{ELEC} = Electric Energy)
- Conversion #3: gross EC_{ELEC} to net EC_{ELEC} (final output of Net Supply of EC)

A comparison based on our grammar clearly indicates that nuclear energy and fossil energy present a striking similarity in the overall structure of energy transformations. Indeed, nuclear energy and fossil energy present the same set of energy transformations when producing electricity. In addition, within those two systems, Process Heat and Mechanical Energy are introduced as EC although they are not directly delivered to society (End Uses). Also, Conversion #3 does not strictly correspond to an energy transformation but rather to a loss of EC due to the "energy for energy" dissipative part (something common to all power-supply systems).

As a matter of fact, it becomes possible to compare the performance of nuclear energy and fossil energy for making electricity (the "whole") by looking at the characteristics of each one of their sub-processes (the "parts"). In doing so, we can use the following four standard functions describing the unit operations of both systems: (1) Mining; (2) Refining/Enriching; (3) Generating power; and (4) Handling waste/Controlling pollution.

4. Case study – comparison between power-supply systems based on nuclear energy and fossil energy

4.1. The comparison scheme of the process of electricity generation

This study adopts a biophysical representation of the metabolism of socioeconomic systems based on Georgescu-Roegen's [15] flow-fund theoretical scheme. In this scheme, 'flows' (e.g. energy inputs, material flows) refer to elements disappearing and/or appearing over the duration of the representation (time horizon of the analysis), while 'funds' (e.g. capital/power capacity, workers/hours of labor) refer to agents that are responsible for energy transformations and are able to preserve their identity over the duration of the representation (for a more detailed description see Ref. [1], Chap. 7).

In Fig. 3, we present an application of the flow-fund scheme used to compare the various 'processes' (transformation of energy flows) and 'facilities' (making and maintenance of the funds) within each one of the four unit operations for the production of electricity with nuclear energy and fossil energy: (1) Mining; (2) Refining/Enriching; (3) Generating power; and (4) Handling waste/Controlling pollution. Each one of these unit operations is made of sub-processes that make it possible to perform the successive energy transformations presented in Fig. 2. In particular, each energy conversion covers the following sub-processes:

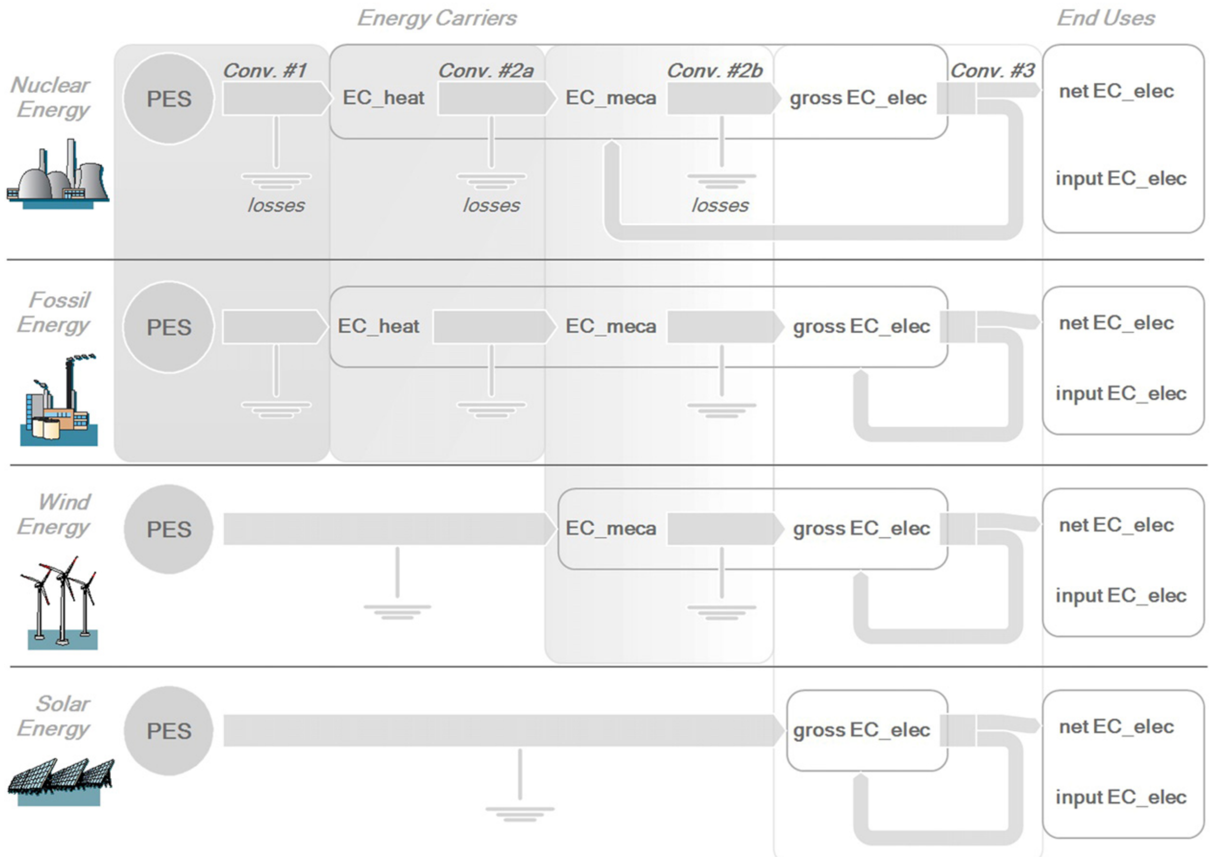

Fig. 2. Standard grammar of energy transformations for power-supply systems.

- Conversion #1: sub-processes of the "Mining", "Refining/Enriching" and "Generating power" ("Generating heat" only) unit operations;
- Conversion #2a: sub-processes of the "Generating power" ("Rankine cycle" only) unit operation;
- Conversion #2b: sub-processes of the "Generating power" ("Generating electricity" only) unit operation; and
- Conversion #3: internal consumption of electricity as losses during the "Generating power" ("Generating electricity" only) unit operation.

Note: the sub-processes of the "Handling waste/Controlling pollution" unit operation occur outside the energy conversions.

The four unit operations for the production of electricity represent the main semantic categories (in relation to the production rules within the systems) used to carry out the quantitative assessment. In this way, it becomes possible to compare the performance of different power-supply systems considering the characteristics of each one of the sub-processes distributed among each unit operation.

From Fig. 3, we see that the various processes of the "Generating power" unit operation are the same. However, since the facilities involved in this unit operation (power plants) are quite distinct between the two power-supply systems, this will translate into significant quantitative differences in the corresponding sub-processes (see the assessments reported in Section 4.3). In relation to the other unit operations, the two systems present qualitative differences in the set of processes and facilities prior to generating Process Heat (Conversion #1 in Fig. 2) – that is during the "Mining" and "Refining/Enriching" unit operations – and after generating electricity (Conversions #2b and 3 in Fig. 2) – that is during the "Handling waste/Controlling pollution" unit operation.

The remainder of this section consists in (i) describing and characterizing the baseline cases of both power-supply systems (Section 4.2); (ii) presenting the general scheme of the study (Section 4.3); and (iii) evaluating the biophysical requirements of the two systems[1] producing electricity when using this grammar (the calculations are given in Appendix A).

4.2. Description of the baseline cases used for the comparison

Two baseline cases are considered for each one of the two power-supply systems assessed leading to a total of four cases identified throughout the study as follows:

- Case 1: Nuclear energy – Light Water Reactor (LWR) power plant;
- Case 2: Nuclear energy – LWR power plant with reprocessing;
- Case 3: Fossil energy – Integrated Gasification Combined Cycle (IGCC) power plant;
- Case 4: Fossil energy – IGCC power plant with Carbon Capture and Storage (CCS).

[1] In this study, we define as "power-supply system" the whole process of production of electricity including all sub-processes (the combination of all unit operations according to the grammar specified in Section 3), either using nuclear energy or fossil energy. For such a production process, it is more correct to use the term "power-supply system" rather than "energy-supply system" since it includes the latter, whereas the reverse is not true [16]. Hence, the term "energy-supply system" (or simply "energy system"), wherever it is used in this study, should be understood as "power-supply system".

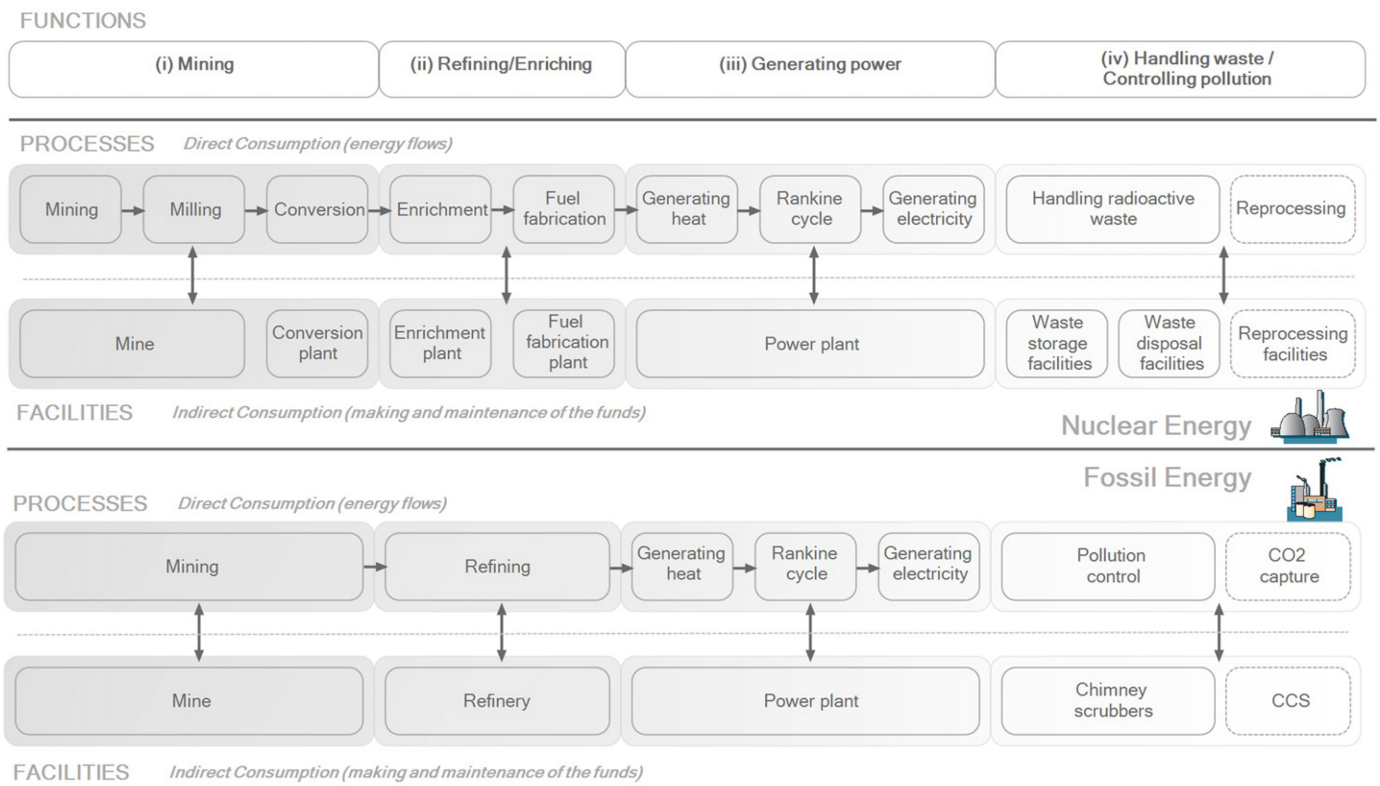

Fig. 3. Comparison scheme of the process of electricity generation – Nuclear energy vs. Fossil energy.

The selection of those two couples of baseline cases for the comparison between advanced technologies of the fossil energy and nuclear energy systems for the production of electricity is mainly motivated by (1) the availability of the selected technology (Cases 1 and 3); and (2) the pace at which new designs can be deployed and become a representative technology in the world-wide electricity generation from either nuclear or fossil energy (Cases 2 and 4).

On that respect, advanced designs of fossil energy power plants including carbon dioxide (CO_2) capture (Case 4) are considered as an available technology (or soon to be) whose deployment would be much faster than the future generation of nuclear power plants (generation IV), a technology not yet available, whose deployment would require many decades (if they are to be ever deployed) before becoming a significant technology of the nuclear energy sector.

The same applies for “fission” versus “fusion”. Indeed, only nuclear “fission” energy is considered here as it corresponds to the only application currently performed from thermonuclear physics for industrial purposes (excluding medical applications) – mainly in the production of electricity.[2] Although, research about potential commercial application from nuclear “fusion” energy is achieving some progress as the experimental stage is expected to start in the mid-term – through the ITER project announced to be in operation by 2019 – followed by a demonstration stage – the future DEMO prototype power plant – announced to be operational by 2040 [16]. Even assuming as accurate these time estimates, we cannot realistically expect nuclear fusion to become a significant (primary) energy source for supplying electricity (an energy carrier) over the 21st century.

Indeed, even the commercial application of nuclear fusion energy before the end of this century can be questioned as (i) there are still fundamental research questions that have not been answered yet by the community of nuclear fusion scientists – such as the experimental impossibility to reach a self-sufficient tritium breeding process necessary for fusion power plant operation [17]; (ii) there is a systemic problem when scaling-up a new nuclear power program mainly due to the different degrees of complexity between academic-reactor operations and an operational-reactor fleet – which has been the case during the first nuclear fission energy era [18–20]; and (iii) the deployment of fusion nuclear power plants would imply a nuclear–fuel cycle transition which requires between 50 and 100 years to happen [21] which would be further delayed if a new fleet of Generation IV reactors is to be deployed in the mean time, or simply because of the existing technological lock-in that affects nuclear technology [22,23]. For those reasons, nuclear fission energy is very likely to remain the only nuclear energy source over the entire 21st century and maybe beyond into the future.

As far as the nuclear fuel cycle, according to a study from the Massachusetts Institute of Technology (MIT), the LWR partly-closed fuel cycle consisting in reprocessing the plutonium and uranium implies a reduction of the enriched uranium fuel demand of about 15% and 10% respectively [21]. According to the same study, the spent used nuclear fuel (SNF) can only be reprocessed one or two times [21]. The partly-closed fuel cycle is therefore currently used only as an experiment both in France and in the UK. Its potential large scale deployment would require between 50 and 100 years [21]. In addition, since it also raises proliferation concerns it does not represent today a significant fuel cycle option. Nevertheless, it has been considered in this study (Case 2) in order to evaluate the effects of the reprocessing operations on the performance of the nuclear-based power-supply system, letting alone the other problems raised above.

[2] The use of nuclear fission energy for the production of industrial process heat is not within the scope of this study although it represents one possible application of the same technology based on nuclear energy.

It should be noted that the sizes of the two plants (nuclear and fossil) that are compared are different. However, this does not affect the validity of the comparison. In fact, the relative size of these two types of power plants (1300 MW for nuclear power plant and 480 MW for IGCC power plant) reflects the typical size of existing plants. In fact, it is well known that the most significant technologies for nuclear power and IGCC technology do show different power outputs in the range of the power output considered here. The power output of these two technologies is, in fact, determined by optimization factors determining their size, meaning that this "typical size" should be expected as associated with the technology. Clearly, moderate changes in the size around these typical values may affect the technical coefficients calculated here. In any case, the different orders of magnitude in the requirement of some production factors per unit of net supply of electricity between the two systems (see Section 4.4) suggests that the issue of scale, unless of dramatic changes in the technology, can be neglected in this type of comparison.

4.2.1. Case 1: nuclear energy (LWR power plant)

For the nuclear-based power-supply system, we consider the same baseline case of a typical 1300 MWe power plant with a light water reactor (LWR) as used by Lenzen [24] along with a once-through nuclear fuel cycle meaning that no reprocessing is being considered during the process of production, as shown in Fig. A.1.

LWRs – including pressurized water reactors (PWR) and boiling water reactors (BWR) – represent about 90% of the worldwide installed capacity of nuclear power plants connected to the grid [25], while most new plants are on average 1300 MWe – from 1000 MWe to 1600 MWe. The capacity load factor (CL) of 79% – shown in Table 1 – corresponds to the average power output over the period of availability of all currently operating LWRs in the World [25]. This factor reflects the actual use of the converter, that is, its actual "net output of energy" (which corresponds to our "gross supply of electricity" before taking into account the input of electricity required by the overall power-supply system). The burn-up (or heating value) corresponds to the amount of thermal energy extracted from initial nuclear fuel in the reactor, expressed in gigawatt-days per metric ton of uranium (GWd/t). It depends on the nuclear fuel re-load of the reactor – 45 GWd/t corresponding to the average value for LWRs [24]. The uranium fuel (UO2) consumption of 25t/y comes from the mass balance evaluation detailed in [26]. This is consistent with the average values of 20t/GWe per year [21] corresponding to about 26t/y for the selected baseline case. This corresponds to 181tU/y of natural uranium requirements,[3] the main difference with the uranium fuel consumption coming from the depleted uranium (UF6) that exits the system after the enrichment process (see Fig. A.1).

It shall be mentioned that the burn-up depends only on the technology used for the reactor, not on the uranium ore quality. Indeed, as mentioned before, the burn-up is imposed by the frequency at which uranium fuel is re-loaded into the reactor while uranium fuel is adapted to the reactor type. The quality of uranium ore (grade or natural enrichment) then plays a role in the enrichment process – the lower the uranium grade, the more enrichment effort required ([26], Section 4) – hence ultimately influencing the requirements of production factors (labor, materials, power capacity) of the overall system in order to process the same amount of natural uranium (Yellow Cake, U3O8) and then supply the same amount of uranium fuel (UO2) to the power plant (reactor).

[3] Natural uranium requirements are expressed in terms of tonnes (t) of contained uranium (U) rather than in terms of uranium oxide (U3O8).

Table 1
Parameters of Case 1 (Sources: [24,25]).

Parameter	Value	Unit	Source
Burn-up	45	GWd_{th}/t_U	[24]
Uranium fuel consum.	25	t_U/y	See Fig. A.1
Process heat generated	97,600	TJ/y	
Plant capacity	1300	MW_{el}	[24]
Capacity load	79%	(World av. for LWR)	After [25]
Electricity generated	9000	GWh_{el}/y (gross supply)	
Rankine cycle efficiency (gross)	33%		

Such a defined nuclear power plant generates about 100,000 TJ of process heat (or enthalpy, in our case of an isobar process) corresponding to about 9,000 GWh of (gross) electricity per year.

4.2.2. Case 2: nuclear energy (LWR power plant with reprocessing)

Case 2 differs from Case 1 by including a reprocessing phase into the nuclear fuel cycle, as shown in Fig. A.2. The reprocessing operation consists in the partial recycling of the used fuel (uranium) and products of the fission reactions (plutonium), as well as in the reprocessing of the depleted uranium (UF6) which operations reduce the consumption of natural uranium down to 152 tU/y for the same power plant. This process is further detailed in [26]. Table 2 presents the parameters of the baseline Case 2 which are essentially the same as Case 1 since the reactor technology remains the same. The only difference is that the nuclear energy production process now is not only burning enriched natural uranium (corresponding to 16tU/y) but also reprocessed fuel – i.e. mixed oxide fuel (MOX, corresponding to 5tHM/y) and reprocessed uranium (UO2rep, corresponding to 4tU/y), see Fig. A.2 – so that the annual heated material (HM) consumption remains equal to 25 tHM/y as for Case 1.

4.2.3. Case 3: fossil energy (IGCC power plant)

For the fossil-based power-supply system, a 480 MWe Integrated Gasification Combined Cycle (IGCC) power plant using coal has been considered as the baseline case of this study. The coal-based IGCC technology, presented in Fig. A.3, corresponds to one of the new advanced designs of fossil-fueled power plants discussed in a study from the MIT [27] and whose latest baseline designs have been assessed by the U.S. Department of Energy [28]. The IGCC technology consists in turning the coal into gas in order to remove impurities before it is combusted, improving the overall efficiency of the power plant compared to conventional coal-fired power plants.

Contrary to nuclear energy, the heating value of a fossil-fueled power plant does not depend on the selected technology but rather on the type of coal being mined (e.g. bituminous, lignite, etc.) – from which derives its heating content. As a matter of facts, the

Table 2
Parameters of Case 2 (Sources: [24,25]).

Parameter	Value	Unit	Source
Burn-up	45	GWd_{th}/t_U	[24]
Heated material consum.	25	t_{HM}/y	See Fig. A.2
Process heat generated	97,500	TJ/y	
Plant capacity	1300	MW_{el}	[24]
Capacity load	79%	(World av. for LWR)	After [25]
Electricity generated	9000	GWh_{el}/y (gross supply)	
Rankine cycle efficiency (gross)	33%		

Table 3
Parameters of Case 3 (Sources: [26,28]).

Parameter	Value	Unit	Source
Heating value	26	GJ/t_{coal}	[26], Table 7
Coal consum.	1.45	Mt_{coal}/y (av.)	After [28]
Process heat generated	37,100	TJ/y	
Rankine cycle efficiency	40.4%	(av.)	After [28]
Electricity generated	4200	GWh_{el}/y (gross supply)	
Capacity load	80%	(Equal to the availability)	[28]
Plant capacity	480	MW_{el}	

Table 4
Parameters of Case 4 (Sources: [26,28]).

Parameter	Value	Unit	Source
Heating value	26	GJ/t_{coal}	[26], Table 8
Coal consum.	1.52	Mt_{coal}/y (av.)	After [28]
Process heat generated	39,100	TJ/y (gross)	
Rankine cycle efficiency	40.4%	(av. w/o CCS)	After [28]
	33.7%	(av. w/CCS)	After [28]
Process heat generated	36,500	TJ/y (net)	
Electricity generated	3700	GWh_{el}/y (gross supply)	
Capacity load	80%	(Equal to the availability)	[28]
Plant capacity	420	MW_{el}	

heating value of 26 GJ/t – shown in Table 3 – has been calculated according to the proportion of each coal type being exploited in recoverable reserves (see Ref. [26], Table 7). The capacity load factor (CL) is taken equal to 80% [[28], Section 2.5], where it is assumed that the capacity load factor is equal to the availability of the converter since “each new plant would be dispatched any time it is available and would be capable of generating maximum capacity when online” (more details on those factors are provided for the evaluation of the power capacity, Section A.4). This leads to a coal consumption equal to 1.45 Mt/y (after [28]). The Rankine cycle efficiency is considered equal to about 40% (after [28]), which shows some improvements in the efficiency over the previous IGCC designs (38% in [27]). On that respect, it shall be noted that the Rankine cycle efficiencies have been evaluated by removing the electricity requirements of the “Mining” and “Handling waste/ Controlling pollution” unit operations for which electricity requirements will be accounted separately in Appendix A. The difference of efficiencies between Case 3 and 4 is therefore due to a lower performance of the same processes – i.e. the lower efficiency of Case 4 only translates the losses in the same equipments when the system contains a CCS technology and does not include the electricity requirements that go into the equipments of the CCS itself.

Such a defined fossil-fueled energy power plant generates about 37,100 TJ of process heat and about 4,200 GWh of (gross) electricity per year. The corresponding power plant capacity is then equal to 480 MWe.

4.2.4. Case 4: fossil energy (IGCC power plant with CCS) – 90% of CO_2 capturing

Case 4 differs from Case 3 by adding a carbon capture and storage (CCS) technology which reduces the CO_2 emissions of the power plant by 90%. The IGCC technology is one of the leading candidates for electricity production with CO_2 capture [27–29], which justifies our baseline case of IGCC + CCS. Although those new designs are still under development – especially the CCS technology included in this Case 4 – they are considered as the next generation of fossil-fueled power plants and are already being deployed in some places.

The CCS technology requires a certain amount of process heat – depending on the rate of CO_2 being captured, being here 90% – mainly due to the gas-compression needed before injecting the carbon into the ground (see Fig. A.3) so that the Rankine cycle efficiency drops from 40% down to about 34% (after [28]) as shown in Table 4. In order to compensate part of the loss of efficiency, the coal consumption is increased to 1.52 Mt/y (after [28]) so as to generate the same amount of gross process heat. The (gross) process heat of such a defined fossil-fueled power plant is equal to about 39,100 TJ per year which difference with Case 3 is due to the higher annual coal consumption. Then, the net process heat (36,500 TJ/y) generated by the selected fossil-fueled energy power plant can directly be derived from the loss of Rankine cycle efficiency. The corresponding power plant capacity is then equal to 420 MWe.

4.3. Description of the general scheme of the study

As shown in Fig. 4, all inputs and outputs referring to the semantic categories are expressed in their own units referring to their corresponding formal categories as described in Fig. 1. As discussed in Section 1, we do not perform any aggregation based on fixed conversions referring to “quality indexes” for different energy forms (the approach of reductionism) reduced to a single measurement unit.

There are two main categories of inputs that enter into the system: (1) the requirements of PES (uranium and coal) necessary to generate the supply of EC; and (2) the production factors necessary for the processes to operate properly and that include (i) electricity; (ii) power capacity (derived from the fossil-fuels requirements), (iii) labor; and (iv) other key materials. In addition, the outputs exiting the systems refer to (1) the Net Supply of EC (electricity) generated by the system, as well as (2) the waste and pollution generated during the process of production.

This integrated evaluation is carried out in two steps: (1) defining the Net Supply of electricity generated by the system (net GWh) using a given set of energy transformations (see Fig. 2). This is an assessment based on intensive variables – e.g. requirement per unit of output; and (2) evaluating the inputs and outputs (unit per net GWh) relevant for the later analysis of external and internal constraints. This analysis uses both intensive variables – e.g. technical coefficients, when analyzing qualitative differences – and extensive variables – e.g. total requirements or total emissions – when scaling qualitative information. Indeed, as explained in Section 3, in order to compare the two energy systems, all inputs must be expressed per unit of Net Supply of electricity obtained after evaluation of the electricity requirements (Input) and Gross Supply of electricity generated within each system. That way it becomes possible to compare power-supply systems (fossil energy and nuclear energy) independently from their specific power capacities.

In order to make possible such a comparison, all cases must address the implications of the internal requirements of electricity (Input) of the system (see Fig. 4) in order to evaluate the Net Supply of electricity to which the biophysical requirements will be compared. This is of capital importance for the study because the whole process might differ in terms of requirement of input of electricity – and so in terms of net supply of electricity – also when the Rankine cycle efficiency of the power plants (producing the gross supply of electricity) are of the same order of magnitude. Again, although we provide the characteristics of each unit operation according to the grammar (Section 3), the aim of the study is to characterize the performance of the “whole” (overall production process) after characterizing the performance of the “parts” (subprocesses distributed within the four unit operations).

After the integrated evaluation of the performance of the systems (inputs entering into the system, the technical factors necessary to operate the processes and the outputs exiting the

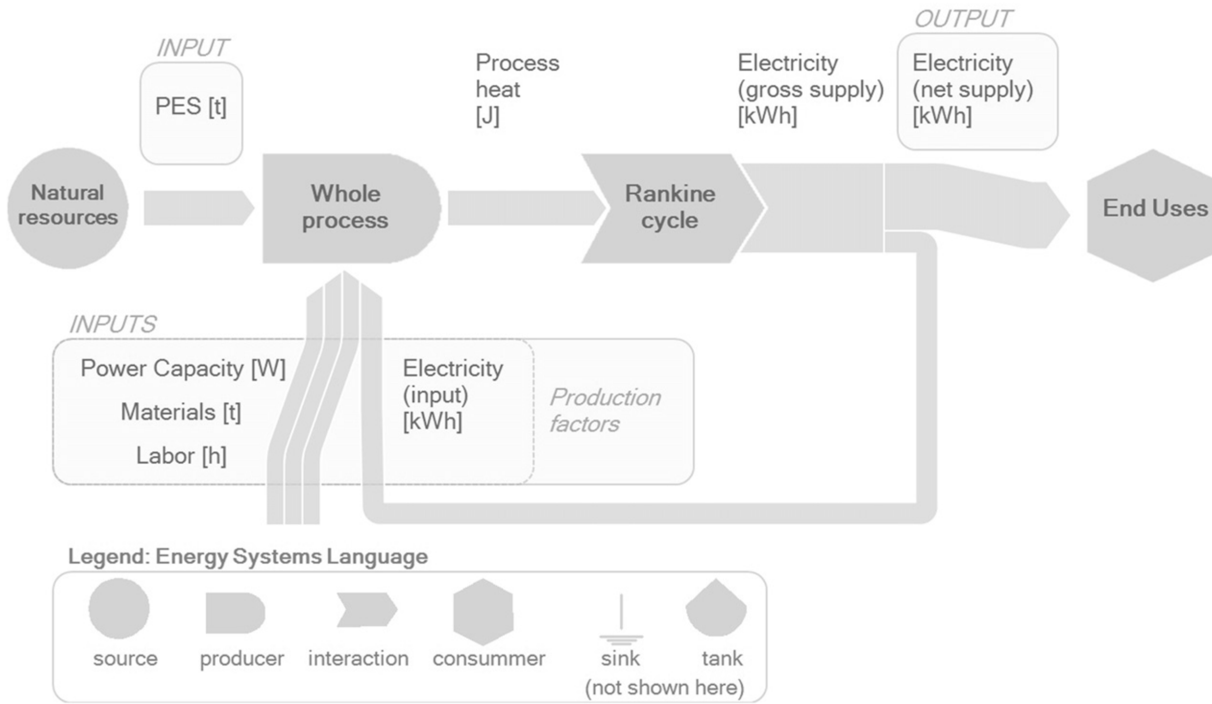

Fig. 4. General scheme of the study (Cases 1–3).

systems), it becomes possible to perform the actual integrated assessment of the two systems in relation to different external referents. Such an integrated assessment provides a "contextualized" picture of the performance referring to the severity of external constraints and internal constraints as seen in Fig. 1. For reasons of space, we will only provide an example of assessment of the PES requirements of the two systems in relation to the World coal and uranium reserves, the main objective being here to present our new approach of using grammars to assess the performance of power-supply systems.

Figs. 4 and 5 use the energy systems language first proposed by H.T. Odum [30] as a common denominator expressing all the flows and processes together in order to understand a whole system and the full interaction of the parts [31].

As shown in Fig. 5, the general scheme of Case 4 differs from the other cases by considering an additional internal requirement of

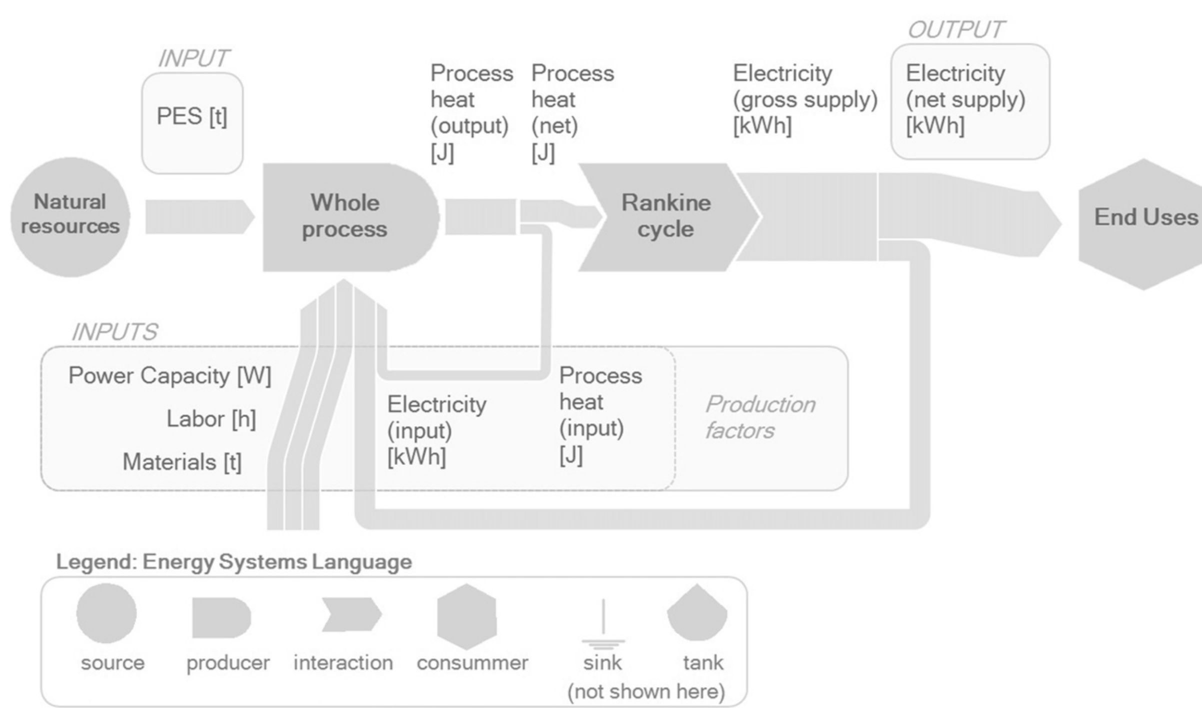

Fig. 5. General scheme of the study (Case 4).

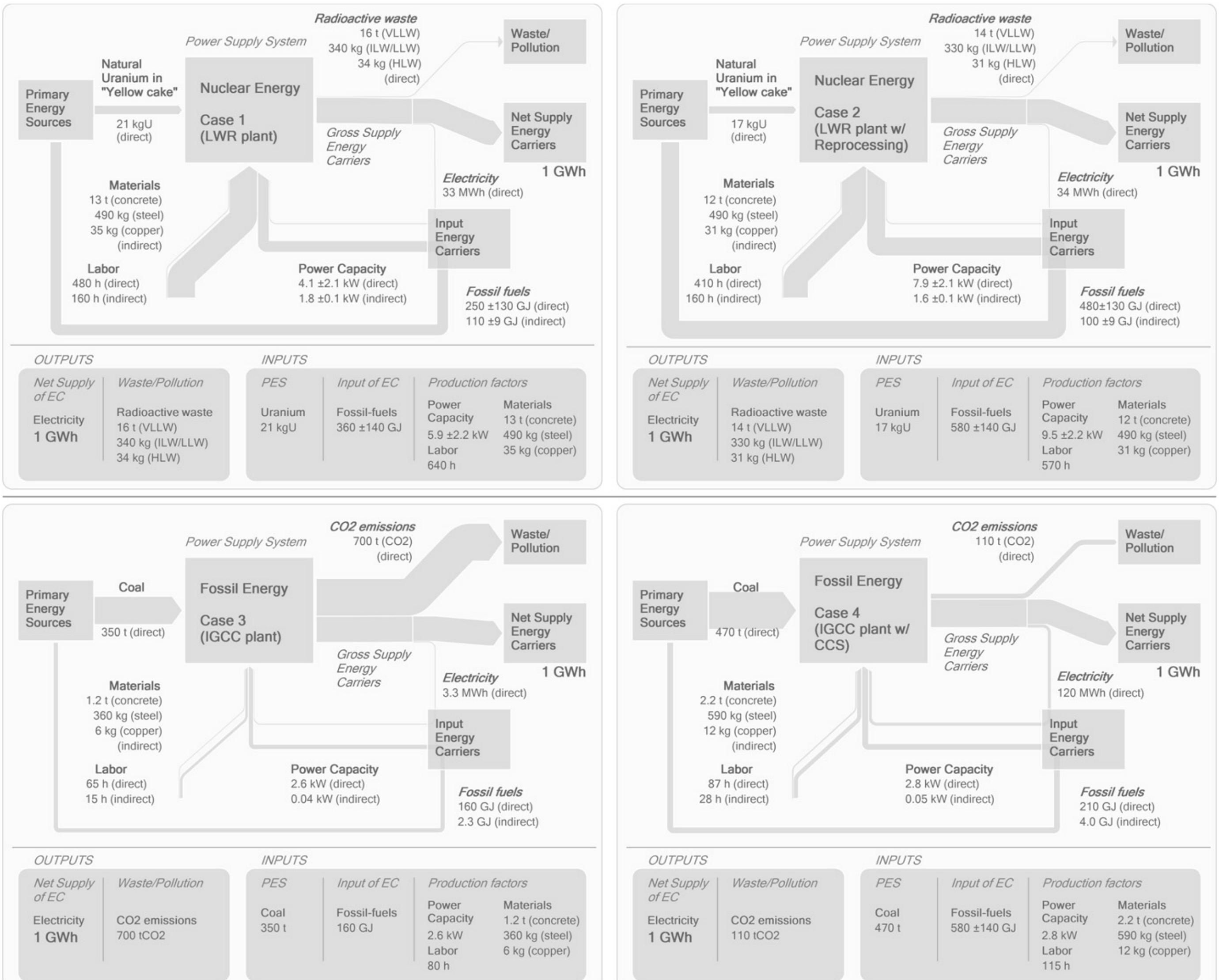

Fig. 6. Comparison of the performance of nuclear energy and fossil energy.

process heat (J) due to the CCS technology as explained in Section 4.2.4.

In order to evaluate the different biophysical requirements for the four cases of the study, the annual material balance has been performed for each production process. Each material balance includes the different sub-processes related to the fuel in all its successive forms – from the mining of natural resources to the handling of waste or pollution. Results of the material balances are shown in Figs. A.1 and A.2 of the appendices for nuclear energy, and in Tables 3 and 4 for the fossil energy. More details on the calculations can be found in [26].

4.4. *Integrated characterization of the performance of the power-supply systems*

The integrated characterization of the performance of the power-supply systems is performed in Appendix A [4] which presents the evaluation of all inputs and outputs for the four baseline cases presented in Section 4.2 following the general scheme presented in Section 4.3.

4.5. *Discussing the performance of nuclear energy and fossil energy*

Fig. 6 summarizes the integrated evaluation comparing the performance of the nuclear- and fossil-based power-supply systems (considering two technical solutions for each PES) whose inputs, outputs and technical coefficients have been evaluated in Appendix A. The summary presented below adopts the semantic and formal categories presented in Fig. 1.

4.5.1. *Characteristics relevant for the analysis of external constraints*

4.5.1.1. Biophysical constraints on the supply side: requirements of PES (inputs). From Fig. 6, we see that the requirements of PES is between 17 and 21 kg of uranium per net GWh of electricity for nuclear energy and between 350 and 470 tonnes of coal for fossil energy.

In relation to the analysis relevant for external constraints the overall requirements of PES (uranium and coal) must be compared to the overall availability of the natural resources (mineral form and

[4] Supplementary material is published online alongside the electronic version of the article.

fossil form, respectively) to provide meaningful information. That is, in order to be complete, the assessment of external constraints must be performed in relation to an external referent, namely the amount of PES available at the level of one country or a group of countries depending on the scale of analysis. Although this is not within the scope of this paper that mainly focuses on the definition of a new methodology for assessing the performance of power-supply systems, this approach flags the crucial importance of two key factors that could potentially affect the functioning of those systems: the availability and the quality of PES. An example of the integrated assessment of PES in relation to external constraints is provided in Section 4.6 (and Fig. 7).

4.5.1.2. Environmental impact on the sink side: waste and pollution (outputs). The other quantitative indicators relevant for the analysis of external constraints are the quantities of waste and pollution determining the sink capacity required from the environment. In the case of radioactive wastes they have to be handled for a long time period before they can be neutrally released to the environment. The duration of this period can reach the order of magnitude of 100,000 years in the case of the most radioactive wastes (HLW) – a very long time span that is very difficult to account for in energy analysis. Indeed, over such a time scale the "handling waste" operation becomes a fund element in relation to the time scale of the analysis of energy flows (generally fitting the lifetime of the power plant). Fund elements are constituent that preserve their identity during the analytical representation so that they participate to the definition of "what the system is". As a matter of fact, this means that when discussing the performance of nuclear energy compared with other power-supply systems, we should consider the biophysical costs associated with additional fund element even though these costs cannot be assessed within the same time scale. This fund element will remain there thousands of years after the original power plant will be decommissioned!

In the case of CO_2 emissions, the fund element of the power plant refers to the structures controlling emissions after the process of production of electricity. The biophysical costs of these fund elements become significant when intending to capture most of CO_2 emissions so as to prevent them from being released to the atmosphere. The controlling efforts (carbon capture) intend to ensure that the CO_2 molecules will degrade into the ground before the carbon elements reach the atmosphere – a phenomenon that requires hundreds of years after injection into the ground. Nevertheless, in the case of carbon capture, the secondary trapping mechanisms (residual phase trapping, solubility trapping, mineral trapping and adsorption trapping) – that depend on chemical phenomena – rapidly take advantage over the structural and stratigraphic trapping – that requires efforts of control – after injection. This means that in the case of CO_2 emissions, the time period of control is much shorter than in the case of the radioactive wastes for which handling efforts must be ensured until radioactivity drops to a level neutrally compatible with the environment.

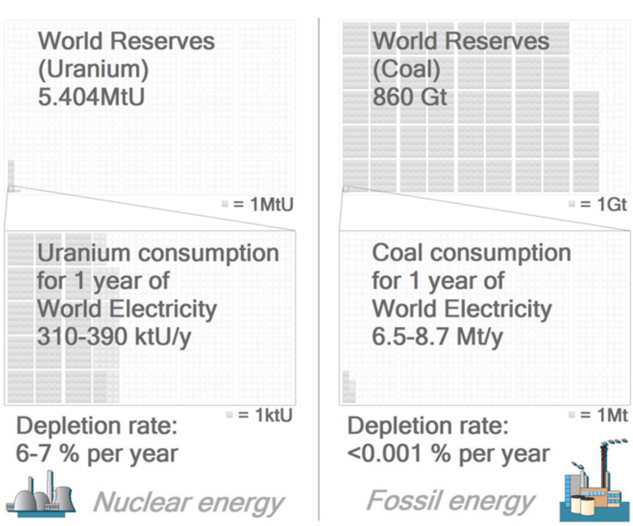

Fig. 7. Assessment of external constraints of nuclear energy and fossil energy: PES requirements at Global level. Source: [33]. Uranium and coal reserves excluding unconventional resources.

4.5.2. Characteristics relevant for the analysis of internal constraints (production factors)

In relation to the requirement of production factors for building and operating the power-supply system we make a distinction between the capability of handling two types of energy flow:

4.5.2.1. Requirements of fossil-fuels (input of EC) for the fund elements. In relation to this indicator, the fund elements required for nuclear power-supply systems are more dependent on fossil-fuels consumption than the fund elements required for fossil energy systems. In fact they require about twice as much fossil-fuels for the making of 1 GWh of electricity (360–580 GJ vs. 160–210 GJ). Moreover, this assessment can get even worse when considering the error bars for nuclear energy that are almost equal to the entire requirements for the fossil energy system (±140 GJ). This higher biophysical cost of the fund elements of the nuclear power plants (making and maintenance of facilities) is due to higher intensity of the "Generating power" unit operation of the nuclear energy system that equals the requirements of the "Mining" and "Refining" unit operations of the fossil energy system. On that respect, it should be noted that the indirect fossil-fuels requirements for the building and maintenance of fund elements of fossil energy is almost negligible when compared to nuclear energy.

4.5.2.2. Requirements of power capacity for the fund elements

* Direct inputs of EC (fossil-fuels) used for the generation of the gross supply of electricity – in relation to these requirements the overall PC of the power-supply system in the case of nuclear energy is about twice as much as fossil energy (4.1–7.9 kW/GWh vs. 2.6–2.8 kW/GWh). More importantly, it should be noted that the requirement of PC for fossil energy is within the same order of magnitude of the error bars for nuclear energy. This fact is determined by the higher requirements of fossil-fuels during the processes of the nuclear energy system coupled with a lower utilization factor (UF) due to less flexibility (CL) and longer unavailability periods (OL), when compared with fossil energy power plants;

* Indirect inputs of EC (fossil-fuels) used for the construction and maintenance of the fund elements of the power-supply systems – the higher amount of indirect fossil-fuels requirements translates into an indirect PC of nuclear energy that is about 2 orders of magnitude higher than for fossil energy (1.6–1.8 kW/GWh vs. 0.04–0.05 kW/GWh). This means that for making 1 GWh of electricity, the nuclear-based power-supply system requires a significant capital investment (for making and maintaining the facilities) whereas it seems not to be an issue with fossil energy. In this case, the power capacity required by the fossil energy system is not even within the error bars of nuclear energy system.

4.5.2.3. Requirements of labor (paid work) for both the flow and the fund elements

* Direct use of labor in the control of flows through the power-supply system – it is much larger in the case of nuclear energy (410–480 h per net GWh of electricity) than for fossil energy (65–87 h/GWh). This is explained by the special characteristics of the "Mining" unit operation of the nuclear energy system being highly labor intensive.

* Indirect use of labor for the production and maintenance of fund elements – again we find values much larger with nuclear energy (about 160 h/GWh) than with fossil energy (15–28 h/GWh).

All things considered the differences in labor demand (570–640 h found with nuclear energy versus 80–115 h with coal-fired power plants) are quite relevant (from 5 to 8 times).

4.5.2.4. Material requirements for the production and maintenance of the fund elements. Also when looking at material requirements associated with the production and maintenance of fund elements, nuclear energy is about 5–8 times more intensive than fossil energy. When considering three key materials (concrete, steel and copper) we find that 13–14 tonnes vs. 1.6–2.8 tonnes are needed in order to make and maintain the facilities necessary for the power-supply systems to operate. This difference in material intensity of the structural elements explains the difference in indirect labor requirements (160 h vs. 15–28 h).

4.6. Example of an analysis referring to external constraints

As explained in Section 4.3, after generating an integrated characterization of the performance of the systems per unit of output – as the one presented in Fig. 6 – it becomes possible to perform the actual integrated assessment of the two systems in relation to different research questions. Such an integrated assessment provides a "contextualized" picture of the performance that can be used to study the severity of both external constraints and internal constraints as seen in Fig. 1. Here we provide an example of analysis of external constraints by comparing the relative scarcity of the PES specific for the two systems (contextualizing their requirement against World coal and uranium reserves). For reason of space we consider here only one type of constraint (availability on the supply side) and only a scale of analysis (the entire World). Again we remind the reader that the main objective of this paper is to illustrate the potentiality of our approach based on grammars and not to provide an exhaustive assessment of performance (an objective that would be impossible without having first specified the goal of the assessment). That is, the objective of our study is not to assess the quality of a specific power plant but just to illustrate the potentiality of our method to characterize the performance of energy systems in a context of energy policy choices. This means that the problem of depletion of primary energy sources (PES) becomes relevant only at the societal level. For instance, to assess the requirements of PES in a given country – associated with the adoption of a given energy system – in relation to both its domestic availability and to the risk of heavily relying on imports.

In this example, we compare the worldwide availability of uranium (PES of the nuclear energy system used in Cases 1 and 2) and coal (PES of the fossil energy system used in Cases 3 and 4) in relation to the pace of consumption of the quantity of PES which is required to generate one year of World electricity. This makes it possible to discuss the relative scarcity of the PES which the two systems depend on for their feasibility. Clearly, this analysis refers to a very large scale perspective. When adopting a different scale of analysis the criteria of contextualization could become quite different. For instance, when considering the national level an energy system may result "better" in a given country with a clear biophysical availability of the chosen PES (e.g. coal in Germany) but this assessment would not necessarily apply to a country with different PES availabilities.

The comparison of PES requirements for one year of World electricity in relation to their worldwide availability is given in Fig. 7. In 2009, the worldwide annual electricity consumption was about 18,500 TWh [32]. Then, using the evaluation of the consumption of PES from our study (Fig. 6), it is possible to evaluate the consumption of PES that would be necessary for supplying the worldwide electricity demand. This would translate into a consumption of PES assessed in: (i) a consumption of natural uranium of 310–390 ktU/y in the case of nuclear energy; and (ii) a coal consumption of 6.5–8.7 Mt/y in the case of fossil energy.

In this hypothetical example where the worldwide annual electricity consumption would have to be supplied by either only nuclear energy or only fossil energy, uranium demonstrates a higher depletion rate (6–7% per year) than coal (less than 0.001%) – about 4 orders of magnitude higher. This means that, in this context, the possibility that the availability of PES will become a limiting factor preventing the nuclear power-supply systems from supplying a significant share of the worldwide electricity demand is much stronger than for coal power-supply systems. This example of analysis in relation to external constraints (being here the availability of PES) illustrates how the given grammar can be used to discuss and compare the viability of alternative energy sources after having chosen a given narrative about the option space within which a given power-supply system can operate.

In the analysis of the possible limiting constraint on the supply side for these two types of PES, there is another significant factor that has to be considered: the change in time of their quality. Indeed, every natural resource (mineral and fossil) in a mature state of exploitation shows a declining "quality" defined as a continuous increase in mining and refining efforts – e.g. a higher requirement of production factors in our grammar – to get the same amount of fuel supplied to the power plant. In the case of nuclear energy the natural uranium shows a significant decline of its quality [24,34] – i.e. uranium ore grade (natural enrichment) – compared with coal. This phenomenon is very important as it results in a continuous decrease in the "net supply of EC" provided by the energy system over time – the so-called 'energy cliff' [34] – which, especially in the case of nuclear energy, is affected by large doses of uncertainty on the actual quality of the natural resources that will be extracted in the future. As a matter of fact, it is crucial that the resource quality is systematically included in discussions about the performance of power-supply systems, and more generally of alternative (primary) energy sources.

Finally, it should be noted that in this example, we have focused on a possible analysis of limiting factors on the supply side – World availability of PES. Obviously, if we would have considered potential problems on the sink side, we should have provided a comparison of the problems associated with the generation of wastes – e.g. by comparing the negative effect of CO_2 and radioactive wastes.

5. Conclusion

5.1. The peculiar characteristics of this integrated assessment

In this paper we presented an innovative method of biophysical analysis of the characteristics of power-supply systems which is quite different in its logic from the conventional approach used in economic analysis. This fact is due to the special status of Primary Energy Sources (also called "non-manmade energy inputs"). In energetic terms we can consider the energy input provided by PES as free, as its existence does not require the use of production factors (investments of power capacity and human activity). As observed by Hall and Klitgaard "*... we do not pay Nature for energy, but only the cost of exploiting it*" ([9] p. 135).

For this reason, when looking at internal constraints the investments of production factors under human control refer only to the "biophysical costs" associated with the building, maintenance and operation of fund elements used in the exploitation process. That is the exploitation process can be studied by characterizing the internal loop of energy for energy, that defines (is determined by) the quality of the PES. A low quality PES can be associated with "a large requirement of energy investment under human control", also described as "a low output/input of energy carriers" and finally also described as "a low EROI (Energy Return on the Investment) of the process of exploitation". The internal loop of energy for energy in the autocatalytic loop is of crucial importance because it affects two key characteristics of the power-supply system:

(i) the requirement of fund elements (production factors) needed to control its transformation;
(ii) the requirement of PES needed to get a net supply.

This explains why the flow of coal or the flow of uranium getting into the power plant is not considered among the inputs when characterizing the energetic characteristics of the autocatalytic loop. Rather the flow of coal and uranium is considered as a flow of material input that has to be available to the system. That is, the quantitative assessment of this material flow is used to check the biophysical feasibility in relation to external constraints – i.e. tonnes consumed versus tonnes available.

On the contrary, the biophysical viability of the power-supply system in relation to internal constraints is assessed by considering energy flows, but only in terms of the flows of energy carriers. This information is then used to assess the amount of power capacity and the amount of labor required to operate the power plant. This information refers to the biophysical costs paid by society to get a net supply of energy carriers [1,2].

This peculiarity of our method of accounting implies that the biophysical analysis of performance obtained in this way generates a description of the performance of a process of production of electricity, that is non-equivalent to that provided by economic analysis. That is, this information complements that provided by economic analysis. In fact, in economic analysis the total cost of a net supply of 1 kWh of electricity is determined by:

(1) the economic cost of production factors required (technical capital, labor, and other inputs);
(2) the economic cost of the Primary Energy Sources consumed (the flow of PES);
(3) other transaction costs (e.g. administrative, security, possible liability in the case of accidents).

This economic representation can be applied to each one of the various unit operations, but it loses the holistic vision of the whole process. When assessing the economic cost of 1 tonne of PES, considered as an input to the power plant, using the price per tonne, we lose information about the technical characteristics (i.e. requirement of individual production factors) of the other unit operations – e.g. the "Mining" process. Therefore, we can no longer study the possible effects that future changes in the existing technical characteristics of the various unit operations may imply on the overall performance of the power-supply system.

5.2. What we can see using this approach

The approach of integrated analysis proposed here makes it possible to characterize and compare the performance of power-supply systems producing the same type of energy carrier – in the given case study nuclear energy and fossil energy used for producing electricity. The comparison can be based on an integrated set of indicators of performance (biophysical costs and benefits) chosen according to the goal of the study. To obtain this result the process of production of electricity is analyzed using a grammar defining: (i) a set of modular elements (structural and functional types); and (ii) a set of semantic and formal categories used to define the attributes of performance (fund and flow elements used to describe the network of transformations). Having organized the quantitative analysis in this way, it becomes possible to carry out an integrated assessment of the performance of power-supply systems in relation to both external and internal constraints. In this way we can characterize the option space within which a given power-supply system can operate by checking the viability of different technical options in a given situation.

For example, using the results discussed in the text we can say that:

(1) in relation to internal constraints – when considering the requirement of power capacity, human labor, and key materials (concrete, steel and copper) – the production factors making possible the system to operate – nuclear energy has a biophysical cost generally between 1 and 3 orders of magnitude higher than fossil energy. In addition, the estimates referring to nuclear energy have higher variations and a larger level of "uncertainty". This fact translates into a lower performance of nuclear energy compared to fossil energy in the supply of the same amount of electricity.
(2) in relation to external constraints – when comparing their relative scarcity of PES type – calculated by comparing the consumption of uranium and coal required for supplying the World electricity consumption of one year to the worldwide availability of the reserves of uranium and coal – nuclear energy demonstrates a natural resources depletion rate of about 4 orders of magnitude higher than fossil energy.

5.3. What we don't see using this approach

This approach makes it possible to characterize the performance of power-supply systems in terms of a set of biophysical indicators which can be used as benchmarks. However, the information it provides is necessary but not sufficient to characterize the viability of these systems.

First, the comparison is based on a "steady-state" narrative and therefore it does not provide information in relation to turnover times. Indeed, information like the payback time – which is extremely important for investors – would require expressing the characteristics of the power-supply systems over a larger time scale (several decades) so as to capture their overall behavior, which is not possible within the present approach. Our numbers reflect assessments averaged over one year of electricity generation.

Second, the comparison of the relative performance of the two energy systems – nuclear energy and fossil energy – is based on a definition of a grammar that looks for functional relations defining a typology of whole (the power-supply system) made of different parts (unit operations). However, in the economic representation, these different unit operations are often carried out by different economic actors that, in order to break even in economic terms, have to consider different typologies of economic costs and profits determined by the prices associated with the mix of production factors used in their operations. In order to consider the perspective of economic agents (economic viability) a complementing analysis based on an economic approach based on price is still essential.

Third, when carrying out an analysis of external constraints, in our example, we adopted a very large scale perspective (using the Global context and the average characteristics of the metabolic pattern of modern countries as a generic reference context). As mentioned earlier, a more local level (for a specific country or for a specific entrepreneur) would require developing different grammars based on a selection of other criteria and data specific for particular purposes, both in relation to the characterization of the performance of the system itself (type of reactors used in a country, etc.) and for the availability of resources (i.e. type of PES).

5.4. What is the beef of this approach?

As discussed in the introduction, the usefulness and effectiveness of quantitative analyses provided for governance of sustainability requires using simultaneously several non-equivalent narratives, dimensions, and scales of analysis. The biophysical approach to energy quality proposed here is based on the use of a grammar as a quantitative analytical tool capable of handling the inherent ambiguity associated with energy accounting. It characterizes the process of production of electricity in modular elements, defined using quantitative attributes referring to a given set of semantic and formal categories. In this way it becomes possible to individuate similarities and differences in the process of production of electricity, and then measure and compare "apples" with "apples" and "oranges" with "oranges". By adopting this approach, it becomes possible to assess the quality of primary energy sources by defining the performance of power-supply systems in a multi-criteria space. For example, in our case study we found that nuclear energy demonstrates a low performance compared to fossil energy when considering the requirements of production factors for the net supply of electricity explaining the difficulties nuclear energy encounters to gain interest from investors.

This analysis of the supply side – looking at the characteristics of the processes taking place in power-supply systems within the energy sector – should be coupled to an analysis of the demand side – looking at the characteristics of the metabolic pattern of energy use in the various sectors of the economy [2]. As a matter of fact, we plan to do such an analysis (comparing nuclear energy and fossil energy power-supply systems) in our next paper on this subject. In any case, we believe that the case study presented in this paper clearly illustrates that by systemically adopting a complex framework of analysis – (i) a hierarchical understanding of the functioning of energy systems through the characterization of their parts and the whole; (ii) a combination of semantic and formal categories to describe the network of energy transformations; (iii) looking at external and internal constraints using different indicators – it becomes possible to generate an integrated assessment of the overall performance of energy systems by adding more relevant information in an integrated way. In this way it becomes also possible to identify those characteristics that limit the (bio-)economic competitiveness of energy systems, a very relevant piece of information for the discussion of alternative energy sources.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.energy.2012.11.014.

References

[1] Giampietro M, Mayumi K, Sorman AH. The metabolic pattern of societies: where economists fall short. Routledge; 2011.
[2] Giampietro M, Mayumi K, Sorman AH. Energy analysis for a sustainable future: multi-scale integrated analysis of societal and ecosystem metabolism. Routledge; 2012.
[3] Giampietro M, Mayumi K, Munda G. Integrated assessment and energy analysis: quality assurance in multi-criteria analysis of sustainability. Energy 2006;31(1):59–86.
[4] Giampietro M, Allen TF, Mayumi K. The epistemological predicament associated with purposive quantitative analysis. Ecological Complexity 2006;3:307–27.
[5] Funtowicz SO, Ravetz JR. Uncertainty and quality in science policy. Dordrecht: Kluwer Academic Publishers; 1990.
[6] O'Connor M, Faucheux S, Froger G, Funtowicz S, Munda G. Emergent complexity and procedural rationality: post-normal science for sustainability. In: Costanza R, Segura O, Martinez-Alier J, editors. Getting down to earth: practical applications of ecological economics. Washington, D.C.: Island Press; 1996. p. 224–47.
[7] Munda G. Social multi-criteria evaluation for a sustainable economy. Springer; 2008. p. 210.
[8] Toulmin S. Return to reason. Harvard University Press; 2003.
[9] Hall CAS, Klitgaard KA. Energy and the wealth of nations. Springer; 2012. p. 407.
[10] Smil V. Energy in nature and society: general energetics of complex systems. Cambridge, MA: The MIT Press; 2008.
[11] Giampietro M, Mayumi K. The biofuel delusion: the fallacy of large-scale agro-biofuel production. Earthscan 2009.
[12] Hall CAS, Cleveland CJ, Kaufman R. Energy and resource quality. New York: John Wiley & Sons; 1986.
[13] Murphy DJ, Hall CAS. Year in review—EROI or energy return on (energy) invested. Annals of the New York Academy of Sciences 2010;1185:102–18. http://dx.doi.org/10.1111/j.1749-6632.2009.05282.x.
[14] Giampietro M, Sorman AH. "Are energy statistics useful for making energy scenarios? Energy 2012;37:5–17. http://dx.doi.org/10.1016/j.energy.2011.08.038.
[15] Georgescu-Roegen N. The entropy law and the economic process. Harvard Univ Press; 1971.
[16] ITER. ITER & beyond. ITER Organisation [Online] Available: http://www.iter.org/proj/iterandbeyond; 2012.
[17] Dittmar M. Nuclear energy: status and future limitations. Energy 2012;37:35–40. http://dx.doi.org/10.1016/j.energy.2011.05.040.
[18] Bupp IC, Derian JC. Light water: how the nuclear dream dissolved. New York, NY: Basic Books, Inc.; 1978.
[19] Yang CJ. Belief-based energy technology development in the United States: a comparison of nuclear power and synthetic fuel policies. Amherst, NY: Cambria Press; 2009.
[20] Grubler A. The costs of the French nuclear scale-up: a case of negative learning by doing. Energy Policy 2010;38:5174–88. http://dx.doi.org/10.1016/j.enpol.2010.05.003.
[21] Kazimi MS, Moniz EJ, Forsberg CW, Ansolabehere S, Deutch J, Driscoll M, et al. The future of the nuclear fuel cycle: an interdisciplinary MIT study. Cambridge, Mass.: Report for Massachusetts Institute of Technology, ISBN 978-0-9828008-4-3; 2011. Available: http://web.mit.edu/mitei/research/studies/nuclear-fuel-cycle.shtml; 2011.
[22] Arthur WB. Competing technologies, increasing returns, and lock-in by historical events. The Economic Journal 1989;89:116–31. Available: http://www.jstor.org/stable/2234208.
[23] Cowan R. Nuclear power reactors: a study in technological lock-in. The Journal of Economic History 1990;50:541–67. Available: http://www.jstor.org/stable/2122817.
[24] Lenzen M. Life cycle energy and greenhouse gas emissions of nuclear energy: a review. Energy Conversion and Management 2008;49:2178–99. http://dx.doi.org/10.1016/j.enconman.2008.01.033.
[25] CEA. Nuclear power plants in the world (Ed. 2010), Status on 2009-12-31. Commissariat à l'Énergie Atomique. Available: http://www.cea.fr/content/download/49912/925958/file/Elecnuc2010_les_centrales_nucleaires_dans_le_monde.pdf; 2010.
[26] Diaz-Maurin F. Biophysical requirements of power-supply systems: nuclear energy and fossil energy. Spain: Institut de Ciència i Tecnologia Ambientals, Universitat Autònoma de Barcelona. Available: http://www.recercat.net/handle/2072/179690; 2012.

[27] Katzer J, Deutch J, Moniz EJ, Ansolabehere S, Beer J, Ellerman AD, et al. The future of coal: options for a carbon-constrained world. Cambridge: Massachusetts Institute of Technology. Available: http://web.mit.edu/coal; 2007.

[28] U.S. DOE/NETL. Cost and performance baseline for fossil energy plants. In: Bituminous coal and natural gas to electricity, DOE/NETL-2010/1397, revision 2, vol. 1. U.S. Department of Energy, National Energy Technology Laboratory. Available: http://www.netl.doe.gov/energy-analyses/pubs/BitBase_FinRep_Rev2.pdf; 2010.

[29] Rubin ES, Chen C, Rao AB. Cost and performance of fossil fuel power plants with CO_2 capture and storage. Energy Policy 2007;35:4444–54. http://dx.doi.org/10.1016/j.enpol.2007.03.009.

[30] Odum HT. Environment, power, and society. New York, NY: Wiley-Interscience; 1971.

[31] Brown MT. A picture is worth a thousand words: energy systems language and simulation. Ecological Modelling 2004;178:83–100. http://dx.doi.org/10.1016/j.ecolmodel.2003.12.008.

[32] OECD/IEA. Key world energy statistics 2011. Paris, France: International Energy Agency. Available: http://www.iea.org/publications/freepublications/publication/key_world_energy_stats-1.pdf; 2011.

[33] WEC. 2010 survey of energy resources. London, UK: World Energy Council. Available: http://www.worldenergy.org/documents/ser_2010_report_1.pdf; 2010.

[34] Storm van Leeuwen JW. Energy security and uranium reserves – secure energy Factsheet 4. Oxford, UK: Oxford Research Group [Online] Available: http://www.oxfordresearchgroup.org.uk/sites/default/files/energyfactsheet4.pdf; 2006.