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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