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Power capacity: A key element in sustainability assessment

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ABSTRACT

In the field of complex energetics, human societies to survive follow the same 'maximum power principle' as other living systems. In this view, human societies developed because they have been able to increase "their capacity to convert energy at a given time rate" rather than simply increase "their level of energy consumption". This was translated into an increase of the level of 'power capacity' in human societies so far. Yet, one can expect that the level of power capacity will be altered in light of the unavoidable progressive depletion of fossil energy resources. The systemic study of power capacity in sustainability assessment is therefore essential for facing the external constraints ahead.

Starting from the characterization commonly used in energy systems engineering, this paper seeks to clarify the concept of power capacity when used in sustainability assessment. It provides explicit methods of assessment for the different types of power capacity used by human societies. Power capacity refers to the converters transforming energy flows at a given time rate. Dealing with societal transitions therefore requires being able to characterize properly those converters in addition to the study of energy flows. However, this requires extending the timescale typically considered in conventional energy analysis which entails several epistemological problems over sustainability assessment.

1. Introduction

Conventional assessment of the sustainability of human societies deals only with one scale at a time. It typically adopts the timescale of one year so as to consider the average annual consumption of energy and other natural resources. However, this choice over a fixed time horizon makes such analyses unable to properly address societal transitions in quantitative terms.

The study of the energetics involved in societal transitions requires considering a much larger timescale. When doing so it becomes possible to move from a discussion over exosomatic energy 'flows' to a discussion over exosomatic energetic 'funds'. Exosomatic energetic funds are the capital funds (facilities and appliances) able to convert energy flows at a given 'power level' either on the demand or on the supply side. The study of power level (the time rate at which energy flows are converted) and of the associated power capacity (the energy converters and energy supply systems) is one of the missing pieces in sustainability assessment (Giampietro et al., 2012). 'Power density' (the rate of energy flows per unit of area) also is an important measure that is still largely overlooked in sustainability assessment (Smil, 2015).

This paper endorses the claim that the development of human societies followed the same 'maximum power principle' as observed in ecosystems. That is, human societies developed because they have been able to increase "their capacity to convert energy at a given time rate" rather than simply increase "their level of energy consumption". This was translated into an increase in 'power capacity' which corresponds to the converters consuming and supply systems generating energy flows—a definition commonly used in energy systems engineering.

To understand the importance of power capacity processing energy flows for the sustainability of human societies, we can use the metaphor of the bucket and the well. Let's imagine that a family requires collecting freshwater from a well every day for drinking. The quality of their supply of drinking water does not depend only on the quality of the water nor only on the quantity of the water

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Abbreviations: AG, agriculture and fisheries; BM, building and manufacturing; CBE, converter-based evaluation; CL, capacity load; EC, energy carrier; EI, energy input; ELEC, electricity (energy carrier); EM, energy and mining; EO, energy output; ET, energy throughput; EU, end uses; FBA, flow-based approximation; FUELS, fuel products (energy carrier); GER, gross energy requirement; GSEC, gross supply of energy carrier; HA, human activity; HEAT, process heat (energy carrier); HH, households; IPCD, input of power capacity dissipative; IPCH, input of power capacity hypercyclic; LT, lifetime; LU, land use; M&M, minerals and materials; MR, metabolic rate; NSEC, net supply of energy carrier; OL, operating load; OPCH, output of power capacity hypercyclic; PC, installed power capacity (dissipative or hypercyclic); PCD, power capacity dissipative; PCH, power capacity hypercyclic; PES, primary energy sources; SG, services and government; UF, utilization factor; WS, whole society.

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stored in the well. Besides, the quality of the supply also depends on the characteristics of the bucket used to collect the freshwater. For instance, if the bucket has a hole at the bottom it will carry less water for every lifting-up cycle. And if the hole becomes too large, the bucket will no longer perform its function at the expected rate and will probably have to be repaired or replaced unless the family will remain thirsty sitting on top of a stock of freshwater. . .

Similarly, human societies require power capacity—coming from human labor, animal labor or machines—dissipating energy in order to be able to perform its functions.

In addition to its use in engineering, power capacity can also be a key production factor in sustainability assessment acting as a constraint on the reproduction of the socio-economic process. In doing so, the paper focuses on the power capacity required to dissipate 'exosomatic' energy, that are flows *under* human control but *outside* human (and animal) bodies. In human societies, exosomatic energy flows correspond to the various forms of energy processed by the energy sector, including primary energy sources and energy carriers.

This paper proposes an accounting framework that seeks to clarify the concept of power capacity and provide explicit methods of assessment. In doing so, it aims at making a case for the systemic inclusion of power capacity in the sustainability assessment of human societies.

The paper starts in Section 2 with a discussion about the different possible timescales at which energy conversions can be perceived. The meta timescale of analysis implies that any use of energetic analysis for dealing with societal transitions requires being able to characterize properly the energy converters and energy supply systems.

In Section 3, the paper defines the concept of power capacity, makes the distinction between the different types of power capacity and proposes a taxonomy as well as assessment methods for its formalization. Those assessment methods of power capacity make it possible to describe energy converters and energy supply systems as production factors of the socio-economic process which can then be integrated in energetic analysis.

Section 4 provides some examples of assessments of power capacity using the methods introduced in Section 3. It then makes a comparison of the assessments illustrating some characteristics specific of power capacity.

The paper concludes in Section 5 by identifying some empirical efforts further needed to achieve the systemic inclusion of power capacity in energetic analysis and sustainability assessment more in general.

2. The different timescales of energy conversions

The interdisciplinary field of 'energetics of complex systems' deals with the systemic analysis of energy transformations describing the interaction between human societies and the environment (Diaz-Maurin and Giampietro, 2013a). In this field human societies are considered as complex living systems self-organized around metabolic patterns (Giampietro et al., 2011). This is Zipf (1941) who started to compare the organizational pattern of societies to the metabolism of 'bio-social organisms'. He identified the existence of a pattern of self-organization over power laws in socio-economic systems. Those laws and principles were originally developed in theoretical ecology (Odum, 1971, 1983, 1996).

The metabolic perception of human societies entails the acknowledgment of the existence of hierarchical relations and interdependences across scales in the description of their 'functional' processes like the one characterizing living systems. A quantitative analysis of the energetics of human societies therefore requires dealing simultaneously with multiple scales (Diaz-Maurin and Giampietro, 2013a).

The unavoidable existence of multiple non-equivalent perceptions and representations in energetics implies that, when dealing with hierarchically organized adaptive systems, it is virtually impossible to have "a correct assessment" of energy conversions. Rather the analyst has to address a set of relevant characteristics of the processes of transformations that are level and scale dependent in order to be able to decide about the relevance of the chosen perceptions and representations. This implies that the analyst should acknowledge the co-existence of a variety of non-equivalent perceptions and representations of energy transformations across scales and take responsibility for the choice of adopting only a limited (set of) scale(s) at a time. Energy conversions controlled by human societies can also be perceived at various *space* scales, which entail various possible quantitative representations (see e.g., Giampietro et al., 2012; Diaz-Maurin and Giampietro, 2013a; Giampietro and Diaz-Maurin, 2014). This section focuses on the various *time* scales at which energy conversions can be perceived. This requires going back to the concept of 'power level'.

The power level or metabolic rate corresponds to the ability of living systems to metabolize energy flows in time (Diaz-Maurin and Giampietro, 2013a). It is essential for expressing their functions and reproducing themselves. The quest for an increased metabolic rate is at the core of the very definition of life where "in the struggle for existence, the advantage must go to those organisms whose energy capturing devices are most efficient in directing available energies into channels favorable to the preservation of the species" (Lotka, 1922: 147). Building on Lotka's (1922) maximum energy flux principle, H.T. Odum proposed a general maximum power principle for the development of ecological systems which consists in the 'survival of the fittest' by means of "the persistence of those forms which can command the greatest useful energy per unit time (power output)" (Odum and Pinkerton, 1955: 332).

The introduction of the maximum power principle into the analysis of the energetics of living systems such as socio-economic systems brings the time dimension back into the scientific discourse (Diaz-Maurin and Giampietro, 2013a). For some, including H.T. Odum, the field of energetics should even be based on the study of *power* rather than on the study of *energy*—to the extent that it has been proposed as the fourth thermodynamic law (Odum, 1963, 1994). This is the rationale behind the approach for the systemic study of power capacity proposed in this paper.

Previous work has been done already in dealing with the various timescales at which human societies metabolize energy flows (Giampietro et al., 2012) as well as how they metabolize water flows against the structural and functional stability of ecological funds (Madrid et al., 2013). This section elaborates further on generalizing those distinct timescales of analysis and on discussing their implications for the analysis of the energetics of human societies. It should be mentioned that this study refers only to 'exosomatic' energy flows that are the energy conversions under human control but outside human body. In this view human labor is therefore not accounted for as an 'endosomatic' energy flow (inside human body) but rather as a production factor of the socio-economic process referring to the use of human time (for an in-depth discussion over the problems of accounting human labor in energy analysis, see Giampietro et al., 1993).

Fig. 1 summarizes the four timescales useful to describe the energy conversions of human societies.

The remainder of this section details the various timescales at which exosomatic energy conversions can be perceived.