Complex Systems and Energy☆

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Glossary

Complex energetics An innovative approach to the systemic study of transformations among different energy forms able to deal with the specific characteristics of self-organizing dissipative systems.
Complex system A system that allows one to discern many subsystems, depending entirely on how one chooses to interact with the system.
Dendrogram An alternative analytical tool used in complex energetics able to generate a set of forced relations between multiple flows and multiple funds across scales.
Dissipative systems All natural systems of interest for sustainability (e.g., complex biogeochemical cycles on this planet, ecological systems, human systems when analyzed at different levels of organization and scales beyond the molecular one); self-organizing open systems, away from thermodynamic equilibrium.
Epistemological complexity Complexity that is at play every time the interests of the observer (the goal of the mapping) are affecting what the observer sees (the formalization of a scientific problem and the resulting model).
External constraints to metabolism External constraints refer to the availability of favorable boundary conditions (gradients) required by the metabolic system in interacting with its context (outside view). E.g., an external constraint is present when the system has plenty of technical capital but it does not have enough primary energy inputs.
Feasibility of a metabolic pattern The compatibility between the requirement of primary energy sources on the supply side and the requirement of sink capacity on the waste side against their availability at the macro scale. The feasibility domain reflects the existence of external constraints.
Hierarchical systems Systems that are analyzable into successive sets of subsystems; when alternative methods of description exist for the same system.
Hierarchy theory "A theory of the observer's role in any formal study of complex systems" (Ahl and Allen, 1996, p. 29).

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Impredicative loop analysis An alternative analytical tool used in complex energetics able to generate forced relations of congruence between the characteristics of the parts and those of the whole.
Internal constraints to metabolism Internal constraints refer to the ability to generate enough applied power (useful work) for carrying out the set of useful tasks (functions) required by the metabolic system (inside view). E.g., an internal constraint is present when the system does not have enough technical capital to take advantage of available energy inputs.
Multi-level/multi-dimension matrix An alternative analytical tool used in complex energetics able to represent series of congruence constraints across levels and, "at the same time", congruence constraints across dimensions in the analysis of the viability of a metabolic pattern. Its functioning is very similar to a Sudoku grid.
Multi-purpose grammar An alternative analytical tool used in complex energetics able to link non-equivalent descriptive domains by generating a set of expected relations between a given set of semantic categories and a given set of formal categories. A multi-purpose grammar can be tailored and calibrated so as to define the relevant characteristics of the system depending on other characteristics and new relevant qualities in the analysis.
Scale The relation between the perception of a given entity and its representation.
Viability of a metabolic pattern The congruence of the characteristics of flow and fund elements across the micro and meso scale. The viability domain reflects the existence of internal constraints.

Nomenclature

AG	Agricultural sector
BM	Building and manufacturing sectors
EC	Quantity of energy measured in joules of energy carriers
EM	Energy and mining sectors
EMD	Exosomatic metabolic density (energy flow measured in joules of GER per hectare of land)
EMI	Exosomatic metabolic intensity (energy flow measured in joules of GER per Watt of installed power capacity)
EMR	Exosomatic metabolic rate (energy flow measured in joules of GER per hour of human activity)
ET-m	Energy throughout in the form of mechanical energy measured in joules of energy carriers
ET-t	Energy throughout in the form of thermal energy measured in joules of energy carriers
EU	End uses
GER	Quantity of energy measured in joules of gross energy requirements
GSEC	Gross supply of energy carriers
HA	Human activity
HH	Household sector
MuSIASEM	Multi-Scale Integrated Analysis of Societal and Ecological Metabolism
NSEC	Net supply of energy carriers
PC-m	Installed power capacity required for the consumption of mechanical energy
PC-t	Installed power capacity required for the consumption of thermal energy
PES	Primary energy sources
PF	Primary production sectors generating flows (AG and EM sectors) or simply primary flows.
PS	Primary and secondary production sectors or simply productive sectors
PW	Paid work sector
REU	Requirement of end uses
SG	Services and government sector
TET	Total energy throughput
THA	Total human activity
TML	Total managed land
TPC	Total installed power capacity

Introduction

This updated overview of the interdisciplinary field of 'energetics of complex systems' is used to give a very simple message: human societies will face dramatic changes in their energetic pattern in the next decades and for this reason it is crucial to improve our ability to carry out an effective energy analysis. The oil crises of the 1970s and 1980s have given an early warning to the community of practitioners working in the field of energy analysis, and to the scientific community in general, about the dangerous dependency on fossil energy of modern civilization. However, the rebound of economic growth following these energy crises gave a temporary relief to the world economy. The prosperous economic growth in the 1990s was used to dismiss early concerns about sustainability. So the emergence of a new scientific field looking at the biophysical roots of the economic process – e.g. a systemic analysis of energy transformations describing the interaction of human societies with the environment – was first stopped and then abandoned.

The remaining sections of this paper are organized as follows:

- Section "The troublesome birth of energetics" provides an historical discussion about the early attempts to deal with the energy transformations of human societies. This section concludes showing that dealing with the energy transformations of living systems such as human societies requires adopting a 'complex systems thinking' approach;
- Section "The introduction of complexity in energy analysis" explains that a 'complex systems' reading of the energy transformations of living systems requires a new formulation of energetics capable of handling the systemic problems found in energy analysis. More specifically this section: (1) introduces a few concepts of complexity in science and in energy analysis; (2) provides a critical assessment of the systemic problems founds in conventional energy analysis based on complexity theory; and (3) discusses theoretical and practical implications of these two sections for the field of energy analysis.
- Section "The 'complex formulation' of energetics" presents the 'complex' formulation of energetics based on a transdisciplinary approach to science. In particular, it provides (1) an overview of innovative theoretical concepts that can be integrated to build a 'complex energetics'; (2) an overview of alternative analytical tools making it possible to generate effective analysis of the energetics of complex systems; and (3) a summary of the 'multi-scale integrated assessment' toolkit that can be used for a 'complex energetics';
- Section "Conclusion: The implications of the complexity revolution in natural sciences" suggests that a revolution in 'complex energetics' may pave the way to a more general 'complexity revolution' in sustainability sciences since the solutions adopted for dealing with the epistemological predicaments of multiple scales in 'complex energetics' can be used also to cope with the epistemological problems faced in economics.

The Troublesome Birth of Energetics

'Energetics' emerged from the first revolution in classic science posed by the development of classical (equilibrium) thermodynamics in the 19th century. The field of energetics later lived its own first revolution with the development of non-equilibrium thermodynamics in the 1960s (the second revolution in classic science). However, those two scientific revolutions have not been sufficient for 'energetics' to be considered as an actual scientific field by the scientific community and society at large. Here we explore the historical foundations of energetics and discuss the reasons of such a failure.

The 'Classical Formulation' of Energetics

The classical (equilibrium) formulation of energetics intrinsically is linked to the emergence of thermodynamics in the middle of the 19th century which led to the first revolution in quantitative science. Thermodynamics was developed by engineers outside the domain of traditional physics, when developing the steam engines that would make the industrial revolution happen. In particular, a group of engineers from Scotland including Kelvin, Joules, Rankine and Maxwell focused on thermodynamic cycles building upon the first experiments made in France by Carnot and Clapeyron. Retrospectively thermodynamics started with practical applications which were later on turned into theoretical discussions. The term "energetic" was coined by Rankine himself. Energetics that was originally defined as a systemic study of transformations among different energy forms was rapidly generalized as "the science of energy". However such general claims about its scope clashed against the weakness of its formulation in scientific terms. Certainly, this mismatch between huge claims and little theoretical understanding resulted into a scientific fiasco of this emergent field. This implied the movement from a "science of energy" – the grand claim of energetics – to "thermodynamics" – a more restricted rigorous analysis of transformations of thermal and mechanical energy under controlled conditions. More specifically:

(1) in relation to its 'idealistic' formulation – The rigorous quantitative formulation of thermodynamic laws by Boltzmann, Planck, and Gibbs was made at the expense of an irremediable simplification over the representation of the external world. In particular, by assuming that energy transformations can be measured and controlled with the required accuracy, in order to describe them usefully with thermodynamic equations we have to accept two quite heavy assumptions: (i) all the energy forms relevant for the observed phenomena can be well defined and measured; and (ii) system attributes are not changing in time over the duration of analysis. These two assumptions have been proven impossible by the later developments of thermodynamics (this is what the second principle of the thermodynamics is about!) as theoretically formalized later on. Put in another way, the 'classical formulation' of thermodynamics formalized in thermodynamic laws was obtained by reducing the external world to a mechanical system with boundaries assumed to be perfectly known both in space and time. As a matter of fact, "ideal cycles" were considered as the reference in the engineering applications of thermodynamics despite the fact that they do not exist (and they cannot exist!) in practice.

(2) in relation to its 'unrealistic' scope – Outside the technical development of thermodynamics, energetics was seen by its pioneers as a science of energy capable of providing an alternative to the leading mechanical (Newtonian) view of the external world – e.g. Ostwald, 1907; 1911. Going one step further on this idea, Ostwald's intent with his "energetic imperative" was to make energetics a discipline applied to many domains including the functioning of human societies. Unsurprisingly, such statements over the scope of energetics very rich on the semantic side clashed against its reductionist formulation in technical

applications – the development of thermal engines. The new born field of energetics was unable to deal with socio-economic systems for the good reason that it was entering into the category of living systems governed by laws that were still unknown at that time (partially addressed later on with the development of non-equilibrium thermodynamics). According to the very general principles of thermodynamics, living systems were all “special” and therefore it was impossible to describe their relevant features with the narratives of thermodynamics. As a matter of fact, according to the narratives of equilibrium thermodynamics the most probable outcome of energy transformations is the destruction of all gradients, “the heat death of the universe”. In fact, life emerges from a phenomenon called ‘symmetry breaking’ in physics (Anderson, 1972), hence far away from equilibrium. Something not directly related with the ideal cycles imagined in classical thermodynamics. Moreover, ‘open self-organizing living systems’ started to be characterized by biologists in the late 1970s outside the field of energetics (see section “**Integration of innovative theoretical concepts**”). For these reasons the first formulation of energetics was unable to successfully address problems typical of living systems that were not properly understood in this field.

The ‘Non-Equilibrium Formulation’ of Energetics

The second formulation of energetics emerged from the development of non-equilibrium thermodynamics in the early 1960s (the second revolution in classic science). Contrary to classical thermodynamics that was developed through engineering applications, non-equilibrium thermodynamics resulted first from theoretical discussions associated with the characterization of ‘becoming systems’ (Prigogine, 1961; see also section “**Integration of innovative theoretical concepts**”) and the famous question of Schrödinger (1967) – “what is life?”. Non-equilibrium thermodynamics was therefore seemingly able to deal with the energetics of living systems. However, although the ‘non-equilibrium’ formulation has been very beneficial to the field of energetics in semantic terms, it failed to provide a practical operationalization of those new concepts (an example of how to deal in practice with the energetics using a complex systems approach is presented in section “**The ‘complex formulation’ of energetics**”). Indeed the application of energetics to socio-economic systems was not accompanied with proper methods capable of addressing the “expected” characteristics of complex self-organizing systems: organization across multi-scale, unavoidable openness determining fuzzy boundary definition, impredicativity (chicken-egg paradoxes). As a result, even after the emergence of non-equilibrium thermodynamics, energy analysis was still unable to provide sound quantitative assessments in response to the first energy supply crises of the 1970s and 1980s. In spite of a surge in the interest in this field at the time both the concepts and the protocols proposed did not delivered the expected results (Giampietro et al., 2013). This fact, certainly explains the further delusion of the scientific community in relation to the field of energetics.

The Need for a Second Revolution in Energetics

Attempts to apply energy analysis to human systems have a long history. Pioneering work was done by, among others, Podolinsky, Jevons, Ostwald, Lotka, White, and Cottrel (for a review see chapter 6 of Giampietro and Mayumi, 2009). However, it was not until the 1970s that energy analysis became a fashionable scientific exercise, probably due to the oil crisis surging during that period. During the 1970s, energy input–output analysis was widely applied to farming systems and national economies and was applied more generally to describe the interaction of humans with their environment. Odum (1971, 1983, 1996), Georgescu-Roegen (1966, 1975, 1976), and Pimentel (1980; Pimentel and Pimentel, 1979), among others, developed theoretical approaches to generate systemic analysis of energy flows within ecological and socio-economic systems. At the IFIAS workshop of 1974, the term ‘energy analysis’ (as opposed to ‘energy accounting’) was officially coined. The second energy crisis during the 1980s was echoed by the appearance of a new wave of interesting work by biophysical researchers and a second elaboration of their own original work by the “old guard.” However, quite remarkably, after less than a decade or so, the interest in energy analysis declined outside the original circle. Indeed, even the scientists of this field soon realized that using energy as a numeraire to describe and analyze changes in the characteristics of agricultural and socio-economic systems proved to be more complicated than one had anticipated. Systemic problems in energy analysis (discussed in section “**Critical assessment of conventional energy analysis based on hierarchy theory**”) can only be addressed only after a second revolution in energetics based on complexity theory.

In relation to this point, the following quote from the lectures in energetics of Professor Parolini at the University of La Sapienza in Rome remarkably summarizes the new foundations which a second generation of ‘energetic analysis’ had to be based on in order to solve the epistemological impasse it was so far engaged into: “In relation to the unavoidable second revolution within energetics the following points should be kept in mind: energetics should deal with both qualitative and quantitative aspects of both scientific and technological solutions; applications must be interdisciplinary and address simultaneously several dimensions of analysis – i.e. referring to ecological systems, demographic processes, fresh water availability, material resources, interfacing the knowledge creation with biology, cosmology, metaphysics into a holistic vision of the world.” (Gino Parolini, 1983 in: Amendola, 2005).[1]

This call for a more holistic approach in the field has been the rationale behind the introduction of ‘complexity’ in energy analysis paving the way to a third formulation of energetics.

[1](From the lecture, Energia: quantità e qualità, given at the Consiglio Nazionale delle Ricerche (CNR), Roma, 11–13 April 1983. Quoted in Amendola (2005, pp. 13–14) (translation by Mario Giampietro))

The Introduction of Complexity in Energy Analysis

In this section we briefly describe how complexity emerged in science (section "**The emergence of complexity in science**") and its latent presence in energy analysis throughout the 20th century (section "**The underlying complexity in energy analysis**"). Then, we provide a critical assessment of conventional energy analysis based on complex systems theory (section "**Critical assessment of conventional energy analysis based on hierarchy theory**"). We conclude this section with the main implications of the introduction of complexity theory in energy analysis (section "**Principles introducing complexity in energy analysis**").

The Emergence of Complexity in Science

Unsurprisingly, the emergence of the concept of 'complexity' in science has been quite complex. While some early references to complexity can be found in chaos theory, cybernetics, and other emergent fields of the late 1980s, there is no clear consensus on an actual formulation of an organic science of complexity. This is due to the fact that the term complexity is a semantically-rich concept very easy to convey to the general public (everything that cannot be easily represented often is labeled as "complex"). This ambiguity results into a co-existence of various interpretations of the term in science – even in the same scientific field as in the case of biology, let alone when the meaning and role of complexity is discussed in relation to science. For instance, the theory of chaos – which notably emerged from the field of biology by studying the fractal patterns of biological systems (Mandelbrot, 1975; 1977; 1983) – corresponds to the first scientific interpretation of the complexity of nature (e.g. Bak et al., 1987) – critical organization and power law distributions – which was later turned into a branch of mathematics. Another interpretation of complexity in biology was referring to the existence of multiple scales when analyzing the organization of living systems – hierarchy theory (e.g. Allen and Starr, 1982; Ahl and Allen, 1996; Salthe, 1985).

In the specific case of the energetics of living systems, 'complexity' certainly can be associated with the need of using simultaneously non-equivalent descriptive domains reflecting the simultaneous use of multiple scales for their observation and representation. In this interpretation of complexity we can define complex systems as follows: systems that allow the observer to discern as many subsystems as needed depending on the chosen scale (or set of scales) of representation (Simon, 1962; Koestler, 1968; Pattee, 1973; Allen and Starr, 1982; Salthe, 1985; O'Neill et al., 1986; O'Neill, 1989; Allen and Hoekstra, 1992; Ahl and Allen, 1996; Giampietro, 2003; Giampietro et al., 2011). Indeed, although the complexity of systems can be seen as a general attribute of any living system, when we move to the task of generating a quantitative representation of complex systems we have to deal with the implications of the unavoidable choice of the observer about how to interact with the observed system. In fact, if one observes the same system with a microscope, naked eye or a telescope one will obtain different typologies of observations (Giampietro, 2003). This fact entails a key epistemological problem faced by modern science: the decision of "how to observe" the external world translates into the establishment of an "observer-observation complex" that ultimately defines "what is observed" – Allen et al., 2003 (see section "It is impossible to give a substantive quantitative definition to 'energy'").

As we see, the interpretation of complexity in biology and ecology is more about the existence of hierarchical relations and interdependences across scales, looking for a useful description of 'functional' processes characterizing living systems. As a matter of fact, we can say that this interpretation of complexity may be used to perceive and represent 'structural complexity' or 'functional complexity' using hierarchy theory (an analysis carried out across contiguous levels of organization). This approach is at the basis of the application of 'complex systems theory' for the formulation of energetics presented here. Indeed, the integration of hierarchy theory in energy analysis has been the milestone of the second revolution in energetics although the integration of complex systems thinking was not explicit at the beginning.

The Underlying Complexity in Energy Analysis

The application of complex systems thinking to the relation between energy and society is not entirely new. Indeed it was underlying much of the early discussions on energy transformations in society, even though the term complexity was not explicitly used. For instance, Ostwald (1907; 1911) already suggested an alternative view on society seen as a functional body coordinating its individual organs to maximize its energetic efficiency – a characteristics typical of living systems. Later, Soddy (1926) – another epistemologist coming from chemistry – was highlighting the peculiar role of energy in economic systems. Then, the application of complex systems thinking to energy analysis was two-fold:

(1) energetic principles of living systems (FUNCTIONAL SIDE) – First, Lotka (1922) formulated a general principle to study the performance of biological systems: surviving organisms are the ones that better direct available energy into their reproduction and preservation. In the same line, Vernadsky (1986 [1926]) suggested the biochemical cycles as a big picture of the energetic process of self-organization on the planet Earth. This formulation clearly individuates as a key attribute of living systems the existence of autocatalytic loops of energy flows. The strength of the autocatalytic loop is an essential factor determining the fitness of living systems;
(2) socio-economic systems as living systems (STRUCTURAL SIDE) – Second, Zipf (1941) started to compare the organizational pattern of societies to the metabolism of 'bio-social organisms'. As a matter of fact, Zipf was the first one to identify the existence of a pattern of self-organization over power laws in socio-economic systems (in fact the "power law" is also called

"Zipf's law" in his honor). His pioneering work individuating an expected set of characteristics for bio-social organisms can be considered as the first attempt to define the existence of metabolic patterns in human societies considered as living systems.

Additional contributions to the foundations of an 'energetics of complex systems' include the work of Cottrell (1955), the first to establish the relation between socio-economic changes and changes in the metabolic pattern associated with societal 'structure' and 'function', and H.T. Odum (1971; 1983; 1996), who applied the same set of basic principles developed in theoretical ecology to the analysis of the metabolic pattern of socio-economic systems. Yet, these attempts to formulate concepts and methods of energy analysis to be applied to socio-economic systems were not capable of reaching any kind of scientific consensus. Rather, they attracted strong criticism when they were not ignored by the rest of the scientific community. This lack of success was due to three systemic problems found in conventional energy analysis that hampered a general acceptance of the emerging field of energetics:

(i) the impossibility of defining a clear boundary for open dissipative systems both in space and time;
(ii) the epistemological challenge of how to handle and aggregate different kinds of energy flows, that makes it impossible to define the overall size of a network defined by heterogeneous energy transformations using a single quantitative mapping of energy flows;
(iii) the impredicative nature of energetic pattern (based on autocatalytic loops) in which a part of the energy output generated by a process (the energy return) must be accounted at the same time as the input of the process generating the output.

These three predicaments represent 'the' epistemological conundrum of energy analysis. And despite the fact that they were discussed in several dedicated workshops (IFIAS, 1974; IES, 1975; Roberts, 1978), they cannot be resolved without the introduction of complexity.

Critical Assessment of Conventional Energy Analysis Based on Hierarchy Theory

For those already being familiar with the epistemological implications of complexity, it is well known that practical procedures used to generate numerical assessments within a linear input–output framework are unavoidably doomed to clash against the ambiguity and arbitrariness implied by the hierarchical nature of complex systems. Yet such a linear characterization of input–output is still the standard approach in conventional energy analysis.

We detail here the systemic methodological problems of an energy analysis based on a linear input–output analysis which were identified as early as the 1970s (e.g. Chapman, 1974; Leach, 1975; Herendeen, 1978):

(1) truncation problem – The truncation problem refers to the co-existence of multiple relevant scales of analysis due to the existence of several non-equivalent valid representations of the same process. This results in an unavoidable arbitrariness over the definition of the boundaries of analysis both in space and time when dealing with complex systems operating simultaneously at different scales. Indeed, when trying to evaluate the energetic 'cost' of a given product in a modern economy (e.g. the problem faced by those attempting an extended Life Cycle Assessment) it is impossible to include all the processes involved directly and indirectly in its production. For this reason, any analysis must be based on a sub-system of the world for which it becomes possible to define a plausible and finite set of inputs and outputs. This implies that the choice of a sub-system is the first crucial step in evaluating an energy cost (Chapman, 1974). However when focusing on just one sub-system of the 'whole', we do not know whether the chosen boundaries and set of inputs and outputs include the most relevant ones nor we can know about the importance of other functional parts (and therefore additional inputs and outputs) being left out. Moreover, the scale to be adopted to study the processes generating the supply of inputs (e.g. large ecological processes) is different from the scale to be adopted to study the processes converting inputs into outputs (e.g. local technical processes of energy transformations). An input–output analysis has to adopt one scale at a time, and therefore the answer to these questions will be dramatically different depending on the chosen scale of the analysis, that in turn depends on the nature of the issue to be investigated. If we accept the epistemological predicament of complexity we have to acknowledge that systems operating simultaneously on multiple scales require the adoption of several non-equivalent descriptions. Therefore the choice of just one of the possible perceptions and representations of the same system – the choice of just one specific scale of analysis and related boundary definition – entails an important loss of potential information about the perceptions and representations referring to other scales. Put in another way, it is important to acknowledge that in energy analysis the choice of a scale – the narrative used to define "what the system is" and "what it does", that in turn requires defining what should be considered as an energy input, an energy converter, useful work and the relevant processes outside human control determining favorable boundary conditions – may significantly affect both the usefulness and the pertinence of the representation.

A notorious illustration of the truncation dilemma in energy analysis is the impossibility to build a substantive quantitative assessment of the energetics of human labor. Given the amount of efforts dedicated by the community of energy analysts to this issue, this can been considered as one of the largest theoretical fiascos of energy analysis (for an overview of issues, attempts and critical appraisal of results, see Fluck, 1981; 1992; Giampietro and Pimentel, 1990; 1991; 1992; Giampietro et al., 1993).

The truncation dilemma highlights the fact that the quantification of an energy input required for a given process – as well as the energetic equivalent of a given output – depends on the information gathered at a given scale that in turn depends on the choices made in the pre-analytical step as regards to the boundary definition (Giampietro et al., 2006). When dealing with complex systems operating simultaneously across different levels of organization it is impossible to calculate a single "correct" assessment of embodied energy. To overcome the truncation problem it is essential to learn how to link non-equivalent characterizations of energy transformations across scales (see section "**A quantitative analysis in energetics requires dealing simultaneously with multiple scales**").

(2) aggregation of different energy forms – The problem of aggregation of different forms of energy was already clear to the pioneers of energy analysis. As Long (1978) summarized it: "not all calories are equal". In fact, there are qualitative differences affecting the usefulness of a joule, which are related to the characteristics of the conversion process of one energy form to another. As a matter of fact, the classic studies of thermodynamics discussed earlier were focusing on the efficiency of thermal engines in order to deal exactly with the fact that thermal and mechanical energy are not of the same quality. The conversion of thermal into mechanical energy entails important losses! Therefore, the quantitative analysis of different energy forms requires extreme care when coming to aggregation and accounting. Joules referring to energy forms of different quality – i.e. thermal and mechanical – cannot be summed as such. To aggregate their assessments we have, first, to transform their respective quantities into a standard energy form used to define an equivalence class. This has been the rationale behind the setting of Joules of calorific value – e.g. Tons of Oil Equivalent – as the standard to be used to aggregate different energy forms by international organizations like the International Energy Agency. However, these benchmarks can change over time – i.e. coal replaced wood in the 1970s, then oil replaced coal in the 1980s, and now natural gas is replacing oil as a benchmark source of calorific value in international statistics. This succession in the definition of the reference "Primary Thermal Energy Source" perfectly illustrates the obvious fact that the choice of how to formalize the accounting of different energy forms ultimately depends on their use, determining the equivalence class of reference. This point is of capital importance for understanding the systemic problem of aggregation of different energy forms. As Maddox (1978, p. 136) said: "there is no unambiguous energy measure that allows one energy form to be compared to another. Energy cannot be treated as a single entity, because its various forms possess irreconcilable qualitative distinctions." Therefore, any attempt to provide a quantitative assessment in energy analysis entails pre-analytical choices over the characterization of the different relevant qualities of end uses. In turn end uses depend on the characteristics of the converters involved in the energy transformations. Again we are back to the general problem of the co-existence of multiple non-equivalent perceptions and representations of the same energy system.

To overcome this problem all together, the IFIAS recommended that energy analysis should always display flows and assessments of different energy forms separately (Leach, 1975). Accepting this advice requires adopting at least three non-equivalent perceptions for defining the performance of a given set of energy transformations associated with the metabolism of a society: (i) the set of gross primary energy flows – primary energy sources required by the society when interacting with its context; (ii) the net supply of various energy carriers delivered to the functional compartments of society; and (iii) the specification of the characteristics of end-uses associated with the expression of the set of expected functions required at the local scale (see section "**Wrapping-up the 'multi-scale integrated assessment' toolkit in 'complex energetics'**"). As discussed earlier, it is impossible to describe in quantitative terms these three non-equivalent views of energy transformations using a single set of quantitative assessments. Unfortunately, in spite of this clear epistemological impossibility this is exactly the approach adopted by energy statistics to provide a quantitative representation of energy flows in modern economies (Giampietro and Sorman, 2012).

(3) joint-production dilemma – The joint-production dilemma refers to the difficulty of accounting 'energetic output' and corresponding 'energetic costs' (input) when dealing with a complex network of transformation in which more than a single output is coming from a single process of conversion (e.g. Cleveland, 2010). This problem calls back to the impossibility of simplifying complex networks of energy transformations into a linear representation (input–output) of energy flows. To make things worse, when the analysis deals with autocatalytic loops of energy (in which part of the output is fed back to the process in form of an input) we are facing a clear case of 'impredicativity' (the ultimate nightmare of reductionism), inducing non-linearity in the representation. For this reason conventional energy analysis based on a linear representation and an input–output approach entails an unavoidable failure when dealing with the perception and representation of the energetics of complex self-organizing systems. In more general terms, we can say that the joint-production dilemma is just one of the consequences of the inadequacy of simplistic representations applied to the analysis of complex energy networks. This dilemma cannot be revolved unless we first adopt a complex systems approach in energy analysis that understands and accounts for the specific characteristics of self-organizing systems governed by complex network relations.

This brief overview of the three key epistemological problems faced by energetics shows that, once we accept that the energetics of human societies is governed by a complex network of relations involving different non-equivalent forms of energy and autocatalytic loops operating across different scales, it becomes obvious that its quantitative assessment cannot be based on the traditional principles of reductionism developed by Descartes, Bacon and Newton. For the study of the energetics of living systems and human societies, it is essential to develop an innovative system of accounting able to deal with the epistemological challenges listed above. This task requires the introduction of a few theoretical concepts developed in complexity theory. In turn these concepts entail practical implications on the process of generation of quantitative information.

Principles Introducing Complexity in Energy Analysis

It is impossible to give a substantive quantitative definition to "energy"

This principle derives from the ambiguity associated with the concept of energy in physics. As Feynman and colleagues pointed out in 1963: "we have no knowledge of what energy is . . . energy is an abstract thing in that it does not tell us the mechanism or the reasons for the various formulas". In practice, energy is perceived and described in a large number of different forms: gravitational energy, kinetic energy, heat energy, elastic energy, electrical energy, chemical energy, radiant energy, nuclear energy, mass energy, and so on. A general definition of energy, without getting into specific context and space-time scale-dependent settings, is necessarily limited to a vague semantic statement such as "the potential to induce physical transformations." Note that the classical definition of energy in conventional physics textbooks, "the potential to do work," refers to the concept of "free energy" or "exergy" which is another potential source of confusion. In fact, both of these concepts require a previous formal definition of what we define as work and a clear definition of operational settings to be applied.

Summarizing the problem associated with the ambiguity of the perception and description of "energy", Bridgman says: "the energy concept has no meaning apart from a corresponding process. One cannot speak of the equivalence of the energy of mass and radiation unless there is some process (not necessarily reversible) by which one can get from mass to radiation" (Bridgman, 1961). It shall be noted that the problem associated with the ambiguous definition of energy maps onto a more general problem over energy terms used when dealing with an energetic assessment of complex systems – 'energy' as well as 'work' and 'power' – found when trying to give a general definition that is applicable to any specific space-time scale-dependent settings (Giampietro et al., 2013).

Given this ambiguity over the concept of energy we can safely say that an ultimate quantitative definition of energy does not exist 'per se'. Rather its identity emerges only after the set of pre-analytical and empirical choices required to observe "energy transformations". So the definition of energy depends on the choices of the observer about the relevance of the perceptions about what is transformed and at which scale. This dilemma of the influence of the identity of the observer on the identity of what is observed is nicely illustrated by the famous thought experiment of the Schrödinger's cat in 1935. This thought experiment posed the counterintuitive narrative that a living system can, at the same time, have various non-equivalent identities – e.g. a cat being simultaneously dead 'and' alive before we try to look inside the box where it is locked in – a phenomenon known as 'quantum superposition' in particle physics. The main lesson from this thought experiment therefore was the controversial narrative that "information is everywhere" while, at the same time, "information 'per se' does not exist" but rather is the result of a choice made by the observer in the way it interacts with the system (in this case the decision from the observer to look inside the box the cat is locked in, hence affecting the identity of the cat). This phenomenon brings back to the epistemological dilemma of "the one and the many" posed by the very concept of complexity corresponding to the unavoidable circular relations between a complex system and its context (Morin, 1990). The acknowledgment of this dilemma tamed into a coherent approach to energy analysis is what justifies the need of moving to a complex formulation of energetics.

A quantitative analysis in energetics requires dealing simultaneously with multiple scales

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 flows. 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 (from the micro, meso, and macro scale) and take responsibility for the choice of adopting only a limited set of them. Three heuristic concepts can be used in relation to the task of individuating a set of useful perceptions and pertinent representations:

(i) the concept of 'energy input' – what is the energy input needed by the system for operating properly?;
(ii) the concepts of 'power level' and 'power capacity' – what is the required level of applied power to be associated with the relevant transformations?; and
(iii) the concept of 'useful work' – what typologies of tasks have to be carried out by the applied power?.

In order to provide useful information in relation to these three concepts we have to look at events taking place simultaneously at different hierarchical levels, by perceiving and representing energy transformations at different scales. This requires assigning different identities (defined at different scales) to the various elements to be described in energy analysis: the context, the whole (seen as a black-box), the parts of the whole (inside the black-box), the elements of the processes taking place within the parts.

Again this integrated description entails that the handling of different perceptions and representations over energy terms applies across scales. For example, an energy input can only be measured once we know who is using it. Therefore when dealing with energy systems we must know the characteristics of the converters – e.g., a microwave – in order to quantitatively assess the amount of energy flows going through it – e.g., kWh of electric energy. This implies that a given quantity of thermal energy (e.g. measured in MJ) associated with one gallon of fuel cannot be considered as an energy input for the microwave. In the same way solar radiation is not a Primary Energy Source for making electricity if one does not have available photovoltaic technology.

At the societal level, in order to be able to represent a pattern of energy flows within the socio-economic process we have to define, first of all, the integrated set of functions to be expressed. Put in another way, the analysis of the energetics of a society must start with a multi-scale definition of the identity of the set of 'end uses'. For this reason it is crucial to adopt a system of accounting that makes it possible to deal simultaneously with the various functional compartments of complex systems.

Once we accept the option of using non-equivalent descriptive domains simultaneously, we have to establish a reciprocal logical implication (self-entailment) over the definitions of identity of the various elements used in such an integrated assessment. More specifically in order to characterize the set of energy transformations required to stabilize the metabolism of a self-organizing adaptive society it is necessary to define the following pieces of information:

(i) the identity of the whole system in relation to the identity of the environment making available favorable gradients (primary energy sources and sinks for the wastes coming out from the conversions);
(ii) the identity of the converters (the organized structures in charge of energy transformations – something called 'fund elements' in the jargon of metabolic analysis);
(iii) the identity of the energy carriers (the various energy inputs of different nature used by different typologies of energy converters – something called 'flow elements' in the jargon of metabolic analysis); and
(iv) the integrated set of "end uses" (the various tasks that have to be expressed by the different compartments at different hierarchical levels in order to reproduce the whole).

When carrying out this integrated characterization, we have two couples of self-entailment among the proposed identities:

- Self-Entailment 1: The identities adopted for the various converters (at interface level $n/n-1$) referring to the power level of the converter define/are defined by the identities adopted for the energy carriers (at interface level $n-1/n-2$) – e.g., electricity is an energy input to an electric motor (a type of power capacity compatible with this energy form), liquid fuels are an energy input for thermal motors (a different type of power capacity compatible with this energy form).
- Self-Entailment 2: The identities of the set of end uses define what should be considered as "useful energy" at the focal level n. This characterization should address the existence of autocatalytic loops making it possible the reproduction of the socio-economic process, viewed from within (at the meso-scale on the interface level $n/n-1$). In turn, the viability of these autocatalytic loops has to be guaranteed by a given set of tasks to be expressed at the local scale (at the micro-scale). For example, the ability of the energy sector to deliver to the society a net surplus of energy carriers (using much less energy carriers than producing) – a characteristic observable at the meso-scale – depends on the combination of net surplus generated by individual local processes of exploitation of primary energy sources (different power plants generating electricity from different primary energy sources, different extraction processes making available different types of fossil energy inputs to society).

Those self-entailments are capable of:

- Bridging the non-equivalent perceptions of the various levels into an integrated assessment:

  We can scale up the characteristics of local processes (e.g. conversion processes within the energy sector) to the level of whole functional compartments (e.g. the energy sector). Then we can contextualize the characteristics of the whole society in relation to the characteristics of its energy sector. In this way, we can study the compatibility of the identity defined for the whole system in relation to the identities of its internal parts (VIABILITY ANALYSIS – checking the congruence of the characteristics of flow and fund elements across the micro and meso scales). At the same time, by using a different system of accounting, it becomes possible to check the congruence of the demand of services placed by the metabolic pattern of the society on its context (FEASIBILITY ANALYSIS – checking the requirement of primary energy sources on the supply side and the requirement of sink capacity on the waste side against their availability at the macro scale) when studying the interaction of the society with its larger context.

  The viability analysis is obtained when characterizing the autocatalytic loop from the inside (interface across the levels $n-2/n-1/n$), whereas the feasibility analysis is obtained when characterizing the autocatalytic loop from outside (at the interface $n/n+1/n+2$). Therefore an analysis of the sustainability of the metabolic pattern of a society requires studying the ability of a given society to express an integrated set of functions, generated by tasks carried out by the various parts that are required to reproduce and maintain the identity of the whole system. This expression is subject to two different types of constraints: (i) external constraints – the need of favorable boundary conditions determined by processes outside human control; and (ii) internal constraints – the ability of generate enough applied power (useful work) for carrying out the required set of useful tasks (functions). According to this framing of the quantitative analysis: (1) when dealing with the energetics of human societies seen as a black-box interacting with a given context (the focal level being the whole society), we are dealing with an analysis of the external constraints (feasibility), to be studied looking at the availability in the environment of the required flow of input and sink capacity for wastes; and (2) when dealing with an assessment of the performance of energy systems seen as parts operating within the black-box (the focal level being a specific energy technology such as hydropower, nuclear power, or biofuels), we are dealing with an analysis of internal constraints (viability), to be studied looking at the production factors required by the energy system to be operational. This assessment can be obtained by looking at the characteristics of standard unit operations of the system for expressing the expected tasks. For the energy sector the task to be performed is the generation of an adequate net supply of energy carriers, while at the same time keeping low the resulting waste/pollution.
- Bridging the non-equivalent representations across scales:

  The non-equivalent sets of relations and identities, which depend on each other for their definitions, have to result congruent with each other when adopted in an integrated assessment. Therefore, in order to link non-equivalent characterizations of energy transformations across scales we have to acknowledge the need of organizing our quantitative analysis over nested hierarchical levels as illustrated in Figure 1.

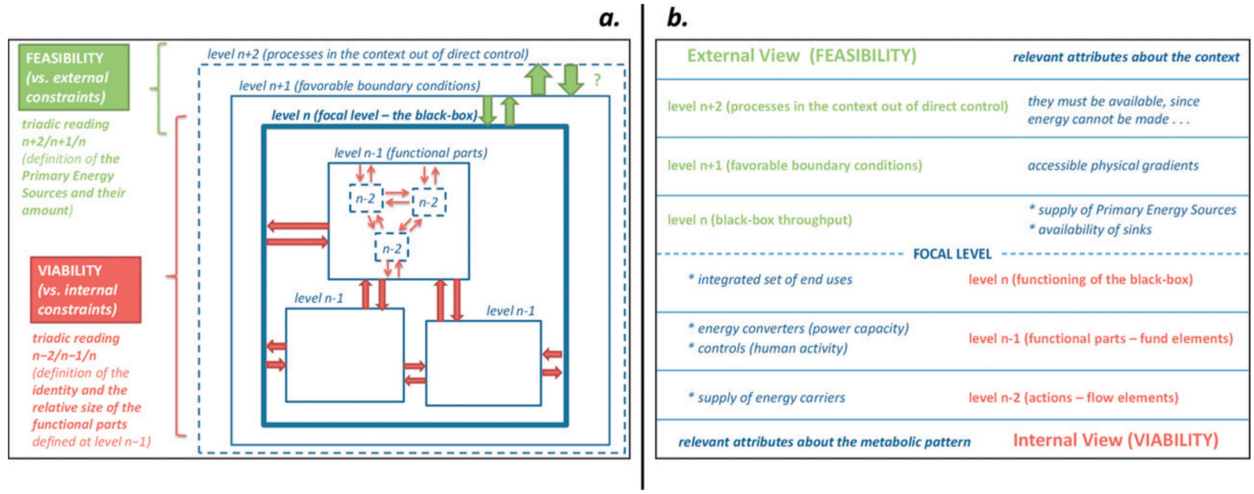

Figure 1 Hierarchical levels to be considered when dealing with the energetics of complex systems.

In specific terms, non-equivalent characterizations of energy transformations, perceived and represented across scales, can be bridged by implementing two sets of forced relations:

- Bridge 1: Conversion rates represented on different levels must be compatible with each other. This implies a constraint of compatibility between the definition of identity of the set of converters defined at level n−1 (triadic reading: n−2/n−1/n) and the definition of the set of tasks for the whole defined at level n+1 (triadic reading: n−1/n/n+1). This constraint addresses the ability of the various converters to generate "useful energy" (the right energy form applied in the specified setting) at a given rate, that must result admissible for the various tasks (specific tasks require specific power levels – e.g. the power required to lift a Jumbo jet implies that electricity is not an adequate energy input/energy carrier for that task). This bridge deals with qualitative aspects of energy conversions. It makes possible the verification of the 'viability' domain of the system defined at level n being the compatibility between the characteristics of a given set of converters defined at level n−1 in relation to the characteristics of the metabolic pattern of the whole defined at level n+1 (see section "**Wrapping-up the 'multi-scale integrated assessment' toolkit in 'complex energetics'**").
- Bridge 2: The flow of energy input from the environment and the sink capacity of the environment must be enough to cope with the rate of metabolism implied by the identity of the black-box. This implies a constraint of compatibility between the aggregate size of the converters defined on the interface level n/n−1 (triadic reading: n−2/n−1/n) and the relative supply of energy carriers and sink capacity related to processes occurring at level n+1/n+2 (triadic reading: n/n+1/n+2). Energy carriers produced (inside the black-box) by the exploitation of Primary Energy Sources (interface black-box-context) will interact with internal elements of the converters (inside the black-box) to generate the flow of useful energy (interface black-box/context) and will be turned out into waste by the process of conversions (in the context). Therefore, the availability of an adequate supply of Primary Energy Sources and of an adequate sink capacity is related to the existence of processes occurring in the environment (at the level n+2) – outside human control – that are needed to maintain favorable conditions at level n+1. Put in another way, the ability to maintain favorable conditions in the face of a given level of dissipation can only be checked by considering level n+1 as the focal one (triadic reading: n/n+1/n+2). This corresponds to the verification of the 'feasibility' of the system (black-box) consisting in the compatibility between the size of the aggregate set of converters (fund elements in the jargon of metabolic analysis) defined at level n−1 and summed at the level n, in relation to the size of favorable boundary conditions defined at level n+1, which requires the existence of processes at the level n+2 guaranteeing these favorable conditions (see section "**Wrapping-up the 'multi-scale integrated assessment' toolkit in 'complex energetics'**").

In conclusion, when dealing with quantitative and qualitative aspects of energy transformations over an autocatalytic loop of energy forms, we have to bridge at least five hierarchical levels (from level n−2 to level n+2). Unfortunately, by definition, the environment or context (processes determining the interface level n+1/n+2) is something we do not know enough about and above all it is something about we do not have control on. Otherwise we would include these processes among those taking place inside the black-box, and we would include them as parts of the modeled system. For instance, a quantitative assessment of the performance of energy systems (defined in this case at level n−1) does not account for the existence of favorable boundary conditions at the interface between the overall energy supply sector (level n – the availability of solar radiation or access to a coal mine) and the rest of society (level n+1). Let alone addressing the processes taking place at the level n+2 (the nuclear reactions within the sun generating solar radiations or the past ecological processes generating coal reserves).

Rather the system of accounting useful for assessing the performance of energy system in society has to move from micro to meso – from energy systems to the energy supply sector – and from meso to macro – from the energy supply sector to the whole society interacting with its context. This means that when dealing with the stability of "favorable boundary conditions," we can only hope that they remain the same at least for the time horizon of the analysis. On the other hand, the existence of favorable boundary conditions is a pre-requirement for dissipative systems. That is, the environment or context is and must generally be assumed to be an "admissible environment" in all technical assessments of energy transformations. Therefore, the existence of favorable boundary conditions (interface level n + 1/n + 2) is an assumption that is not directly related to a definition of usefulness of the individual tasks (interface level n/n + 1) in relation to the issue of sustainability. This implies that the existing definition of the set of useful tasks at level n simply reflects the fact that these tasks – guaranteeing the integrated set of functions to be expressed by society – have been perceived as useful in the past by those living inside the system. That is, the existing set of expressed functions was able to sustain a network of activities compatible with boundary conditions ('ceteris paribus' at work). However, this definition of usefulness for these tasks (what is perceived as good at level n according to favorable boundary conditions at level n + 1) has nothing to do with the ability or effect of these tasks in relation to the stabilization of boundary conditions in the future. In fact, the stability of existing favorable boundary conditions at level n + 1 requires the stability of the processes (at times unknown and certainly outside human control) occurring at level n + 2. Therefore, the information about the future stability of boundary conditions cannot be known in advance. This implies that any analysis of "efficiency" and "efficacy" can only be based on data referring to characterizations and representations that may become obsolete at any moment. The quantitative assessments are based on relevant identities determining the energetic pattern that are defined only on four hierarchical levels (out of the required five!): n−2, n−1, n, and n + 1. That is these assessments are based on the 'ceteris paribus' hypothesis and reflect only information that has been validated in the past. Because of this, they are not very useful in making prediction or studying co-evolutionary trajectory of dissipative systems. More specifically, they do not study relevant processes determining the stability of favorable boundary conditions (the relevant processes taking place at level n + 2). For this reason, when their analysis is based only on the characteristics of the black-box, they cannot assess "how big" is the requirement of the whole dissipative system – an extensive variable assessing the size of the box from the inside – in relation to the unknown processes that stabilize the identity of its environment at level n + 2.

The 'Complex Formulation' of Energetics

A complex formulation of energetics consists in a reinterpretation of non-equilibrium thermodynamics into practical applications able to deal simultaneously with the issue of multiple scales and multiple dimensions of analysis. This activity is known as 'multi-scale integrated assessment' (see section "**Wrapping-up the 'multi-scale integrated assessment' toolkit in 'complex energetics'**").

Once we accept the need for integrating conceptual principles of complexity into energy analysis, we can individuate the main features of a system of accounting able to deal with energy transformations keeping coherence and meaning across dimensions and scales. The basic rationale behind the 'complex systems thinking' approach to energy consists in a hierarchical reading of energy transformations. In particular, studying the energetics of human societies requires generating a framework describing the autopoiesis (the operation of a hypercyclic part linked to a purely dissipative part) of socio-economic systems. That is, the benefit from introducing complexity theory in energy analysis is that it makes it possible to represent the forced relations across scales of the various (non-equivalent) set of energy transformations at play in living systems.

The resulting 'complex formulation' of energetics applies to both mechanical (Newtonian) systems – already described by the first 'classical formulation' – and the living systems (e.g. ecological systems, biological systems, socio-economic systems) – only described in semantic terms by the second 'non-equilibrium' formulation. That is, the first formulation of energetics is still useful for engineering applications (simple energy systems considered at the local scale) but has to be complemented by an adequate 'complex formulation' as soon as one intends to integrate the specific characteristics of complex systems described as 'self-organizing dissipative systems' (across multiple scales). As we saw earlier, this is something impossible using conventional energy analysis.

The 'complex formulation' of energetics presented in this section consists in: (1) learning how to deal with the peculiar characteristics of living systems (section "**Integration of innovative theoretical concepts**"); (2) providing an effective set of alternative analytical tools able to deal with their energy transformations (section "**Alternative analytical tools**"); (3) generating a coherent system of accounting capable of generating a 'complex energetic accounting' known as 'multi-scale integrated assessment' (section "**Wrapping-up the 'multi-scale integrated assessment' toolkit in 'complex energetics'**").

Integration of Innovative Theoretical Concepts

This new formulation of energetics is based on the integration of innovative theoretical concepts derived in various fields. This process of "integration by concepts" (Kapp, 1961) illustrates the interdisciplinary basis of 'complex energetics' emerging as an innovative and alternative approach able to cope with the systemic problems of conventional energy analysis. **Table 1** summarizes the innovative theoretical concepts integrated in the 'complex formulation' of energetics.

Complex self-organizing systems have been studied under different labels: 'complex adaptive systems' (Holland, 2006; Gell-Mann, 1994); 'autopoietic systems' (Maturana and Varela, 1980; 1998; Kampis, 1991); 'metabolic systems' (Odum, 1971; 1996; Ulanowicz, 1986; Fischer-Kowalski and Haberl, 2007; Giampietro et al., 2011). Those different labels introduced several key concepts as properties making possible to describe living systems (biological systems, ecological systems and socio-economic systems) that are very useful when dealing with the energy transformations of human societies. We detail below those four key theoretical concepts of 'complex energetics' derived from complex systems theory.

Table 1 Integration in 'complex energetics' of theoretical concepts derived in distinct fields

Theoretical concept	*Field of origin*	*Benchmark reference(s)*
Negentropy; 'restated' second law of thermodynamics	Non-linear thermodynamics	Schrödinger, 1967; Schneider and Kay, 1994
Becoming systems[a]	Non-linear thermodynamics	Prigogine, 1961, 1978
Autopoiesis[a]	Complexity theory	Maturana and Varela, 1980, 1998
Holon; Nested hierarchy	Complexity theory	Koestler, 1968; Allen and Hoekstra, 1992; Ahl and Allen, 1996
Non-equivalent descriptive domains[a]	Complexity theory	Rosen, 1985, 2000
Semiotic closure	Complexity theory	Giampietro et al., 2006, 2011
Generative grammar	Theoretical linguistics	Chomsky, 1998
Informed autocatalytic loops	Theoretical ecology	Odum, 1971
Maximum energy flux principle; Maximum power principle; Power level[a]	Theoretical ecology	Lotka, 1922; Odum and Pinkerton, 1955; Schneider and Kay, 1994; Giampietro et al., 2013
Fund/flow scheme	Bio-economics	Georgescu-Roegen, 1971; Giampietro and Mayumi, 2000a

[a]key concepts detailed in this overview article

Autopoiesis

The concept of autopoiesis refers to the 'circular organization' of living systems and the dynamics of their autonomy being one of their higher-level characteristics. That is living systems demonstrate the ability to define for themselves which energy forms are relevant for analyzing their own energetics (metabolic pattern) – see definition of 'complex systems' in section "**The emergence of complexity in science**." For this reason, it is impossible to apply to living systems the standard characterization found in classical thermodynamics (see section "**The 'classical formulation' of energetics**").

To address this issue Schneider and Kay (1994, p. 26) introduced the "restated second law" that was able to describe semantically the circular organization of the energetics of living systems: "ecosystems will develop structures and functions selected to most effectively dissipate the gradients imposed on them while allowing for the continued existence of the ecosystem". However, Schneider and Kay also acknowledged the difficulty of formalizing the notion of entropy and entropy production in general terms for non-equilibrium systems, including living systems (systems being far away from equilibrium). This difficulty is reflected by the unavoidable ambiguity in the meaning of the expression 'gradients'. Indeed, an operational definition of what should be considered as a 'resource' (favorable gradient) or what should be considered as a 'waste' (unfavorable gradient) for a living system is not substantive, but rather depends on the identity (i.e. the specific characteristics) of the metabolic system under study. The misunderstanding of this concept explains the persistence of the truncation problem in conventional energy analysis (see section "**Critical assessment of conventional energy analysis based on hierarchy theory**").

This particular characteristic of living systems is at the core of the very definition of 'life'. Indeed, living systems are characterized by their ability to define their identity by forcing a given perspective on the external world (Schrödinger, 1967). This circular definition between living systems and their interaction with 'their' external world has been formalized by introducing the concept of 'negative entropy' (negentropy). That is living systems define themselves in respect to the existence of negentropy. In other words, negentropy corresponds to "the existence of a 'system-specific' set of favorable boundary conditions determining the possibility for the living system to discharge entropy". The introduction of negentropy therefore made it possible to integrate the autopoietic nature of living systems. In return, it entails that the definition of negentropy must be specified for every typologies of living systems.

Once we accept the unavoidable impredicativity of the definition of energetic concepts, it becomes obvious that the specific definition of potential energy of complex systems depends on the identity of the converter that is the bridge with the external world. For this reason, the general principles developed in classical thermodynamics lose their relevance as soon as we deal with living systems although they remain useful for deterministic systems: "In ecology, as in all other disciplines that treat dissipative systems, the first law is not violated, but it simply does not tell us very much that is interesting about how a system is behaving" (Ulanowicz, 1997, p. 24).

Going further on the idea of impredicativity in living systems, H.T. Odum described ecosystems as systems self-organizing by means of 'informed autocatalytic loops' (Odum, 1971). The existence of informed autocatalytic loops makes it possible the definition of a metabolic identity 'frozen' in time as describing their path-dependent definition of negentropy. That is living systems use 'patterns of recorded information' to guide their process of self-organization. Those patterns of recorded information act as the memory of the energetics of living systems making possible for them to deal with different energy forms in the same way that, at the micro-scale, neural circuits regulate the activity of biological neural networks (see **Figure 4**).

Non-equivalent descriptive domains

Systems operating on multiple scales require the simultaneous adoption of non-equivalent descriptive domains (representations) in multi-scale analysis. The non-equivalence of representations comes from the existence of several valid perceptions over the same process depending on the chosen scale of interaction with the system. The existence of non-equivalent representations is typical of complex living systems with nested hierarchy (see section "**The emergence of complexity in science**").

Considering the example of nuclear energy, it is clear that a representation with a focal level being the nuclear power plant (level n−1) – whose sub-levels (n−2) are the various cooling systems, feedwater pumping systems, power-supply systems, etc. themselves made of numerous distinct equipments (n−3) – is not equivalent to a representation with a focal level being the overall 'nuclear energy system' (level n) – including the various facilities (n−1) such as the mine, the enrichment plant, the power plant or the waste-treatment plant required in the four standard functions describing the unit operations of electricity generation in power-supply systems: (1) Mining; (2) Refining/Enriching; (3) Generating power; and (4) Handling waste/Controlling pollution (Diaz-Maurin and Giampietro, 2013).

Therefore, every time we choose a particular hierarchical level of analysis for assessing an energy flow we also have to select a space-time scale at which we will describe the relative set of energy conversions (e.g. a nuclear power plant over a year or a day; a nuclear energy system over 30 years; the nuclear industry over centuries; etc.). That is, depending on the purpose of the analysis, the resulting set of relevant energy flows may be assessed over different time spans. As a matter of fact, depending on the chosen perception over the system under study, we have to adopt a non-equivalent definition of its context ('environment') and as a consequence of this choice we will generate an assessment not reducible to the others. An assessment of the energy flows of a nuclear power plant over a year will be useful for optimizing the costs of production; an assessment of the same power plant over a day will be useful for comparing the compatibility of the technology with the patterns of electricity demand. However, these two assessments will not be sufficient for dealing with the viability and desirability of nuclear energy in a context of forced energy transition. Assessing the quality of nuclear energy as an alternative energy source would require an assessment of the overall nuclear energy system considering the entire life-span of its various facilities (when considering the handling of nuclear waste defining a time horizon for assessing the identity of this complex becomes anything but easy!).

The unavoidable existence of non-equivalent representations of complex systems implies that, whatever we choose as a quantitative model to carry out an energy analysis, the various identities involved – i.e., that of energy carriers, parts, whole and environment – have to make sense in their reciprocal constraining, if we are serious about our claim of dealing with multiple scales at the same time. Obviously, this implies that distinct choices of focal level also require the adoption of distinct systems of accounting for inputs and outputs.

Becoming systems

Systems far away from thermodynamic equilibrium are becoming in time because of their metabolic nature. Indeed, according to Prigogine (1978) the predicament of modeling those systems is associated with the fact that dissipative systems are always 'becoming' something else in time. This implies that a substantive formal representation of their energetic interactions with their context virtually is impossible. This problem applies to biological systems as well as to ecological and socio-economic systems that are continuously – qualitatively as well as quantitatively – evolving or coevolving with their environment. Therefore, given the unavoidable evolutionary nature of living systems, the use of a predicative representation is far from satisfactory for simulating their evolution (Giampietro et al., 2011). Moreover, the phenomenon of emergence – typical of complex living systems – implies that the representation of metabolic systems requires a continuous update of the selection of relevant attributes and pertinent approaches used for their quantitative analysis.

The existence of becoming systems points at the neglected issue of time in energy analysis. The presence of a time dimension in a quantitative assessment of energy transformations forces the analysts to deal with the issue of scale – something that is not properly addressed in conventional energy analysis (see section "**Critical assessment of conventional energy analysis based on hierarchy theory**") – and ultimately with the notion of power corresponding to the time dimension of energy flows.

Power level

The power level or metabolic rate corresponds to the ability of living systems to metabolize energy flows in time. It is essential for expressing their functions and reproducing themselves. In fact, the quest for an increased metabolic rate maps onto the very definition of life: "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, p. 147). This idea is also at the core of Schneider and Kay's interpretation of the second law of thermodynamics: "ecosystems develop in a way which systematically increases their ability to degrade the incoming solar energy" (Schneider and Kay, 1994, p. 38).

Building on Lotka's maximum energy flux principle, H.T. Odum proposed a general maximum power principle for the development of ecological systems: "Under the appropriate conditions, maximum power output is the criterion for the survival of many kinds of systems, both living and non-living. In other words, we are taking 'survival of the fittest' to mean persistence of those forms which can command the greatest useful energy per unit time (power output)" (Odum and Pinkerton, 1955, p. 332).

The introduction of the maximum power principle takes one step further the analysis of the energetics of living systems (including socio-economic systems) by bringing the time dimension back into the scientific discourse, to the extent that H.T. Odum was an outspoken advocate of the idea that this field should be based on the study of power and not on the study of energy. In fact, whereas the concepts of energy and work, as defined in physics, refer to quantitative assessment of energy without taking into account the time required for the conversion process under analysis, the concept of power is, by definition, related to the rate at which events happen. This introduces a qualitative dimension that can be related either to the degree of organization of the dissipative system or to the size of the system performing the conversion of energy in relation to the processes that guarantee the stability of boundary conditions in the environment (see section "**Wrapping-up the 'multi-scale integrated assessment' toolkit in 'complex energetics'**").

Alternative Analytical Tools

The third formulation of thermodynamics whose general principles have been presented in section "**Integration of innovative theoretical concepts**" has been turned into practice through the development of several analytical tools derived from complex systems theory. Those alternative analytical tools make it possible to perform quantitative integrated assessments of the energetics of complex systems – including human societies – that address the systemic problems of conventional energy analysis described in section "**Critical assessment of conventional energy analysis based on hierarchy theory**." In this section we present four alternative analytical tools making possible to apply the above described theoretical concepts to the study of the energetics of complex living systems.

Multi-purpose grammar (from R. Rosen's modeling relation)

Any quantitative analysis dealing with complex systems operating at different scales has to be tailored to the specific characteristics of the complex system under study. That is it has to be based on the definition of the individual elements of the system – "what the systems is" – and the overall configuration of the resulting network – "what the system does". In scientific jargon, we say that such analysis requires a pre-analytical definition of a grammar.

A grammar is a set of expected relations between a given set of 'semantic categories' and a given set of 'formal categories'. With the expression semantic category we refer to a definition of an equivalence class based on the common meaning assigned to a label. Examples of semantic categories are: "primary energy sources" (which can include fossil energy, nuclear energy, solar energy, hydropower), "exosomatic throughput" (energy input processed by a form of power capacity external to the human body), "energy carriers" (e.g. electricity, fuels, heat) or "end uses" (tasks such as illumination, transportation, refrigeration that have to be expressed within a functional compartment) that require the investment of production factors (power capacity, human control, energy input). With the expression formal category we refer to a definition of an equivalence class that can be quantified using a numerical assessment based on a defined protocol and a related measurement scheme. Examples of formal categories are: Joules of thermal energy, Watt (joule per second) measuring a given form of power. In order to generate an effective quantitative energy analysis we need to handle simultaneously semantic and formal categories.

Referring to the technical jargon used in the field of software development, a grammar entails a preliminary definition of (1) a taxonomy – the set of semantic categories and formal categories used in the grammar (the types of types that are used in the grammar); (2) vocabularies for the various categories included in the taxonomy – the attributes used to individuate or characterize the elements of the different sets (relevant meanings or information; names and tokens); and (3) production rules to be applied to formal categories using the distinction between 'tokens' and 'names'.

We saw before that when dealing with complex networks of energy transformations operating across different levels of organization and scales it is impossible to generate a useful quantitative accounting using just a single protocol based on a closed set of semantic and formal categories. The need of using a grammar to make distinctions over different categories of "money" is well known in economic analysis of businesses, where numbers included in the category "gross revenue" do not have the same value as the numbers included in the category of "profit", although they are formalized using the same unit – e.g. US$. In the same way, when dealing with the energetics of modern societies different semantic categories are required for a proper accounting – e.g. "gross energy requirement" versus "requirement of energy carriers" – even when the quantitative assessment is expressed using the same unit – i.e. Joules. Figure 2 presents a generic example of a multi-purpose grammar showing distinct semantic and formal categories useful for assessing the energetics of modern societies in relation to multiple scales of analysis.

A grammar is different from a model in the sense that it provides a description based on an expected set of relations over semantic categories and then it establishes an expected set of relations between semantic and formal categories (data and formal systems of inference). For this reason a grammar is semantically open (e.g., "cheap labor" can be formalized in different ways depending on the year and type of society; the categories describing activities in the agricultural sector can be chosen using different criteria of accuracy, let alone the fact that can be measured in different currencies!). A multi-purpose grammar defines the relevant characteristics of the system depending on other characteristics and therefore can be tailored and calibrated to specific situations and adjusted to include new relevant qualities in the analysis.

Impredicative loop analysis (from theoretical ecology – R. Ulanowicz)

Society is viewed and analyzed as a nested hierarchical system using the concept of "holons" developed by Koestler (1968). Each component of this metabolic system (e.g. the energy supply sector) is part of a larger whole (e.g. the paid work sector), which in turn is part of a still larger whole (e.g. the society) embedded in an even larger process determining boundary conditions (e.g. large-scale ecological processes). At the same time, each part can be analyzed by looking at its lower-level components (the energy supply sector is composed of a set of sub-systems called primary energy sources such as oil, coal, natural gas, nuclear energy, hydro, etc.),

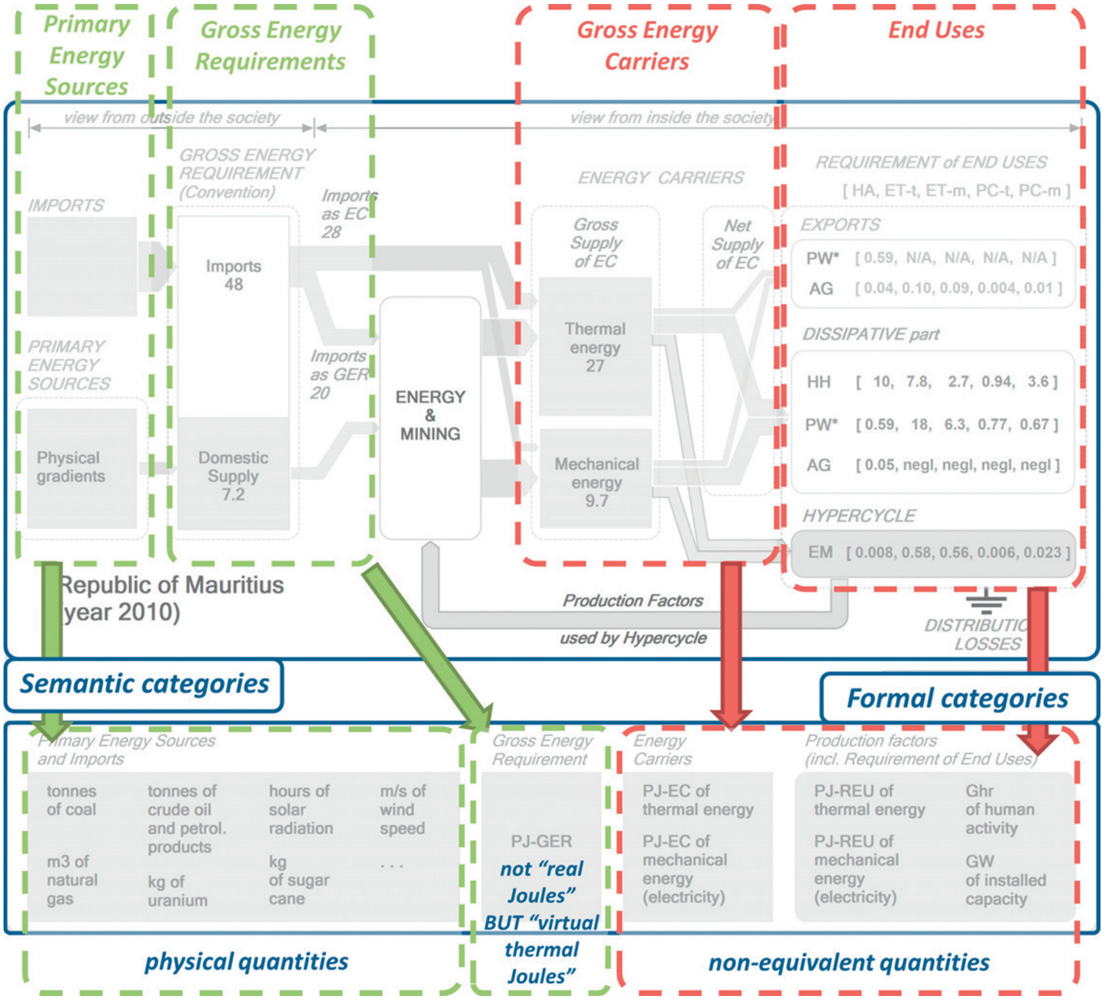

Figure 2 Example of multi-purpose grammar used in energy analysis (Republic of Mauritius, year 2010).

which in turn can be analyzed in still smaller parts (e.g. the nuclear energy system is composed of a set of facilities such as the mine, the enrichment plant, the power plant, the waste treatment plant, etc.). The definition of the identity of the various components at the different scales is based on the identification of a structural and functional relation (the holon) that can be seen (in different ways) from both the higher (as a function) and lower (as a structure) hierarchical level.

Unlike conventional (linear) deterministic models, 'complex energetics' accommodates the chicken-egg predicament typically encountered in the description of complex systems. Having established a relation between the characteristics of the whole and those of the parts of the system in semantic terms in a multi-purpose grammar, they can then be formalized in quantitative terms (using proxy variables) by generating a set of forced relations of congruence between the characteristics of the parts and those of the whole. These forced relations of congruence imply that the characteristics of the parts must be compatible with those of the whole and vice-versa, but they do not define a linear causal relation (hence the label "impredicative").

As shown above, the analysis of the energetics of complex systems requires linking the non-equivalent characterizations of energy transformations across scales. In practical terms, it means that we have to bridge at least four hierarchical levels (from level $n-2$ to level $n+1$, with an assumption about the existence of processes out of human control guaranteeing favorable conditions on level $n+1$) as soon as we deal with complex self-organizing systems (Figure 1). For this task, an autocatalytic loop of different energy forms can be used to study the forced congruence across levels of some of the characteristics of the autocatalytic loop defined on different descriptive domains (Figure 3).

Dendrogram (from complex systems theory – P. Cilliers)

The impredicative loop analysis dealing with energy flows in relation to one fund at a time across levels (e.g. human activity across levels $n/n-1$) can be extended using a 'dendrogram' showing the forced relations between multiple flows and multiple funds across levels. A dendrogram is a pattern associated with a series of splits/divisions of a given quantity over a set of compartments (a profile

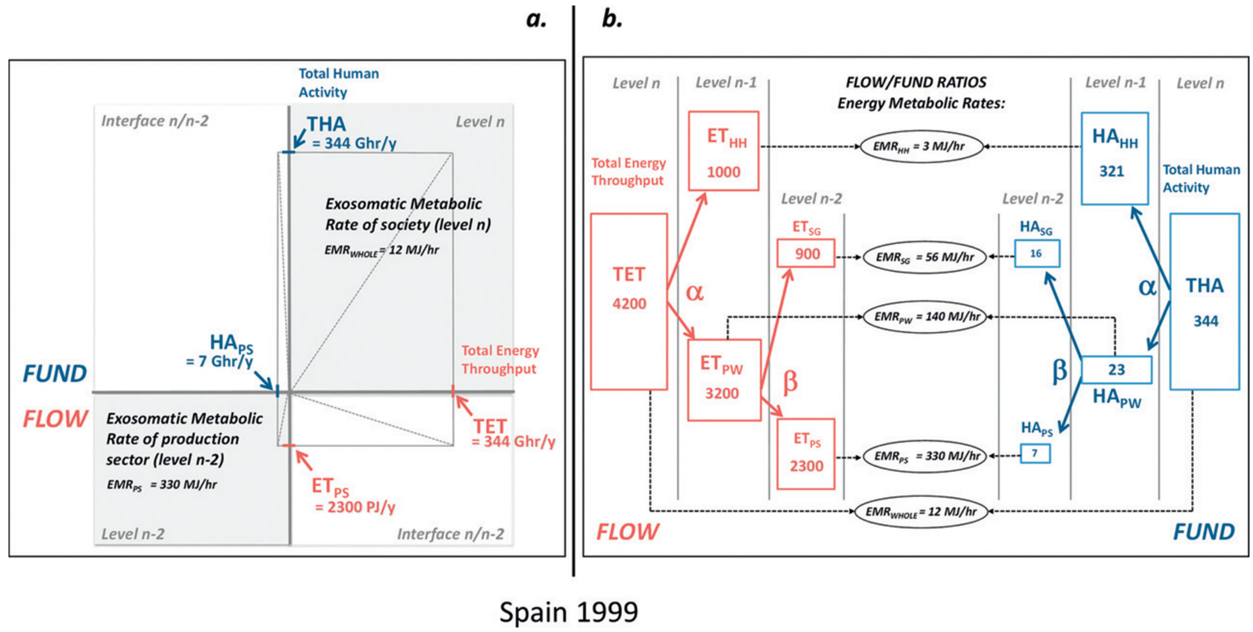

Figure 3 Example of impredicative loop analysis used in energy analysis (Spain, year 1999). Data from Giampietro and Mayumi, 2009.

of distribution) making it possible to describe the profile of allocation of the total amount of fund and flow elements over the given set of functional/structural compartments.

Referring to the technical jargon used in the field of neuroscience, a dendrogram corresponds to a ‘neural network representation’ showing the forced relations (like synapses in neural circuits) between flows and funds across levels. Such a representation makes it possible to formalize the ‘patterns of recorded information’ mentioned in section “Integration of innovative theoretical concepts” through a set of flow/fund ratios corresponding to the benchmarks of the metabolic pattern of the systems under study. The usefulness of neural network representations (or ‘connectionist models’) when dealing with complex systems was first developed by Paul Cilliers (1998).

When dealing with the energetics of human societies we can consider three fund elements – human activity (labor), power capacity (infrastructure and technology) and land – associated with three categories of flow/fund ratios: (1) ‘exosomatic metabolic rate’ (EMR, energy flow per hour of human activity); (2) ‘exosomatic metabolic density’ (EMD, energy flow per hectare of land); (3) ‘exosomatic metabolic intensity’ (EMI, energy flow per unit of power capacity) – see Figure 4.

Multi-level/multi-dimensional accounting (T.F.H. Allen’s Hierarchy Theory)

The application of a multi-purpose grammar to perform an impredicative loop analysis across the nested hierarchical organization of the system makes it possible to construct a multi-level/multi-dimension matrix that shows strong similarities with the popular Sudoku game (Figure 5). Indeed, when discussing the option space (i.e., possible scenarios of change) of a system whose metabolic pattern has been characterized in this way, we can identify the existence of a series of congruence constraints across levels (characteristics of parts/characteristics of whole) and, “at the same time”, congruence constraints across dimensions (energy flows, technical requirements, labor requirements, land requirements). The definition of these constraints is similar to the rules for a Sudoku grid (see Chap. 7 of Giampietro et al., 2011).

The example of multi-level/multi-dimension matrix shown in Figure 5 can be used to characterize the production factors required by the hypercycle of energy carriers of human societies. That is the vector corresponding to the energy supply sector (EM at level n−2) can be opened into three vectors at level n−3 (Physical gradients; Imports as gross energy requirements; Imports as energy carriers) made themselves of primary energy sources (at level n−4) either coming from local gradients or from imports. Such multi-level/multi-dimensional accounting makes it possible to tailor the focal level depending on the purpose of the analysis. For examples, it is possible (1) to discuss the relative requirements of production factors for the generation of energy carriers either they are produced locally or coming from imports (at interface level n−3/n−4); or (2) to assess the strength of the autocatalytic loop (also called Strength of Exosomatic Hypercycle – SEH) by looking at the relative requirements of energy carriers by the whole system compared with the hypercycle at interface level n/n−1, which is an essential factor for living systems to survive (see section “The underlying complexity in energy analysis”).

Wrapping-up the ‘Multi-Scale Integrated Assessment’ Toolkit in ‘Complex energetics’

The four analytical tools presented in this section (multi-purpose grammars, impredicative loop analysis, dendrogram, multi-level/multi-dimension matrix) constitute an accounting approach that is semantically open and therefore adaptable to specific

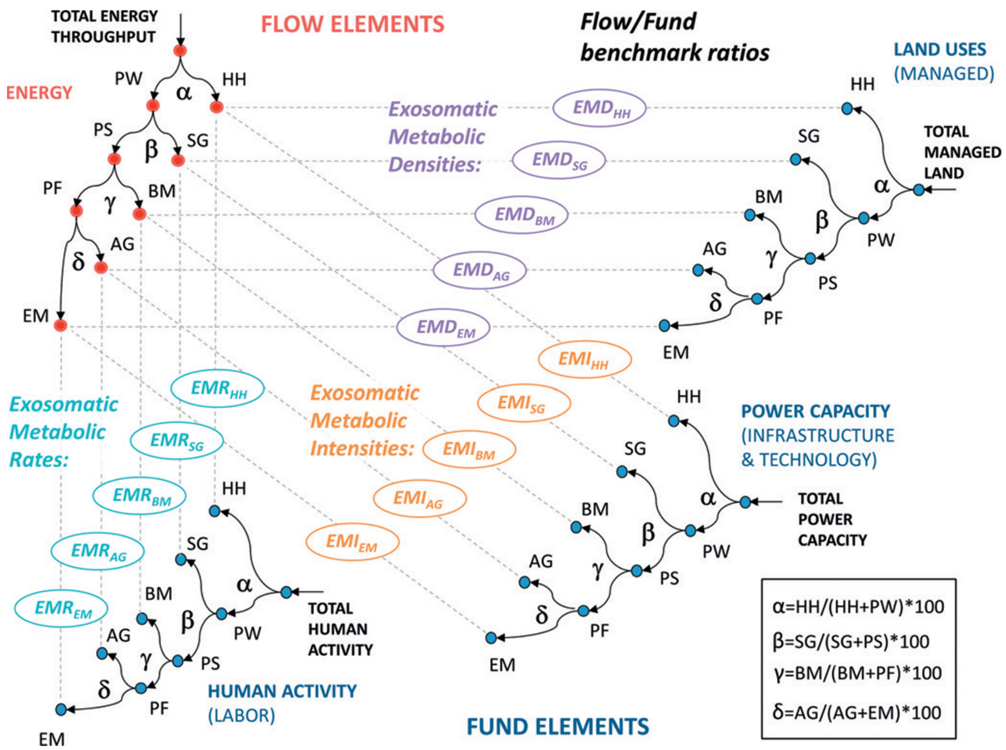

Figure 4 Example of a 'neural network representation' used for characterizing the energetic metabolic pattern of human societies.

situations. They provide a pre-analytical meta-structuring of the analysis (semantic framing) that is tailored to specific instances at the moment of implementing the analysis (contextualized formalization). Therefore, the final protocols of accounting may differ among the socio-ecological systems under study. However, the quantitative representation of large-scale characteristics remains sufficiently robust so as to allow cross-system comparison.

As a matter of fact, the innovative theoretical concepts together with the alternative analytical tools presented in previous sections can be turned into a 'toolkit' of integrated assessment for studying the energetics of complex systems. In practical terms, the approach known as 'Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism' (MuSIASEM – originally proposed as MSIASM by Giampietro and Mayumi, 2000b; 2001; Giampietro, 2003; Ramos-Martin et al., 2007; Giampietro et al., 2013) has been developed as a multi-purpose grammar that explicitly requires tailored definitions of categories (when selecting semantic categories, formal categories and proxy variables) based on the specificity of different 'problem structurings' – multi-objective analysis – and different contexts, making possible a selection of indicators 'à la carte'. The MuSIASEM innovative approach to accounting can be used as (1) a diagnostic tool to characterize the existing metabolic pattern of the socio-economic system under analysis by providing integrated information on flows of energy; (2) a simulator tool to provide a feasibility, viability, and desirability check of proposed scenarios in relation to energy transitions. This approach involves the following six steps: (1) Definition of the socio-economic system as a set of functional compartments essential to guarantee its survival, reproduction and adaptability; (2) Quantitative definition of the profile of investment of fund elements over the functional compartments of the system; (3) Quantitative definition of the flows required for expressing the functions; (4) The multi-level/multi-dimensional assessment describing the metabolic pattern across hierarchical levels and dimensions of analysis; (5) Check of the viability and desirability domains for the metabolic pattern (definition of the internal constraints of sustainability); (6) Check of the feasibility of the metabolic pattern in terms of resource requirement (supply side) and environmental loading (sink side) – definition of external constraints to sustainability.

In Figure 6, we present an overview of the toolkit used for the integrated assessment of the energetics of complex systems based on the MuSIASEM approach to accounting. This analytical toolkit makes it possible to perform two important sets of biophysical analysis in relation with the energy transformations of complex systems across levels:

- FEASIBILITY analysis against external constraints – External constraints are determined by the existence of favorable boundary conditions, making it possible to avoid thermodynamic constraints. In biophysical terms this refers to the possibility (either coming from availability of gradients or availability of production factors) of getting input (on the supply side) and the possibility of damping output (on the sink side). These constraints enter into play any time boundary conditions force a change in the metabolic pattern (below what could be done according to internal capacity and below what would be considered as 'desirable'). The feasibility of a system therefore corresponds to the congruence between the energetic metabolic pattern and the

Vectors of end uses required by the Hypercycle of Energy Carriers

	SUPPLY	HA (Mhr)	ET-t (PJ-EC)	PC-t (MW)	ET-m (PJ-EC)	PC-m (MW)	NSEC-t (PJ-EC)	NSEC-m (PJ-EC)
Benchmarks of production factors in energy supply sector (level n-2)	EM (n-2)	460	100	2,600	4.2	130	5,600	850
Local Primary Energy Sources (levels n-3/n-4)	*PHYSICAL GRADIENTS (n-3)*	*430*	*100*	*2,600*	*4.2*	*130*	*4,200*	*800*
	Fossil fuels (n-4)	150	37	370	2.6	84	3,600	750
	Nuclear (n-4)	12	3.2	32	1.5	48	-	42
	Biofuels (n-4)	270	60	2,200	negl.	negl.	600	3.4
	Others (n-4)	negl.	negl.	negl.	negl.	negl.	negl.	5.9
Imports (level n-3/n-4)	*IMPORTS as GER (n-3)*	*35*	*0.85*	*9.2*	*0.03*	*0.8*	*1,200*	*7.2*
	Fossil fuels (n-4)	35	0.85	9.2	0.03	0.8	1,200	7.2
	IMPORTS as EC (n-3)	*negl.*	*negl.*	*negl.*	*negl.*	*negl.*	*260*	*40*
	Fossil fuels (n-4)	negl.	negl.	negl.	negl.	negl.	260	negl.
	Electricity (n-4)	negl.	negl.	negl.	negl.	negl.	-	40

Energy Supply Matrix (South Africa, year 2009)

Figure 5 Example of multi-level/multi-dimension matrix used in energy analysis (investment of production factors and energy carriers in the energy supply sector in South Africa for the year 2009). HA (human activity) expressed in Ghr (hours); ET-t (thermal energy throughput) in PJ-EC (joules of energy carriers); ET-m (mechanical energy throughput) in PJ-EC; PC-t (power capacity required for consumption of thermal energy) inMW(Watts); PC-m (power capacity required for consumption of mechanical energy) in MW; NSEC-t (net supply of energy carrier in the form of thermal energy) in PJ-EC; NSEC-m (net supply of energy carrier in the form of mechanical energy) in PJ-EC.

bio-economic external constraints. It is assessed using two analytical tools: "Environmental impact matrix" – assessing the requirements of natural resources on the supply side (natural gradients) and the sink side (impact factors) – and "Spatial analysis" – checking the flows against spatial constraints based on GIS analysis.

It shall be noted that external constraints can also be interpreted looking at an additional dimension related to human preferences, cultural values, social institutions, etc. In such a case, we speak of 'desirability' against socio-economic external constraints (not shown in Figure 6).

- VIABILITY analysis against internal constraints – Internal constraints are determined by the ability of the system to stabilize the metabolic pattern (in terms of power capacity, human activity, land) and economic activity (e.g. a lot of modern societies are stabilizing their metabolic pattern because of trade). These constraints are determined by the characteristics of the parts operating in the black-box determining the overall characteristics of the capability of processing flows within the black-box. Internal constraints are at play when external boundary conditions make it possible a further expansion, but the system cannot do it.

  The viability of a system therefore corresponds to the ability of the system to establish a metabolic pattern of energy budget compatible with its context depending on the other compartments of the system. It is assessed using three analytical tools: 'Multi-level/multi-dimension matrix' – assessing the forced relations across scales in terms of requirements of production factors; 'Impredicative loop analysis' – representing the forced relations between flows and funds across scales; and "Dendrogram" – checking values of flow/fund ratios against benchmarks characterizing the energetic metabolic pattern of the system under study.

Conclusion: The Implications of the Complexity Revolution in Natural Sciences

Edgar Morin (1990) observed that the emergence of complexity in science appeared more as a problem than as a solution. Indeed, this was calling back to the old epistemological problem of overuse of reductionism in science. However, he also pointed

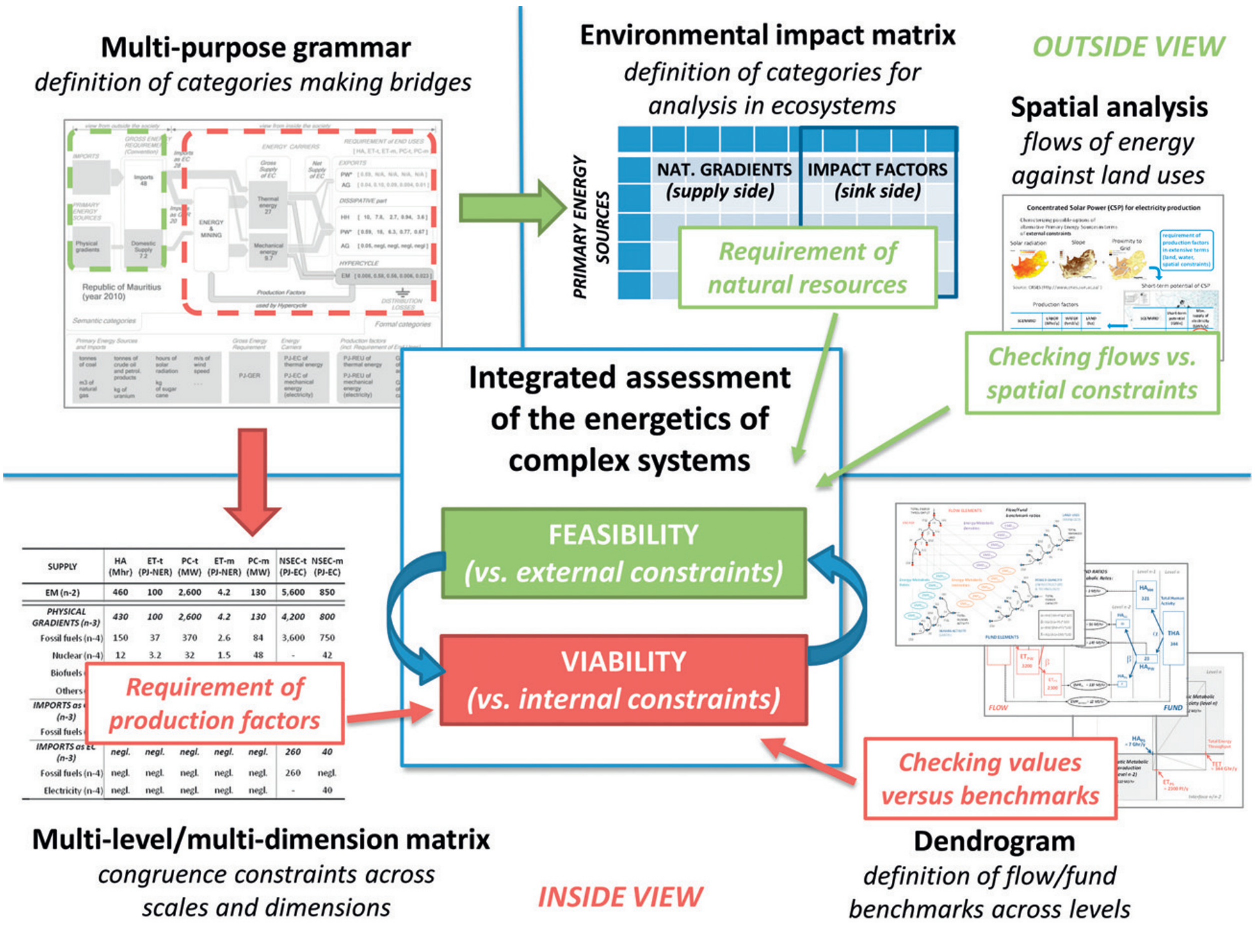

Figure 6 An overview of the toolkit of integrated assessment used in 'complex energetics' based on the MuSIASEM approach to accounting.

out that the epistemological problem of reductionism only is the consequence of a much deeper ideological problem of 'disjunction' that consists in the ideological separation between science and philosophy. The negative consequences of the problem of disjunction in science only appeared in the twentieth century while in fact it dominated Western science since the Age of Enlightenment.

In fact, the use of reductionism in trying to simplify the complex reality to simple representations was an attempt to 'resolve' the problem of disjunction in re-establishing the dialogue between science and philosophy. Unfortunately, this resulted in an even worse situation with the adoption of a new 'paradigm of simplification' with deep ideological consequences on the way scientific knowledge is organized and interferes among the different fields. Reductionism and disjunction therefore were the two faces of the same coin of the 'paradigm of simplification'.

The philosopher of sciences, Gaston Bachelard, however had earlier mentioned that the 'simple' does not exist. What exists only is the 'simplified'. This means that there is an ideological bias between the 'simple' – that refers the representation of the reality – and the 'complex' – that refers to the reality itself. The problem arises from the fact that the "blind intelligence" (Morin, 1990) resulting from the adoption of the 'paradigm of simplification' cannot conceptualize the unavoidable link between the observer and the observed reality. The later complex relation was ironically discovered in particle physics – dealing with the tiniest – while it had been kept away from classical mechanics – dealing with the biggest of our universe. This is another illustration of the emergence of complexity in science. Nevertheless, complexity did not emerge 'per se' in science; rather this was as a result of a process of 'integration' in science.

Indeed, any attempt to escape from the fatal ideological attractor of 'simplification' forces the scientists to engage into a new dialectics in science ('dialogic') which translates into a strong commitment to interdisciplinary (e.g. Morin, 1990; Farrell et al., 2013). This is what occurred with the introduction of complexity in energetics. In fact, the integration of available knowledge in non-linear thermodynamics, theoretical ecology, and complex systems theory demonstrated that an energetic analysis of complex networks of energy transformations is possible. We shall remark here that complexity re-emerged in science from the very same door it had been fired out: the field of thermodynamics. In fact, the first formulation of classical thermodynamics considering "ideal cycles" (the 'simple') as the reference for representing the external world was put in trouble by the emergence of 'non-linear' thermodynamics which attempted to re-introduce complexity in science by bridging the gap between biology and physics.

The lesson from the second revolution in energetics therefore is that the interdisciplinary process of 'integration by concepts' proposed by Kapp (1961) makes it possible to address systemic problems found within one field. As a matter of fact, the solutions adopted for dealing with the epistemological predicaments of multiple scales in 'complex energetics' – that made it possible to reconcile claims, theories and methods in the field of energetics – could be used also to cope with the epistemological problems faced by other fields, especially economics.

Indeed, like Joseph A. Schumpeter used to say before the rise of neoclassical economics, the whole field of economics is once again in "state of crisis" (Schumpeter, 1982 [1931]). This is due to the fact that the current paradigm of neoclassical economics demonstrates persistent and increasing failure at solving old and new problems that is how crises are recognized in science (Kuhn, 1962). As a matter of fact, it is clear that similar integration efforts are urgently needed in economics in order to tame the evident contradiction between neoclassical economics and much of the knowledge developed in natural sciences, especially in thermodynamics and ecology (Georgescu-Roegen, 1966, 1971). Moreover, even though the emergence of neoclassical economics is a rare case in science where a paradigm shift did not follow a radical change (Gerber and Steppacher, 2012, p.5), it is such a unifying work between macro- and micro-economics in the second half of the twentieth century – the so-called 'neoclassical synthesis' – which led to the dominance of this branch of economics since then. As a matter of fact, this experience from the past demonstrates that the same kind of unification of theories is possible also in the field of economics, even though such a process has so far almost exclusively been possible within the realm of natural science – such as the revolution in 'complex energetics' explored in this overview article.

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