# First steps towards a deeper understanding of energy efficiency impacts in the age of systems

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## Abstract

So far technologies have been mostly conceived as silver bullets entering seamlessly into everyday life without any subsidiary effect on other technologies and in general on ideas and practices. One of the consequences of this mindset is that energy analyses are typically performed by assessing the energy impact of single energy end-use technologies during their lifecycle without paying much attention to the effects of their interactions with other technologies and with the daily practices they are embedded in. Such an approach may lead to wrong estimates of technologies overall energy impact and often it does not allow identifying those cases in which energy efficiency improvements (EEI) boost higher energy consumption. This is particularly the case in the present historical situation when most of our daily activities rely on the employment of an increasing number of different devices consuming commercial energy and when all these devices end up with becoming a system whose overall energy performances depends more on how all its energy using components interact than on the energy efficiency of each component. This paper aims to provide a series of insights concerning EEI impacts based on practice theory, actor-network-theory and complex adaptive systems theory whereby technologies are viewed both as elements of daily practices and nodes of a network of technologies interconnected by these practices (e.g. refrigerators are viewed as part of practices related to eating, drinking, cooking, shopping, and as such linked by these practices to technologies used for food preparation, food conservation, food transportation, etc.). Besides presenting a different perspective to analyse EEI impacts, this paper illustrates the epistemological implications of considering technologies as part of larger systems and explains how the point of view proposed may allow identifying important drivers of energy consumption.

## Introduction

The following sections aim to illustrate how an evolutionary perspective applied to networks of practices and technologies can help to better understand energy efficiency improvement (EEI) impacts in the age of systems. This objective is achieved in a series of subsequent steps. First of all the main characteristics of a system are described and the effects of the epistemological rupture that has determined the passage from the age of tools to the age of systems are generally analysed by focusing on the changes induced on the role played by technologies and human artefacts in everyday life. Some of the theories that seem to better reflect the epistemological assumptions of systems are then briefly described. Two phenomenological thermodynamics principles formalised in the framework of the complex adaptive systems (CAS) theory and their implications for systems power output and systems efficiency evolution are analysed in particular. Then the challenges connected to long term and large scale evaluation of EEI impacts on systems evolution are briefly discussed and a simplified approach to assess systems' energy diversity is presented. Finally some general conclusions are drawn concerning how energy policy making could take systems dynamics into account in order to limit the impact of technological systems on existing energy sources.

## From the age of tools to the age of systems

According to several scholars (Cayley & Illich, 2005; Rifking, 1998; Robert, 2011; Arney, 1991) a very important and often neglected epistemological rupture took place around the 1950s concerning the way in which a large category of human artefacts named tools or instruments are conceived and perceived. Until the mid of the twentieth century these artefacts were mostly perceived as means used or designed by human beings to achieve predefined ends, in the same way in which e.g. a typewriter can be seen as a device designed and used to print letters of the alphabet on a sheet of paper. While allowing achieving predefined ends, these tools were seen as objects which could embody human intentions and remain clearly detached from the body of the persons using them. This perceived separation or distality (Cayley & Illich, 2005) between the tools and their users was at the roots of the separation between an objective reality and the subjects who know and act on it by using tools. On the other hand it typically generated two contrasting views concerning the responsibility for the consequences of tools mediated actions, According to some people (probably the majority) it appeared indeed that tools could be employed by any person provided with sufficient skills and information background without affecting or redefining his or her intentions. For this reason a kind of neutrality and objectivity was generally ascribed to them, whereas the full responsibility of the consequences of the actions they allowed to perform had to be attributed to the will of their users. For other people this responsibility had instead to be entirely attributed to tools that appeared as able to deeply redefine human intentions with unexpected and often disastrous consequences for humans and their environment[1]. These contrasting assumptions and perceptions, still largely present in contemporary society, have deeply influenced any field of knowledge and human activity since they entered diffusely the public discourse presumably around the XII$^{th}$ century[2].

It was mainly because of the scientific progresses registered in the field of cybernetics (Bateson, 1972) that a new epistemological approach to the interpretation of reality started spreading in Western countries in the twenties of the XX$^{th}$ century and culminated in the invention of computer technology and the discovery of the double helix structure of the DNA in the 1950s. The computer became the main metaphor for a new awareness of the world and of the self and the underlying theory of systems became the new reference point to re-conceptualise knowledge. In order to grasp the nature of systems and somehow overcome the abstractness of any definition that can be formulated, it may be helpful to think of neural networks or ecosystems as possible material representations of this concept. Strictly speaking the main characteristics of a system can be assumed to be those sketched by Gregory Bateson, one of the pioneers and fathers of cybernetics[3]. According to this anthropologist any system can be defined as an entity with at least the following six characteristics: (1) it as an aggregate of interacting parts or components whose (2) interaction is triggered by difference[4] thanks to the (3) consumption of some collateral energy. Moreover (4) it requires that circular (or more complex) chains of determination take place within it and (5) the effects of difference are to be regarded as transforms (i.e. coded versions) of the difference which preceded them. Finally (6) the description and classification of the processes of transformation taking place in a system discloses a hierarchy of logical types[5] immanent to phenomena. Generally speaking a system can be considered as a self-corrective network of circuits where information and any associated material flow thanks to the consumption of some collateral energy. When an aggregate of interacting parts is seen as a system, its evolution is interpreted in terms of a series of incredibly complex feedback loops allowing to keep an equilibrium or homeostasis of information flows within it despite possible (minor or major) fluctuations in its boundary conditions due to interactions with an ever changing environment. Thanks to these feedback loops the system can keep constant the values of its internal parameters as happening for example with the temperature of a house where a thermostat and the feedback loops that this can activate allow keeping a constant indoor temperature despite outdoor temperature fluctuations. Systems are indeed supposed to be able to autonomously pursue their own ends. With them a new kind of teleology enters the scientific scenario and the Aristotelian causa finalis is readmitted to the scientific discourse after three centuries of hegemony exerted by the causa efficiens[6]. When the interaction between a person and a material object is described in terms of a system, the interacting parts can constitute a whole pursuing own ends. Systems can inscribe persons' intentionality into their workings. For example Heinz von Förster (Cayley & Illich, 2005) described a man walking a dog as a system with the man, the leash and the dog forming a unit processing informational signals that managed to make its way down the sidewalk. In the same way the system made of a man interacting with a modern internet-connected computer can be described in terms of a two components unit processing signals to achieve own ends in the surrounding environment. The distality between user and object used that characterized the age of tools gets lost

1. The current debate on increasing access limitations to weapons for US citizens is an example of this dichotomous perception. Part of the public opinion attributes the responsibility for the increased number of murders being registered in US to the wide presences of weapons among US citizens. Another part (weapons manufacturers especially) maintains that the responsibility for murders has to be ascribed to the will of murderers and not to the weapons themselves.

2.According to some scholars the origin of the separation between body and tools dates back to the XIIth century (Cayley & Illich, 2005). The concept of tools as "instrumenta separata", as objects independent from the hand that holds them, was not very largely known before the twelfth century. Before this century it was not possible to distinguish even linguistically between e.g. a hammer, a pencil or a sword and the hand that held them. The hand, the hammer and the hammering hand were all called organon. It is only after this century that a hammer can be seen as something made for hammering and the sword something for killing irrespective of the type of person using it.

3. Bateson referred these characteristics to what he defined a "Mind". In the opinion of the authors of this paper the concepts of "Mind" and "System" overlap perfectly.

4. The concept of "difference" was employed by Bateson as a synonymous of "information" that was defined by him as "a difference which makes a difference". According to Bateson the elementary unit of information is a difference which is able to generate a difference along the pathways of the system where it travels. The concept of difference is thus closely related to the concept of entropy.

5. Logical types were first defined by A.N. Whitehead and B. Russel in their "The Principia Mathematica". See (Bateson, 1979)

6. In his Metaphysics, Aristotle distinguishes among four kind of cause: causa formalis, causa materialis, causa efficiens, causa finalis. The difference among these can be grasped by the classical example of the sculptor. To make a statue the sculptor (causa efficiens) is supposed to produce changes in a block of marble (causa materials) with the aim of producing a beautiful object (causa finalis) having in mind his idea of the statue to be carved (causa formalis).

with systems. A man can still decide whether to use or to leave a hammer and the hammer remains the tool of a man as long as this hammer is conceived as an instrumentum. The system man-hammer is instead a kind of cyborg made of quasi-objects and quasi subjects, to use Bruno Latour terms[7]. Change and stability become the result of positive and negative information feedbacks which generate along system loops following environment perturbations and the distinction between action and reaction becomes often meaningless because circular causation loops are the only ontological entities of systems. At the same time the body of persons becomes an immune system capable of keeping the value of its vital parameters (e.g. blood pressure, glycemic rate, etc.) within predefined variation ranges in a changing environment while body health is identified with a risk profile, i.e. a list of numbers representing the conditional probabilities that the measured values of its vital parameters may correspond to a system evolution towards a status threatening its own existence.

If the present age can be assumed to be the age of systems, this means that reality is being at the same time reinterpreted and rebuilt in the light of the above assumptions. Coming to the main objective of this paper it is therefore useful and important to try to understand which are the implications of these assumptions for actions undertaken to improve energy performances of technologies which apparently have to be seen as parts of larger systems.

## Some examples of how systems have changed human-practices and technologies

The fact that human action starts being driven by the epistemological assumptions of systems has radical implications on how human activities are organised and on the role of human artefacts named technologies within society.

Some examples can perhaps help to better grasp the nature of this change. The first example relates to the transformation of the production processes organized according to a Fordian structure into a Post-Fordian structure (Ruzzenenti & Basosi, 2008a). Whereas a Fordian production structure is supposed to reflect a star structure where all the materials used to manufacture a given product converge to a centre, a Post-Fordian structure can be considered as an evolution of the Fordian structure and can be supposed to be better reflected by a structure like that represented in Figure 1.

In a Post-Fordian structure the production chain develops in production centres which are dispersed over the territory thanks to an improved transportation system for goods and each production centre can in principle provide its contribution to the final product by connecting itself to several different production centres. Ruzzenenti & Basosi (2008a) attribute this transformation to the free market competition supposed to have generated an outsourcing process whereby firms have externalized part or all of the production phases. This outsourcing process has indeed been at the basis of what they call a geographical gradient that has pushed some geographical areas to specialise in specific production intermediate processes as depicted in Figure 2.

At the same time production outsourcing has induced the creation of a series of additional and higher hierarchical levels needed to control the overall process and has changed the nature of the decisions to be taken and the parameters to be considered for production. Interestingly, the partial outsourcing of the production process represents a competitive advantage in so far as a given firm becomes able to choose among different production centres based e.g. on cost-benefit analyses, and this competitive advantage can be hence associated to the increased *connectivity* showed by the second graph reported under Figure 1. This increased competitiveness is in its turn associated to an increase in production system *complexity* and can be described in terms of a higher system *adaptability* because the increased number of connections that can potentially be established allows to maintain the production system "alive" by switching from a production centre to another in case the conditions for production change unexpectedly. Nevertheless the externalization process at the basis of the dynamics illustrated above exposes the system to more uncontrollable factors (e.g. the free market forces) and determines a general loss of autonomy of system components. It is quite straightforward to identify the main characteristics of a system, including the six minimum requirements described in the previous section, in the example just illustrated. It is moreover worth mentioning that the increase in connectivity described above translates into an increased exchange rate of materials and information needed for production, which can be associated to an increase in the consumption of commercial energy and has been possible thanks to the increased energy performances of the transportation system. This point will be further elaborated in the following paper sections.

A second example can be taken at a different scale by considering how practices related to food preparation and consumption have changed during the last 50–60 years in the households. It should not be difficult to realise how, also in this case, the process related to food preparation and consumption reflected more a star like structure when households mostly cultivated feeding products in their kitchen gardens and used more extensively their personal labour to cultivate, prepare and cook foods and to maintain all tools needed to these ends. Present food preparation and consumption practices are instead better reflected by a process structure similar to the one reported in Figure 3.

Figure 3 is just a very simplified representation of the main present practices typically contributing to households food preparation and consumption (reported within rounded boxes) and some of the main technologies consuming commercial energy (reported within rectangular boxes) contributing to the reproduction of these practices. When compared to practices of the recent past the same transformations observed for the passage from a Fordian to a Post-Fordian production structure can be identified for this case. The outsourcing process at the basis of the industrial production structure transformation can be indeed identified with a progressively increasing delegation by households of the tasks to be accomplished for food preparation and consumption. This delegation has taken two different directions probably more clearly visible for the example of food preparation than for the example of the Fordian industrial process structure: on the one hand this delegation has led to the involvement of an increasing number of persons in each (food) production proc-

7. See Latour (1993).

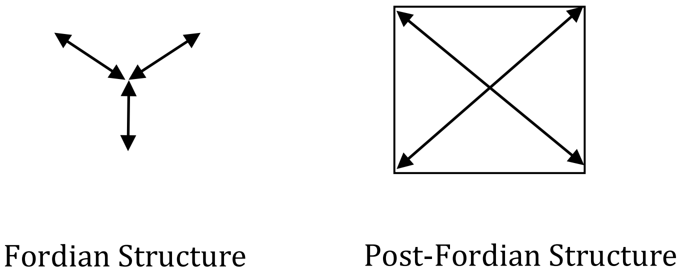


*Figure 1. Paths reflecting a Fordian and a Post-Fordian production structure. Authors elaboration of graphs reported in (Ruzzenenti & Basosi, 2008a).*

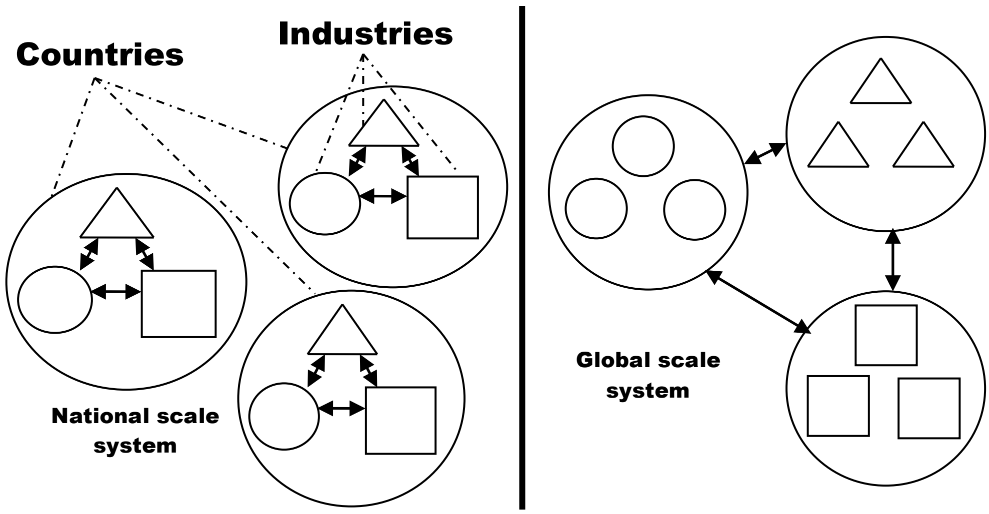


*Figure 2. Geographical gradient generated by production outsourcing (Ruzzenenti & Basosi, 2008a).*

ess[8], while on the other it has implied a progressive substitution of human labour with work accomplished by machines consuming commercial energy. Both directions have progressively made households practices more heteronomous and have implied an increasing loss of control by single households on the production processes involved. However these transformations have accelerated the production process and liberated a lot of time that households can decide to employ to perform other activities. As happened for the first example described, additional hierarchy levels have been created in the organization of this process and their introduction has progressively made households' food production and consumption more a question of information and time management than a question of manual activities to be accomplished. All in all, it should not be difficult to identify the transformation trends leading to the creation of a system fulfilling the minimum requirements sketched in the previous paper section also for this second case.

Another example can be provided even at the scale of single technologies with the forthcoming diffusion of so-called smart appliances which automatically turn on when the electricity is cheaper. Smart appliances represent indeed a striking example of how technologies tend to become part of systems integrating technologies and electricity supply networks. The intentionality of humans using these technologies becomes subordinated to information exchange loops that concern availability of energy at low price. These loops introduce complex additional hierarchy levels in the decision processes related to the usage of technologies, as happened in the examples previously described.

It is however worth mentioning that the epistemic rupture caused by systems cannot be necessarily detected by a static analysis. An analysis concerning how material objects functions and structure evolve with time is indeed generally necessary. The passage from tools to systems implies a marked increase of the functions executed and practices reproduced by material objects that, as partly showed in the following paper sections, can be represented in terms of an increased material objects' "connectivity". However, when I look at a car in the age of systems I still see an object with a given structure and given functions as it was in the age of tools. As the next paper sections will try to illustrate, it is by analysing how material objects *evolve* that this rupture becomes more evident.

8. Notice however that this does not imply that the total number of persons involved in all daily food production processes has increased.

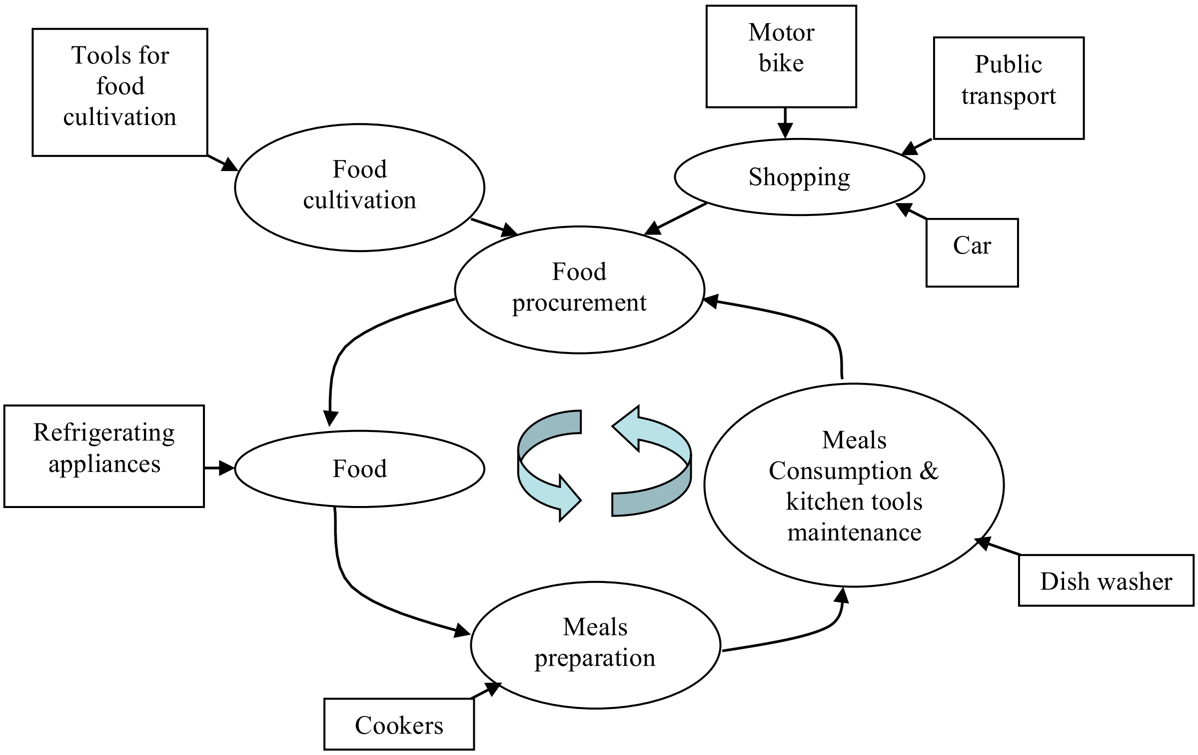


*Figure 3. Some of the practices and technologies related to food preparation and consumption.*

## Theories reflecting the epistemological assumptions of systems

Besides cybernetics, some of the theories better reflecting the assumptions of systems' are probably the *practice theory*, the *actor-network theory* and the *complex adaptive system theory*. Whereas practice and actor-network theories originate in the field of social sciences, complex adaptive system theories have much wider application fields including physics systems and ecosystems. Practice theory is based on the concept of *habitus* as formulated by Bourdieu (1998) and explains human action in terms of creation and perpetuation of a practical knowledge consisting of material elements (i.e. material, technologies and tangible, physical entities), image elements (domain of symbols and meanings) and skill elements (i.e. competence, know-how and techniques) which are linked together and co-evolve in the socio-technical milieu. This theory tries somehow to resolve the antinomy between traditional structuralist approaches to social phenomena and approaches which attempt to explain these phenomena in terms of individual actions and behaviours. The same can be the actor-network theory (ANT) as mainly developed by Callon (1986), Latour, (2005), Law & Hassard (1999) in the framework of their studies on science and technology. ANT is an agent-based approach to social theory which has many similarities with the practice theory in so far as it treats objects as part of social networks and is probably best known for its insistence of agency of nonhumans. On the other hand the complex adaptive systems (CAS) theory is a relatively new theory developed mainly by Holland (2012), Gell-Mann (1994), Morowitz (2002), Arthur (2009) and dealing with aggregates that exhibits certain behaviours like adaptive behaviour, self-organisation, emergence, co-evolution etc. As already mentioned, these behaviours are common across a variety of systems like ant colonies, human settlements, organisations, physics systems, etc. Compared to practice and ANT theory, CAS theory provides, in the opinion of the authors of this paper, a more formalised and better defined description of the dynamics of change that is explained by the concepts of *emergence* and *autocatalytic loops* generated within systems. All of these three theories rely on a representation of reality based on the concept of a network of interlinked biological and physical entities exchanging information and/or materials. All of them support an interpretation of technologies as both elements of daily practices and nodes of a network which are connected to other nodes of this network (i.e. to other technological devices) through these practices. In the following paper sections systems will be identified with the object of analysis of these theories and these theories will be used mostly interchangeably to highlight systems' properties of relevance for the scopes of this paper.

## Thermodynamics applied to systems: the trade-off between power and efficiency

According to a series of scholars, the evolution of CAS is regulated by two different principles depending on energy and time availability. Minimum entropy production or minimization of the input needed to obtain a given output are the expressions coined and most frequently used to refer to the first principle which dominates in a situation of energy scarcity and stable system boundary conditions. This phenomenological principle has been formalized by Prigogine (1961), Glansdorff &

Prigogine (1971), Nicolis & Prigogine (1977) for energy-dissipating systems in a steady non-equilibrium state and applies to systems which are close to the thermodynamic equilibrium. Broadly speaking this principle implies that, in a condition of energy supply limitation and quite stable boundary conditions, system structures and components requiring a lower energy input to produce a given output have a competitive advantage and will prevail over less efficient ones (i.e. over system structures requiring more energy to produce a same output) determining a system reorganisation that can be characterized in terms of an increased system complexity. This reorganisation causes therefore a lowering in the diversity of options available to perform a same function in the short term and may put system survival at risk in case of a change in the boundary conditions. On the other hand it diminishes system stress on the environment supplying energy and contributes to liberate energy whereby new structures can be created and contribute to successful system re-organisation in case a new situation of energy scarcity and new stable boundary conditions occurs in the long term.

The second principle has been instead formalized in terms of maximization of energy flows and has been proposed for the first time by Lotka (1922). Several names have been proposed for this principle by different scholars. It has been defined e.g. as "maximum power principle" by Odum & Pinkerton (1955), as "maximum exergy degradation" by Morowitz (1979), Jørgensen (1992), Schneider & Kay (1994). It establishes that in a situation of energy abundance and time scarcity CAS tend to increase the speed of energy intake in order to speed up the activity of existing structures and generate new structures. This enhanced diversity and intensification of the activities performed takes place at the expenses of system efficiency. The overall effect of the augmented energy intake is hence described in terms of a system growth and increased system power capacity accompanied by a decrease in system efficiency. The higher system power output may determine a higher stress on the environment and on the boundary conditions. On the other hand the higher diversity achieved increases the possibility of a system reorganisation in case of significant systems boundary conditions change. System maximum power output corresponds to a status of higher diversity which is indeed a prerequisite for a higher system adaptability. This status enhances the chances of system survival through a system complexity leap whenever the conditions of energy resources scarcity and minimum entropy production are achieved.

Polimeni et al. (2009) provide an example of household management to illustrate how the principles of efficiency and power output maximization co-operate in the evolution of CAS. According to them, economies made by families during routine activities comply with the above mentioned minimum entropy production principle and allow to save money amounts that can be subsequently reinvested in additional activities. What is saved at the lower level of routine metabolism can indeed be transformed into investments enhancing social interactions and create new activities at a higher level of household organization in accordance to the maximum power output principle. The final outcome of this co-operation process would be a better integration of families' metabolic systems with the environment during their evolution. Nevertheless the reciprocal influence between efficiency and power output represents for Polimeni et al. (2009) an overall drive toward instability. Systems evolution seems to be a question of eliminating the least energy efficient practices in order to be able to employ the available energy to generate more diversity whereby increasing adaptability in a context of continuously changing system boundary conditions. These authors underline that the goal of increasing diversity per se collides with the goal of increasing efficiency as defined at a particular point of space and time, although these two goals co-operate in the long term. Moreover they point out that the phase of increasing diversity is a phase during which additional system outputs are generated and system efficiency cannot be properly defined. For example, they illustrate how energy efficiency improvements in cars have been associated to or have determined the introduction of new categories and variables in the formal identity of cars due to addition of many different gadgets and services and how this has represented an increase in the diversity of possible options available for consumers looking for a car[9]. It is only during the phase of resource scarcity and system reorganisation that an efficiency function can be defined and the different structural types can be mapped on this function in order to eliminate the least efficient and amplify the most efficient ones. Interestingly, these scholars consider identity redefinition as an intrinsic and fundamental property of systems that implies a continuous re-definition of what should be intended by systems output, systems power output, system efficiency and a continuous re-definition of the metrics that can be used to measure these quantities.

This important insight deserves further consideration. If the evolution of the technology of digital cameras is taken as example, it can be observed that when the first models of this new technology were put on the market increasing cameras' image resolution was the main objective of R&D activities and their efficiency was therefore mainly assessed in terms of number of pixels/$cm^2$. After a period of about ten years, digital cameras resolution grew exponentially and allowed in this way to generate new models with new functions and attributes. Consumers' interest in this parameter started decreasing and drifted towards the speed of sensors so determining what could be called a complexity leap. This triggered a new growth in the performance of digital cameras with respect to this parameter that became the new driver of the evolution of this technology generating in its turn new diversity and determining a dumping in the growth of their resolution. The definition of systems efficiency seems hence destined to change during system evolution and the same destiny seems therefore to be reserved to the definition of system power output (i.e. to the metrics employed to measure system outputs, efficiency and number of outputs per unit of time). Despite their continuous redefinition, efficiency and power of systems seem however to remain correlated as depicted by applying the thermodynamics principles briefly described above. It has to be pointed out that what allows power output increase during systems evolution is the peculiar nature

9. Whereas e.g. speed and fuel consumption could be considered as the relevant parameters needed to assess cars performances during a certain phase of the evolution of this technology, subsequent energy efficiency improvements allowed to install air conditioners, four-wheel drive technology, etc. This increase of end-uses associated to cars has determined a change in cars identity requiring a different description and different parameters (e.g. related to how to measure efficiency of motors, efficiency of air conditioners, efficiency of four-wheel drive technology) to evaluate their performances.

of systems power output and the peculiar role played by information during system evolution. While evolving systems manage to increase their power output by continuously re-defining this parameter and this can happen only because the essence of systems power has the same material consistency of information. It is as systems would be endowed by an incredible level of vitality. Whenever the resource they consume to generate their outputs is abundant, they react by intensifying the activity of existing input-output structures and by generating new structures that can increase the possibility of system re-organisation and survival in conditions of resource scarcity[10]. This increased power output will be generally achieved by reducing the amount of material resources wherein this power output is generated, rather than by increasing this amount, given the general scarcity of material resources typically available in the environment. This is confirmed e.g. by the fact that the metabolic rate of small organisms (i.e. watt/kg produced) is higher than that of larger ones[11] and by the fact that in general the exponential power output increase achieved within materials relates to a scaling down of the dimensions of these materials[12].

Ruzzenenti & Basosi (2008b) provide additional insights concerning the relation between efficiency and power in the evolution of systems by focusing on thermodynamic efficiency, i.e. the efficiency concerning conversion of heat into work. The existence of a trade-off and co-operation between thermodynamic efficiency and power is proved by these scholars by referring to the Carnot Cycle. This cycle proves indeed that maximum theoretical efficiency is achieved only under a condition of reversibility and infinitely slow speed (i.e. a condition of machine power approaching to zero). In order to get more than an infinitesimal amount of work and increase machine power, it is necessary to speed-up the process and consequently create a gradient between the temperature of the working substance and that of the heat reservoirs during the isothermal expansion and the isothermal compression of the Carnot cycle. This means that the two temperatures of the working substance during the isothermal transformations must be respectively higher than that of the cold reservoir and lower than that of the hot reservoir, i.e. the difference between the two temperatures of the working substance during the two isothermal transformations must be lower than that of the temperatures of the two reservoirs. The higher the gradients of temperature between working substance and reservoirs, the closer the two temperatures of the working substance during the isothermal transformations. When these two temperatures coincide a condition of zero work and zero power is again achieved, because all the heat absorbed from one reservoir is transferred to the other without work generation. This reasoning demonstrates that the function representing the relation of machine power vs. efficiency for this Carnot model approaches zero at least two times respectively when machine efficiency approaches the maximum theoretical efficiency and the zero value. Therefore machine power must achieve a maximum in this efficiency range as schematically shown in Figure 4. This theoretical model is an exemplification of the trade-off between power and efficiency in CAS and how an increase of power output may be accompanied by a decrease in energy efficiency. Based on this model Ruzzenenti & Basosi (2008b) conclude that in a situation of energy resource abundance CAS will tend to increase their power output at the expenses of their overall efficiency whenever time is a scarce resource, which is always the case in a context of species competition (i.e. in ecosystems) or in a context of economic competition (i.e. in human-made systems)[13]. It may be worth mentioning that all transformations which have led to the substitution of human labour with machine work can be considered as solutions elaborated to increase labour productivity (i.e. the output produced per unit of time) at the expenses of the overall efficiency of the production process[14].

The Carnot model is also used by Ruzzenenti & Basosi (2008b) to illustrate under which circumstances an increase of system power output can be obtained by increasing energy efficiency so reproducing the minimum entropy production principle. This situation results from any technical improvement concerning material improvement or friction reduction in the Carnot Engine parts leading to a faster heat transfer from the heat reservoirs to the working substance and would correspond to a situation of increased system complexity (see Figure 4). Elsewhere the same scholars (see Ruzzenenti & Basosi, 2008a) describe a situation of increased complexity as a situation when a new system organisation is established on a higher hierarchy level. This introduction of a new hierarchy would entail a coherent behaviour for lower level components.

All in all CAS evolution would hence consist in a circular pattern whereby CAS grow and increase their power output and diversity (i.e. they add new activities and intensify existing ones at the same hierarchical level ) while decreasing their overall energy efficiency as long as a condition of energy resources abundance persists. As soon as a situation of energy resource scarcity and system stress is achieved, a complexity leap corresponding to a system reorganisation and to an increased efficiency is realised in such a way that additional energy is liberated and the system can start to grow again while increasing its diversity and power output. A recursive pattern that could then be depicted as growth-saturation-complexity leap-growth would hence be followed by systems. According to Ruzzenenti

10. Clearly the possibility of a system reorganisation cannot be established beforehand and a situation of resource scarcity may also determine the collapsing of the system.

11. A mice has a metabolic rate around 3.0 watt/kg, whereas an elephant has a metabolic rate around 0.5 watt/kg.

12. Computer technologies are probably the most relevant example of an increased power output (as measured e.g. in terms of bit/sec/cm2, or watt/cm2) involving a scaling towards small dimensions of components. It is worth mentioning that the scaling towards small dimensions which typically accompanies these exponential performance improvements can be analysed also in terms of energy performances (e.g. in terms of energy density measured as joule/sec/gr flowing through the system). This analysis shows that computer chips (probably the smallest existing technological devices) are the objects with the highest energy density in the universe (Kelly, 2010). They are therefore the most active and most evolved objects under the energy density point of view. The energy density ranking positions these artifacts respectively before airplanes, cars, the human brain, animals body, motors, plants, the earth, stars and galaxies. This record can ultimately be considered as the result of the progressively improved efficiency in the conversions of the energy inputs into the outputs of computer chips.

13. This model describes increased power output only in terms of activity increase, whereas Polimeni et al. (2009) maintain that power output increase is also due to the emergence of new structures and activities, as previously mentioned.

14.As rightly reported by Ruzzenenti & Basosi (2008b), Jevons (1865) maintained that "coal has never been more efficient or cheaper as an energy source compared to the sun. It was instead simply more economical in the sense that its usage was more fit for economy than the free, efficient, abundant, diffused and un-harnessed energy of the sun. A wind vessel has and will always be more efficient than an engine-powered boat. It is, however, the speed and most of all, the reliability of the shipment which marks the difference."

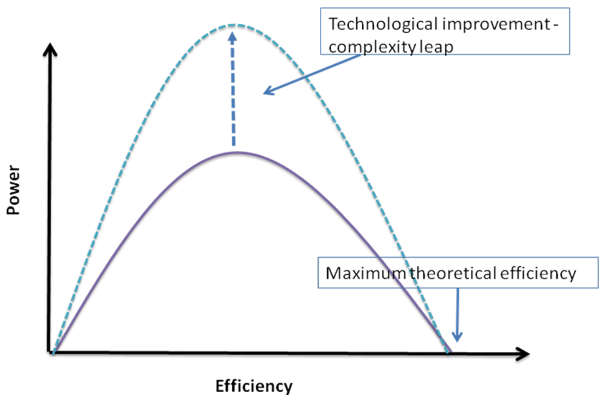


*Figure 4. Simplified sketch of the efficiency-power trade off in a modified Carnot model as illustrated by Ruzzenenti & Basosi (2008b).*

& Basosi (2008b) this pattern would not be necessarily established in case of efficiency improvements related to transformations from an energy type to another (e.g. heat or electricity generation), because these transformations do not necessarily entail the production of work[15]. In general however the application of the Carnot model seems to indicate that energy efficiency improvements in situation of time scarcity are the necessary prerequisite for system and power growth, (measured e.g. according to the metrics of kWh/sec). Ruzzenenti & Basosi (2008b) support this conclusion by examples illustrating e.g. how in the aftermath of the second oil crisis of the 1980 (i.e. in a situation of energy scarcity) efficiency of trucks in the EU was maximized while trucks power increased slightly. As energy prices started decreasing (i.e. as a situation of energy resources abundance was somehow re-established) trucks power started increasing significantly on average while their efficiency started decreasing because of the higher average speed trucks were requested to achieve and of the additional functions they were requested to execute. At a larger scale the increase in truck efficiency would have been accompanied by a structural change from the Fordian production system to the post-Fordian production system characterised by a much higher frequency and distance of shipments as well as by a much higher system power output (Ruzzenenti & Basosi, 2008b).

Overall the power output increase seems to be the main driver of systems development (whatever system power output may be). On the other hand, an increased efficiency in the transformations of systems inputs into systems outputs seems to represent the necessary pre-requisite for system power output enhancements when the resource in term of which the system output rate is measured is scarce (either this resource is represented by time, or space, or bits, or Euros, etc.). When technologies become part of complex systems, technological development becomes a particular case of complex systems development reflecting this phenomenological principle.

15. In the opinion of the authors of this paper, this conclusion is not correct in so far as transformed energy is and can be potentially used to perform different functions (e.g. domestic heat is used not only for space heating but also for DHW heating and other possible applications can in principle arise in the future). Also energy transformers can hence in principle create a structure and dissipate more energy.

## Assessing systems' energy efficiency improvement impacts

The evolutionary perspective illustrated in the previous paper sections can provide some insights concerning the problems connected to long term and large scale evaluation of EEI impacts. While a series of very sophisticated techniques have been developed to assess EEI impacts in the short term and at the level of EEI impacts on the performances of single technologies, the assessment of these impacts in the long term and at large scale is characterised by at least the following challenges when technologies and human practices become systems[16]:

a) systems are typically open systems which are not in thermodynamic equilibrium

b) systems are hierarchically organized and operate on multiple spatial and temporal scales

c) systems evolve thanks to the establishment of circular causation/autocatalytic loops.

Being open, systems exchange energy and matter and coevolve with the environment. As also stated by Prigogine (1987), this implies that systems are always "becoming" something else and makes any formal representation of their behaviour practically impossible. Considering that any assessment related to EEI impacts on systems' total energy consumption relies on a *ceteris paribus* hypothesis (i.e. on the hypothesis that everything but the EEI remains unchanged in a system), this introduces a large degree of uncertainty in the assessment. Any technological improvement can generally increase system activity level and determine a change in its formal identity by an expansion of the option space with the addition of new possible categories and activities, as illustrated in a previous section.

The impacts of systems' EEI on total energy consumption may change according to the spatial and temporal scales considered for the evaluation. It is indeed quite straightforward to understand that EEI impacts can even be reversed when impact assessments are performed at different hierarchical levels. Improving energy efficiency of cars and of mobility infrastructures in a given geographical area may for example result in less energy consumption attributed to each car during its lifetime, but may determine a higher energy consumption to be attributed to all cars circulating in that area because of an increased affluence to car mobility. Similarly EEI impacts for energy end-users may be different when assessed on a daily, monthly, annual or multi-annual basis. This happens for example when an EEI liberates energies that can be used to perform additional activities when accumulated over given thresholds.

Finally systems are by definition characterized by circular causation loops. This often makes the application of any reductionist model practically meaningless. In circular causation loops the direction of causation between two different events may change when assessed at different spatial or temporal scales, as in the famous "chicken and egg paradox". Looking at a single chicken it might be concluded that it is

16. Most of the conclusions and considerations reported in this section have been formulated and described in more detail in Polimeni et al. (2009).

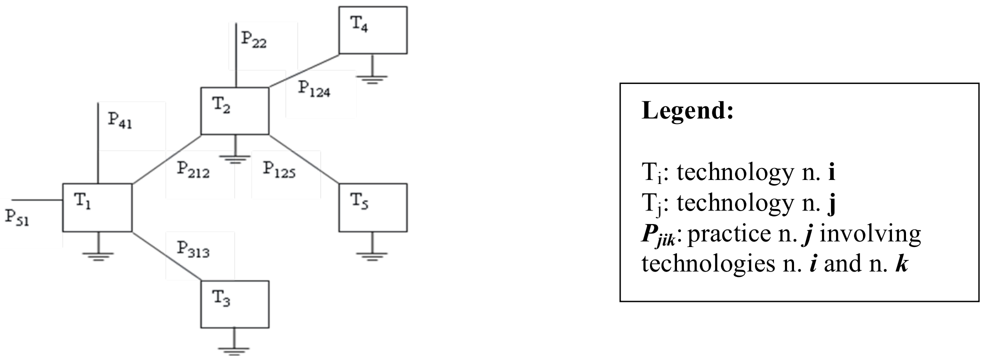


*Figure 5. Outline of a network of practices and technologies.*

the chicken that makes the egg, but when the sequence egg-chicken-egg is considered, it should be concluded that it is the egg that makes the chicken to preserve itself. The creation of circular causation or autocatalytic loops are at the roots of any auto-organization process within systems and may make EEI impact assessment very tricky. Just to mention one example related to energy efficiency, the increased availability of efficient air conditioners made it possible to employ new and cheap construction technologies not able to guarantee sufficiently good comfort conditions in buildings of many countries in the world. The diffusion of these new and cheap construction technologies forced in its turn to install energy efficient air conditioners in an increasing number of newly constructed buildings often determining an overall dramatic increase in residential electricity consumption due to air conditioners. Can it be assumed that energy efficient air conditioners are responsible for the increase in the electricity consumption, or should the new construction technologies be considered responsible for this increase?

## A possible approach to assess energy diversity of human-made systems

If the evaluation of EEI impacts in the long term presents a lot of challenges, it may be worth investigating whether a calculation method to evaluate, at least approximately, human-made systems energy diversity could be developed. This may in principle prove very useful to assess the existing potentialities for system energy efficiency improvements or system evolution as well as to evaluate the level of technology integration into human practices (as measured e.g. through the number of different practices connected to a given technology). A system of human practices and technologies can indeed be represented synthetically as depicted in Figure 5.

Figure 5 is a simplified sketch of how networks of practices and technologies may look like. Information and materials may be generally exchanged along these networks thanks to the consumption of different types of energy. In the opinion of the authors of this paper and also based on the considerations reported in the previous sections, these networks can be assimilated to ecosystems that can be analysed in terms of associated fluxes of commercial energy. For the sake of simplicity it can be assumed that these fluxes originate at network nodes and that the consumption of commercial energy is hence concentrated in the single technologies constituting the network and consuming commercial energy during their usage phase. The properties of this network can be analysed through the same principles of thermodynamics described above and in the light of the recent findings of the science of complexity applied to ecosystems as proposed in the seminal work by Ulanowicz (1997).

A total energy flux can be associated to this network by summing up all the commercial energy consumed by all energy using technologies constituting the network. Network energy diversity can in principle be assessed by developing a calculation approach to assess how this total energy flux is distributed over the different practices. This calculation approach can be derived from the method proposed by Ulanowicz (1997) to quantify a property of ecosystems defined as "ascendency". Empirical analyses have shown that ascendency can be correlated to systems propensity to grow. Here it is not possible to go into all the details of the definition of this indicator. It can be only mentioned that the ascendency index is the product of a factor representing that total energy and/or material flow through the system and a factor representing the difference between the maximum potential mutual exchange of information (defined as development capacity) and the actual mutual information exchange among the nodes of the network whereby an ecosystem can be modelled. Broadly speaking the ascendency index allows one to assess the existing potential to increase ecosystem connectivity, which can be positively correlated to ecosystem's growth. In case of networks of practices and interconnected technologies it can be assumed that network diversity can be assimilated to that part of the ascendency index representing the product between the networks total energy flux and the existing mutual information exchange. This second factor can be defined as $H = -\Sigma_{ijk} (p_{ijk} \bullet \ln p_{ijk})$ where $p_{ijk}$ is the fraction of total energy flowing through the practice i that constitutes the technical system and connects technologies j and k (see Figure 5)[17]. The value assumed by the function H is higher when the distribution of the total energy flux over the different practice is more even (e.g. in case of two practices H is higher when $p_1$=50 and $p_2$=50, than when $p_1$=90 and $p_2$=10) indicating that the more even the flux distribution the higher the system energy diversity. The formula above is a very simplified version of

17. The equation reported is attributed to Shannon and Weaver (1949). The approach proposed has been inspired by Zhongmin et al. (2002).

the general formula allowing to estimated mutual information exchange and has been here proposed just to indicate a possible approach to measure energy diversity. This formula could for example be used to assess energy diversity of a single technology whereby more practices are reproduced (e.g. a car used for shopping, to reach the workplace, to go to holiday, etc.) and could allow one to compare different technologies for their energy diversity content. It could also be used to assess the energy diversity of the economy of a given country using energy in different economy compartments (see Zonghmin et al., 2002).

## Efficiency-power and scarcity-diversity trade-offs

When the efficiency-power trade-off is analysed by paying attention to the implicit assumptions of the model one finds that the efficiency-power or efficiency-diversity tension may have in principle different intensities depending on whether it is observed in a technological framework (i.e. it is observed in terms of *measured* efficiencies and *measured* power outputs) or not. This point can be grasped by focusing on the role played by the concept of *scarcity* in the above dynamics and on the assumptions determining the perception of a situation of scarcity.

According to CAS theory, the driver of the system power growth is represented by two factors: 1) an increase of system diversity (i.e. the creation of new structures) accompanied by the intensification of the activity level of existing structures in a situation of resource abundance and time scarcity; 2) a system re-organisation accompanied by a redefinition of system power output and an improvement of system efficiency in a situation of system input resources scarcity. Two necessary preconditions for the creation of these situations of scarcity within a technological environment are a) the operative definition of a physical quantity and related metrics to assess the number of available resource units and b) the establishment of a conservation principle for this physical quantity as assessed according to the defined metrics (e.g. the operative definition of time and of the related metrics allows to establish that each person has 24 hours/day available, the operative definition of energy and of the related metrics allows to establish that the amount of energy totally available is constant for an isolated system, etc.)[18]. Moreover the definition of a metrics for the power rate associated to a given activity implicitly produces a change of perception concerning the number of different ends/outputs that this activity allows to achieve and connects the output amount that can be generated to the consumption of a scarce resource. This can be easily grasped by observing for example how the assessment of a walk in terms of m/sec walked connects the travelled distance to time consumption. All the possible ends that can in principle be achieved by this activity (the possibility to meet other people while walking, the beneficial effects for the body, etc.) are in this way projected along the Cartesian axis associated to the defined activity power metrics (m/sec) and are subordinated to the value associated to this single unit of measurement when a technologically driven perspective is assumed. Considering that the metrics used to measure the activity power rate (the seconds used to measure the speed of a walk) defines a condition of resource scarcity, people are generally eager to increase the activity power output (the speed of a walk) for example by using a machine (a private car). This will surely produce a lot of benefits but will also typically decrease the efficiency of the performed activity (the energy consumed by a human being during a walk is much smaller than the energy consumed by a car to travel along a same distance) while increasing dramatically the amount of output produced (the amount of meters travelled by car). The most important point of this reasoning is that when the technological system producing the activity output will be somehow forced to perform a complexity leap (e.g. because system boundary conditions will favour the employment of public transport instead of private cars due to the higher energy efficiency of public transport compared to private cars) the different ends achieved by the initial activity (the possibility of meeting people, the possibility of enjoying physical benefits from the walk previously mentioned, etc.) will have a very reduced role to play in this leap. This somehow implies that, in any technological system evolution driven only by the maximisation of the production rate of measurable outputs or by the minimization in the exploitation of some measurable and scarce resource input for each produced output, the possibility for exploiting the potential of diversity represented by a huge number of ends achieved by the initial configuration will generally be very limited. It does not matter whether this happens because the "power" attributed to these ends is not measurable (e.g. because it is context dependent) or is voluntarily not taken into account. The ability for a system to adapt results significantly decreased just because its diversity potential is assessed in terms of an increase in the generation of standardised and measureable outputs in a condition of time scarcity. The relevance of this point should not be underestimated given that a condition of resource shortage can be achieved at very different rates depending on the diversity of functions performed and output types generated by consuming each resource unit (i.e. the higher the diversity, the later the resource shortage condition is achieved). After all, if the diversity of outputs that can be consumed in the unit of time has an upper bound, the fact that more different outputs are generated per single resource unit consumed can result in a slowing down of the resource depletion rate. Also it cannot be excluded that the associated perception of time scarcity can be reduced in this way.

The question is then whether and in which circumstances it can be possible and desirable to create the conditions to increase the diversity and the number of outputs generated by a technological system or equipment per single resource unit consumed in order to alleviate the burden on the resource system producing the flow of resource units consumed[19]. Clearly this is a very general question involving a plethora of mostly contingent factors which are often very difficult or impossible to identify. One of these factors however can certainly be found in type the rules established to administer the usage of equipment, of resource systems and resource units consumed. The influence of these rules on the generation of outputs diversity can indeed be hardly overestimated. Property rights

18.The definition of a metric to measure the availability of a given resource is also the necessary precondition to attribute an economic value to this resource and establish a different type of resource scarcity based on the model of supply and demand.

19. The reasoning presented here is based on a distinction among resource systems producing a flow of resource units, equipment and technological systems using these resource units, outputs generated by this equipment and systems.

on equipment and resource systems are for example just one of the aspects deserving particular attention when the necessity of increasing the number and the diversity of outputs generated by single resource units is at stake. As underlined by Ostrom (1990) a series of very different rules may be established giving individuals rights to use particular types of equipment, to use a resource system at a particular time and place, or to withdraw a particular quantity of resource units. But even when particular rights for the resources used are unitized, quantified, and salable, the equipment and the resource system may still be owned a) in common by people, b) individually (according to competitive market settings) or c) by a central authority (e.g. the state). Central authorities make unitary decisions for equipment and resource system usage under the institutional setting c) or parcel out ownership rights to these goods and then allow individuals to pursue their own self-interests within a set of predefined property rights under the institutional setting b). These institutional settings are particularly suitable to maximise the production rate of measurable and highly standardised outputs of technological systems and can prove effective in minimizing the associated increase of resource units consumption. However, when it comes to produce a significant enhancement of technological systems adaptability without harming the specific resource system they rely on, the institutional setting a) has a very important role to play at least on a small-scale[20]. Self-governing and self-organised institutions whereby equipment and resource systems are owned and managed in common by people can indeed potentially generate a much higher diversity of solutions to employ available resource units and increase in this way technological systems adaptability while reducing their burden on the existing resource systems (Ostrom, 1990).

## Conclusions

Human-made artefacts are becoming systems. The implications of this transformation are that human activities and practices become more and more integrated into networks of technologies. These are hierarchically organised through information feedbacks loops and consume commercial energy during their usage. Human agency is also deeply modifying as it becomes more and more integrated and distributed over an increasing number of different and interlaced material objects which reveal an increasing overall auto-organization capacity. One consequence of this trend is that the phenomenological theories developed to interpret the evolution of systems can be applied also to networks of technologies and practices. These theories (the CAS theory in particular) indicate that such networks evolve to maximise their power output by continuously redefining the nature of their outputs. Moreover they show that, in a situation of resource abundance, a power output enhancement is achieved by increasing the system diversity (i.e. by generating new structures) and by intensifying the activity of the existing structures while the overall efficiency of the resource input-output transformation process results consequently decreased. On the contrary, when the resource employed to generate networks outputs become scarce, these networks reorganise by a complexity-leap by amplifying the most energy efficient structures and eliminating the least efficient ones in order to be able to continue maximising their power output. Overall it has hence to be concluded that systems' power output is the main driver of systems' evolution and that the increasing of systems' efficiency is functional to power growth and to a better system integration into the environment. For this reason a sound balance between the degree of power growth and of energy efficiency improvement should always be achieved. Nevertheless it should not be neglected that systems' diversity contributes essentially to systems adaptability in the long term and that the least efficient practices under given system boundary conditions may become the most efficient ones when boundary conditions change, as the first astronauts had to learn when they tried to use ballpoint pens in the absence of gravity and were obliged to return to the use of pencils[21]. When technology systems are analysed in terms of commercial energy inputs, the big issue is then to understand whether it is possible to limit the total consumption of commercial energy they are responsible for. In the opinion of many experts this objective could be achieved by promoting energy efficiency and simultaneously curbing power growth. According to some of them an increase of the energy price and the "artificial" condition of energy scarcity created could be sufficient to achieve this end. According to others, EEI policy measures should instead be accompanied by measures limiting power growth directly (e.g. by limits to the speed or engines' size in case the vehicles, by volume limits in case of refrigerators, by a minimum price set for bits/sec. transmitted by communication technologies, etc.)[22]. These two approaches however do not take into sufficient account the role that system diversity accompanying power growth plays for adaptability. Moreover, whereas the former approach may become questionable for the social equity issues connected to any energy price increase, the latter is often perceived as a limitation of individual freedom. This impasse can perhaps be overcome by a closer look at the specific nature of the diversity expressed by technological systems during their evolution (i.e. a diversity related to measurable system outputs and inputs). Increasing the energy efficiency of technological systems in order to reduce the impact on resource consumption of the increasing systems' power output is of paramount importance. On the other hand the authors of this paper suspect that most of the approaches aiming at limiting or prohibiting systems' power growth and the accompanying technological development would be destined to fail when a perspective spanning a sufficiently large scale or long term is adopted. This however does not mean that this growth cannot be somehow re-directed and systems' adaptability cannot be increased to avoid harming the existing stocks and funds of (energy) resources. Existing studies indicate that the development of institutional settings based on the self-organisation and self-governance of common technological equipment and resource systems have a very interesting role to play in this respect at least on the small-scale.

20. Existing studies refer to resource systems located within a country and affecting a number of individuals varying from 50 to 15,000 persons (Ostrom, 1990).

21. Example taken from (Polimeni et al. 2009).

22. "Small is beautiful", "slow is beautiful", "sufficiency principle" are some of the expressions employed to describe this kind of approach.

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