Chapter 2
Energy and Complex Systems Dynamics

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Abstract This chapter discusses the role played by energy within complex systems dynamics and compares this role to that played by information. In this respect, it briefly shows how information theory can confirm and incorporate thermodynamics and illustrates how given energy flow principles become unifying principles allowing studying the evolution of any complex system under a same phenomenology. This evolution can be characterized in terms of a proper balance to be achieved between improvements in the efficiency whereby systems inputs are converted into outputs (in a situation of resources scarcity) and a diversification/intensificaton in systems outputs production (in a situation of resources abundance). The ongoing transition to renewables is then presented as a very relevant reinforcing factor of the large-scale construction of complex systems and of the manifestation of the above mentioned dynamics. These considerations are employed by the author to discuss how the role of energy efficiency policies, although still fundamental, becomes ultimately functional to an intensification and diversification of outputs production in the age of renewables and how new types of policies have therefore to be devised and implemented to ensure the sustainability of the ongoing energy transition. To do so, it is necessary to acknowledge that the construction of complex systems is based on a particular and very abstract commodification of natural resources and human activities. This construction relies on the assumption that functions accomplished by people within societies can be reproduced and sustained through an underlying network wherein energy, matter, information and monetary values circulate and it reflexively validates this assumption by contributing to the materialization of this network and by creating a situation of increased dependency thereon. The final part of the chapter is therefore dedicated to discuss how new policies questioning this assumption and allowing escaping the increasing dependence on complex systems dynamics of growth can be devised.

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The Apparently Vicarious Role Played by Energy Within Complex Systems

The relation between energy and information within complex systems is quite intricate. It might seem that complex systems relegate energy to play a vicarious role with respect to information and difference. As mentioned in the sections of the previous chapter, energy has been seen as an extremely powerful explanatory instrument since the mid nineteenth century when it came to represent a kind of primordial cause whereby the dynamic properties of matter could be understood. In the world of complex systems that has come to life after the 1950s, effects are however not propagated through energy exchanges any more: they are brought about by "differences." Nothing—that which is *not*—can be a cause within complex systems in the same way as, for example, "the letter that you do not write can get an angry reply"[1] in the social system where you live. In the world of information a "zero" can generate huge impacts just because it is different from a "one." Although still fundamental (difference can indeed propagate only along the pathways where energy is available) the energy concept cannot apparently serve to explain the dynamics of complex systems. It is the structure and the difference that can be found within systems that ultimately determines their evolution. Bateson explains this by providing the example of a chain stretched by two equal and opposite forces applied at its two extremities. If the chain would not have a weakest link, he states, the chain would never break whatever the intensities of the opposite forces. It is the structure, the difference existing between some parts of the chain that allows understanding and generates the dynamics of the system under study. The tension applied by these forces cannot serve to explain how a particular link came to be the weakest link.[2] The presence of this weakest link has to be considered as a given whereby the evolution of the system can be explained. According to Bateson, energy would belong to the world of quantity, whilst information belongs to the world of structure and it is the latter that drives systems evolution. By looking at how these two concepts are conceived and used within complex systems theories, it is however possible to verify that they are closely interconnected and reciprocally dependent. Information drives energy flows in so far as energy flows can be generated only where some kind of difference is maintained. At the same time, however, information cannot be maintained, created and/or transmitted without energy flows and can actually be seen as a driver of energy flows only within a static description of complex systems. In so far as the evolution of complex systems is at stake, energy remains the ultimate fuel whereby information is produced and destroyed. The way in which information content is statically associated with energy flows within complex systems represents however an important point of conjunction between these two entities and can be grasped by looking, for example, at how this notion is used within ecology.

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[1] See Bateson (1972).

[2] See Bateson (1979).

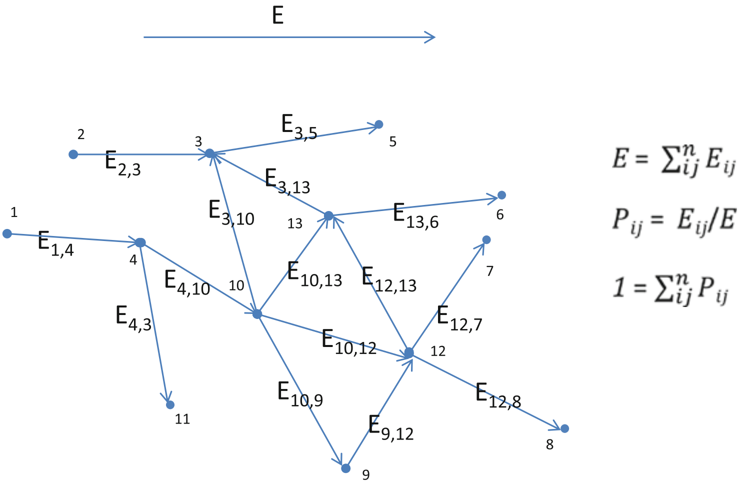

Fig. 2.1 Schematic representation of energy flows and associated probabilities whereby the mutual information exchange within nodes of ecosystems is typically defined

To illustrate this point, the following approach to associate energy and material flows with information within ecosystems can be considered as an example. The example presented here makes exclusively reference to energy but can be very easily generalized to matter flows within any complex system. Very broadly speaking, ecosystems can be represented as networks made of nodes whereby energy and matter flow. Each node (i) of an ecosystem can be assumed to have its own inputs from and outputs to other network nodes. The information content of this ecosystem can be defined based on the probabilities *Pij* representing the fraction of the total energy passing through the ecosystem that flows from the node (i) to the node (j). The probabilities that can be associated with all of its *n* nodes fix all the energy flows travelling through the ecosystem and the function $H = -\sum_{ij}^{n} Pij * lnPij$ can be assumed to represent the information content of the ecosystem (see Fig. 2.1). It can indeed be shown that the value assumed by the function *H* is lower when the distribution of the total energy flux over the different nodes is more even (e.g. in case of two nodes *H* is lower when $P_1 = 50$ and $P_2 = 50$, than when $P_1 = 90$ and $P_2 = 10$) this indicating that the more even the flux distribution, the lower its information content.[3]

Although explained by paying more attention to the substance than to the rigor of mathematical formulas, this example illustrates a very general approach whereby information is generally associated with an energy distribution and, as in a snapshot, with all the energy fluxes existing within a system. The function *H* has been indeed used both by Boltzmann and Gibbs in the 1870s to statistically define the

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[3] A lower information content corresponds to a situation of lower predictability of the flows taking place within the ecosystem.

entropy of any thermodynamic system and by Claude Shannon in 1948 to define an average information content of any communication process made of messages that may occur with a probability *Pij*. In the former case *Pij* is the probability that a thermodynamic system falls in a microstate *ij* that can be univocally characterized by the position and the energies of all of its constituents. In the latter case *Pij* is the probability to get a given combination of characters within a fixed number of possible combinations. Whether we call them probabilities of getting a given distribution of energy flows or probabilities of getting given characters combinations, *Pij* represent a ratio between a number of given (energy values or characters) combinations and a total number of possible combinations. Both the energy and the information content of any system are in this way reduced to a probability distribution. This reduction is made possible by the assumption that all the possible energy states and all character combinations can be counted and that the total amount of energy and of information that can be transmitted are conserved. It is in this way that structure and quantity are reciprocally interlaced within complex systems. The amount of energy and information content is just determined by the number of combinations whereby a given state can be achieved as assessed against the number of all possible combinations corresponding to all the possible states. However, when it comes to assess and explain the evolution of thermodynamic systems which are open and far from equilibrium, further phenomenological energy principles need to be invoked to explain how new information can be created and order may emerge from disorder. As also described in the subsequent chapter sections, the Belgian Chemist Ilya Prigogine has showed in the 1970s how energy drives and maintains organization changes within complex systems which are far from equilibrium. It is energy that causes the gradients/pressures driving organizational change. New structures can be created and maintained within complex systems when small initial fluctuations determined by these gradients can amplify within the system and establish new and comprehensive stationary paths whereby additional energy can circulate and be dissipated. Despite the relevance acknowledged to information within systems, energy remains therefore the ultimate driver whereby order can be created and energy principles remain the principles whereby this creation can be explained. Within complex system theories, energy remains the *reservoir* made of a single, infinitely transformable, degradable but not destructible entity that is awaiting to be transformed into work that is supposed to have been discovered already in the 1850s. The explanations so far provided show nevertheless that information theory can confirm and incorporate thermodynamics. Energy flows and information content can be described by a same mathematical formalism relying on a conservation principle[4] whilst creation and/or destruction of information can be identified with creation and destruction of order and be quantified through the formula whereby entropy is statistically defined.

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[4] In case of energy the quantity conserved is the sum of the amounts of energy entering and exiting the system at stake, whilst in case of information the quantity conserved is the sum of the probabilities whereby the information content of this system is calculated.

At this point, it may also be interesting to observe that energy and information have to a certain extent a same degree of immateriality. Information and energy flows are both present wherever change and difference occur or are detected. Like information, energy materializes only during transformations and change. Paradoxically, however, they are also seen as entities with a separate and self-contained existence.[5] In case of energy this has for example to be considered as a kind of paradox, because classical physics theories already indicate that the amount of energy that can be attributed to whatever isolated system is a physical quantity that can be defined up to an arbitrary additive constant and its absolute value is per se meaningless. Strictly speaking, this implies that the energy content of whatever matter or substance can never be properly defined in absolute terms.[6] What can be defined is instead the amount of energy that can be transferred from this matter to another matter under a given transformation and in a given amount of time. Energy materializes therefore only in terms of a variation and a transformation. It can only manifest itself during change as something that is transferred and flows from one part of a system to the remaining part of this system.[7] Despite this characteristic does not allow localizing it within any physical object, energy is nevertheless still typically imagined as the ultimate resource fuelling our economies.[8]

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[5] The problems caused by the fact that both energy and information are considered at the same time as fluxes and stocks represent one of the interesting and problematic aspects of these types of conceptual artefacts that will be discussed by the author in more detail in another chapter of the book.

[6] Although under a different perspective, this aspect is analyzed also by Giampietro et al. (2013) and Diaz-Maurin and Giampietro (2013).

[7] This is due to fact that, rather than energy (E), the physical quantity that can actually be measured and assumed to have some degree of concreteness is always a variation of energy (ΔE) over a given amount of time (Δt). Whenever we deal with an isolated system, the notion of energy is of some utility in so far as this notion is employed by referring to a system transformation and is used under a conservation principle. As it can be easily realized by considering the example of an isolated system made of two colliding spheres, all that this principle allows establishing is just that, whenever the energy of one part of our isolated system (e.g. the energy of one of the spheres of the mentioned example) varies by ΔE over a given amount of time Δt, the energy of the remaining part of our system (e.g. the energy of the other sphere of the example) shall vary by $-\Delta E$ in the same amount of time. In other words, what can be defined and be measured unambiguously is not energy. What can be measured is a flow of energy ($\Delta E/\Delta t$) passing from a part of an isolated system to the remaining part of this system.

[8] It may here worth to briefly note that, rather than energy, the resources actually consumed to fuel our economies are, for example, coal, oil, biomass, etc. from which work is extracted through transformations that change the status of these resources and that make more and more difficult that further work can be extracted from them. I hypothesize that the misinterpretation mentioned in the text above is due to the fact that the energy concept has initially served as leverage for an industrial revolution which mostly relied on the utilization of resources which were available in the form of stocks of different materials and that had to be processed to produce the desired outputs. The depletion of material resource stocks caused by any industrial process has probably led to associate energy with the resources themselves. Further information on what has to be meant by *stock* can be found e.g. in Georgescu-Roegen (1971).

What Are Complex Systems Ultimately Made of?

The characterization of complex systems provided through the historical enquiry outlined in the previous chapter points to the fact that these systems appeared on a large scale within societies and in the scientific discourse when it became possible to massively produce particular types of single artefacts whereby an increasing variety and number of human functions could be reproduced. Moreover, this characterization has allowed showing how this has happened at the expenses of a progressive integration and loss of differentiation between persons and their artefacts realized through a reduction to information feedback loops equally circulating within and regulating the functioning of these two entities. In addition, it has been discussed how this integration relies on a bidirectional process of translation whereby persons' actions are translated into information that can be processed by machines and information elaborated by machines are translated in their turn into information and signals that can be understood by persons. These bidirectional translation processes have always also to be intended as a reconstruction process, in the sense that they represent also the means whereby functions and structures observed in biological entities are artificially reconstructed by an observer within a technological environment. It would indeed be a mistake to assume that complex systems are just a description of phenomena that pre-exist observation. It is the possibility offered by current theories and technologies to isolate and reconstruct underlying information flows that makes their observation and wide diffusion possible while permitting a variety of extremely useful applications. As suggested by Jacobs (2000), the nature of these information flows can nevertheless be of very various nature. Any not isolated system constituted through the circulation of matter, energy or of any other type of resource whose total amount can be assumed to be conserved during circulation can indeed potentially represent a complex system exhibiting the same characteristic dynamics of energy flow networks (more will be said about these dynamics in the following section). As also suggested by Goerner et al. (2015), either these flows are constituted by monetary flows occurring within economies, or by circulation of energy and matter within biological organisms, or by flows of oxygen, carbon, nitrogen, etc. occurring between organisms constituting an ecosystem, or by flows of cars and trucks circulating within road networks, these flows can be studied through same phenomenal principles observed in case of energy-flow networks. Complex systems become in this way a sort of underlying natural entity whose dynamics can be identified anywhere in physical systems, economies, living systems and ecosystems in general, whilst energy flow principles become unifying principles allowing to study the evolution of any complex system under a same phenomenology. The origin of the above mentioned flows are generally explained through causation mechanisms relying on the presence of two distinct and complementary elements. On the one hand, there are the mechanisms whereby these flows are generated and maintained. On the other hand, there are the circulating abstract units that remain unchanged during circulation. The mechanisms whereby these abstract units may be assumed to be put or maintained in circulation may change across systems. Moreover, they can be identified at different scales within complex systems and be described with the different languages of physics, biology, economics, or even psychology. Money may be for example exchanged because of specific needs and wants animating individual initiatives or because of some type of economic pressure assumed to act at a larger scale between national economies. Energy can be exchanged because of the presence of given spatial gradients observed in matter distribution. Oxygen can be supplied to the cells of an organism by passive diffusion or convective transport mechanisms and information related to a genetic modification occurring within a part of an organism may start spreading because of some type of pressure assumed to be exerted by the surrounding environment. Whatever the causation mechanism, there must then be some object (money, energy, oxygen, information, etc.) whose identity doesn’t get lost whilst it circulates within complex systems and whose circulation is for this reason generally assumed to obey a conservation principle. At the same time, however, the underlying presence of complex systems and of their characteristic dynamics can be substantiated and possibly put in relation to everyday life human activities only if the circulation of the above mentioned entities is associated with some observed structure or with the reproduction of some function. It is at the point where the complex systems underworld made by matter and energy flows has to be jointed with observed structures and functions accomplished during everyday life that the characterization of complex systems proposed in the previous sections play an essential role. It is indeed at the interface between this underworld and the upper world of observed structures and functions that the social construction of complex systems comes into play. In the same way as the observation of given structures within complex systems depends on a selection performed by an observer establishing what is relevant and what is not relevant in the description he is producing for the phenomena under study, it cannot pass unnoticed how the construction of these systems is generally accomplished by massively and artificially joining structures and functions observed in natural entities to bits of information and, thanks to information, to energy and matter flows. These type of artificial joints are being established everywhere. They are being established, e.g. when it is attempted to merge molecular biology (studying life with a thermodynamic/informational posture) and organismal biology (studying life in terms of evolution and adaptation of functions). They are being established, e.g. when it is pretended that each action we accomplish can be associated with the consumption of given units of energy and matter. They are being established, e.g. when we, like cyborgs, act in the world through computerized prostheses thanks to the elaboration of information. Present possibilities to manage huge amounts of bits of information while observing nature from its most microscopic parts up to its most macroscopic aggregates make it even appear that these joints are something created by nature itself. Unfortunately, the establishment of these artificial joints always generate (or is generated through) a *discretization* and a reduction to *standardized* functions and structures of an otherwise *continuous* spectrum of *unique* functions that nature and human beings can generate.[9] This discretization and standardization, certainly very often extremely useful, remains however the sign of the artificial character of an underworld made of energy and matter flows supposed to generate functions reproduced within complex systems. This being said, it is now necessary to briefly discuss how specific energy flow principles can be assumed to represent unifying principles explaining the dynamics observed for any kind of complex system.

Trade-Offs Between Power and Efficiency Within Complex Systems

The two key phenomenological energy principles whereby the evolution of complex systems is generally explained will be briefly described in this section. Based on what was previously discussed, it should not be extremely difficult to understand how these principles can be expressed in the language of information theory. The concepts of entropy and information content of complex systems can indeed be considered as synonyms, whilst the energy flow through a given pattern can be associated with the elementary probability of observing this flow as calculated against all the possible flows that can be observed through all the possible patterns of a complex system (see Fig. 2.1 in a previous chapter section). It should then not be extremely difficult to realize how these energy principles apply also to the circulation of money or of any other type of resource flowing in different types of complex systems (what generally changes in how these principles are described for the different systems is just the metrics whereby the circulating units are measured). Leontief (1951), Boulding (1981), Fischer-Kowalski et al. (1998), Odum (2007), Lindeman (1942), Hannon (1973) can then provide more detailed explanations concerning how these principles apply both to economic networks and to ecosystems.

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[9] The type of *discretization* and *standardization* mentioned here can be seen as the result of an (at least partly) arbitrary resolution of an otherwise unsolvable allocation problem. The problem of having to establish how much energy (or e.g. time) one person consumes when he/she walks (i.e. when he/she accomplishes the function of "walking") can perhaps help clarify this point. Such apparently simple allocation problem actually involves a high level of arbitrariness and standardization. A person walking might indeed actually being also talking, looking at a landscape, making some kind of sport, etc. and all these activities can be assumed to require some type of "additional" energy input. We therefore might discover that in order to establish the amount of energy (or time) consumed while walking it is necessary to refer to a kind of reduced and standard version of walking (e.g. without talking, without exerting sight, etc.). On the other hand, we might discover that a given amount of allocated resources (whether these resources are energy, or matter, or time, or information) can serve to generate only very particular and specific aspects of the functions we are trying to reproduce. Complex systems somehow always invite to take decisions in relation to these types of unsolvable allocation problems and make people blind to the distortions they generate in this way.

This being said, the two above mentioned phenomenological principles will be hence described by using the language of energy. According to a series of scholars, the evolution of complex systems is indeed regulated by two different principles depending on energy and time availability.[10] 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 and Prigogine (1971), Nicolis and Prigogine (1977) for energy-dissipating systems in a non-equilibrium steady state and applies to systems which are close to the thermodynamic equilibrium. Broadly speaking this principle establishes 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 transformation that can be characterized in terms of an increased organization. This reorganization 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 contributes to liberate energy whereby the activity within more efficient structures can be focused and intensified so making the whole systems more robust and capable of generating new diversity in case a new condition of energy abundance will be achieved.

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 it by different scholars. It has been defined, e.g. as "maximum power principle" by Odum and Pinkerton (1955), as "maximum exergy degradation" by Morowitz (1979), Jørgensen (1992), Schneider and Kay (1994). It establishes that in a situation of energy abundance and time scarcity complex systems tend to increase the speed of energy intake in order to speed up the activity of existing structures and to generate new structures so increasing diversity in how activities are performed at the expenses of system efficiency. The overall effect of this augmented energy intake can be described in terms of an increased intricacy, interconnection, diversification and intensification of outputs produced per unit of time accompanied by a decrease in system efficiency. The augmented system power output may determine a higher stress on the environment and on the boundary conditions. On the other hand its increased diversity and interconnections increases the possibility of a system reorganisation in case of a significant change in systems boundary conditions. System maximum power output corresponds therefore to a status of increased diversity which is a prerequisite for higher system adaptability and increases the chances of system survival through a system complexity leap towards increased efficiency whenever the conditions of energy resources scarcity

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[10] These principles have been described by the author also in Labanca and Bertoldi (2013).

and minimum entropy production are possibly achieved. Overall, health and survival of complex systems would depend on a balanced interplay between these two principles. The proper balancing of these two principles can however be assessed only on a long temporal term whose actual length is impossible to establish given the intrinsically unpredictable evolution of the environmental conditions within which complex systems typically operate.

Polimeni et al. (2009) provide an example of household management to illustrate how the principle of efficiency and power output maximization co-operate in the evolution of complex systems. According to them, economies made by families during routine activities can be assimilated to the above mentioned minimum entropy production principle allowing 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 creating new activities at a higher level of household activities 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 increased diversity is a phase during which additional system outputs are generated and system efficiency cannot be properly defined. They illustrate, e.g. 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. It is only during the phase of resource scarcity and system reorganization 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 redefinition of what should be intended by systems output, systems power output, system efficiency and a continuous redefinition of the related metrics.

This important insight deserves further consideration. If the evolution of the technology of digital cameras is taken as an example, then it can be observed that when the first models of this new technology were put on the market the increasing of cameras' 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 during which 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 to remain correlated as depicted by applying the thermodynamics principles briefly described above. However, it has to be pointed out that what allows power output increase during systems evolution is the peculiar nature of systems power output and the peculiar role played by *information* during system evolution. While evolving, systems would manage to increase their power output by continuously re-defining their outputs and this can happen only because the essence of systems outputs has the same material consistency of information. It is as systems could 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 reorganization and survival in conditions of resources scarcity.[11] However, this increased power output will be generally achieved by reducing the amount of material resources whereby 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[12] and by the fact that in general the exponential power output increase achieved within materials relate to a scaling down of the dimensions of these materials.[13]

All in all, complex systems evolution would hence consist in a circular pattern whereby they 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

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[11] Clearly the possibility of a successful system reorganization cannot be established beforehand and efficiency improvements might also determine system collapsing due to the reduction in its adaptability caused by improved efficiency. Similarly, the system might collapse due to a stagnation caused by lack of organization and efficiency in its structures.

[12] Polimeni et al. (2009) point out for example that mice has a metabolic rate around 3.0 W/kg, whereas an elephant has a metabolic rate around 0.5 W/kg.

[13] Computer technologies are probably the most relevant example of an increased power output (as measured e.g. in terms of bit/sec/cm^2, or watt/cm^2) involving a scaling towards small dimensions of components.

stress is achieved, a complexity leap corresponding to a system reorganization and to an increased efficiency is realized in such a way that additional energy is liberated and the system can start growing 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. Within this recursive pattern, energy efficiency improvements in situations of time scarcity would be the necessary prerequisite for a continuous system and power growth. Ruzzenenti and 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 characterized by a much higher frequency and distance of shipments as well as by a much higher system power output.

Overall, a power output increase seems to be the main driver of complex systems development (whatever this system power output may represent) and an increased efficiency in the transformations of systems inputs into systems outputs seems to represent the natural consequence of a pressure exerted by the environment when the resource in term of which the system input rate is measured is scarce (either this resource is represented by time, or space, or bits, or Euros, etc.) and the necessary prerequisite for system survival through subsequent power output enhancements. When artefacts integrate human beings within complex systems, human beings and complex systems survival comes in this way to depend on a continuous process of growth to be achieved through a proper balance between efficiency and increased coupling and diversity among systems structures. Rather than being the result of intentional actions undertaken by persons, this balance would represent the manifestation of principles that con be observed everywhere in nature. Despite we might think that we are contributing to change the course of the events, our struggles to increase complex systems power capacity and efficiency would actually reflect the manifestation of a universal trend according to which existing biological and not biological aggregates have evolved (starting from galaxies, to stars, to the earth, up to plants, motors, animal bodies, human brains, cars, airplanes up to computer chips) by increasing their power outputs and energy densities through and augmentation of the level of their internal organization and efficiency.[14]

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[14] See Chaisson (2001).

Complex Systems and Renewable Energies

If complex systems are the result of a social construction, a massive transition to renewable energy sources can certainly highly reinforce this construction and, if still possible, make complex systems and their characteristics dynamics much more present in our daily lives. There are multiple reasons justifying this conclusion and these reasons are mostly connected to how renewable energy sources are distributed over very large geographical areas and can constitute interconnected funds of low energy intensity supplying energy according to fluctuating rates.[15] Non-renewable energy sources like fossil fuels usually constitute well localized stocks typically generated in millions of years which can mostly be used at will without specific time constraints other than those dictated by associated identification, extraction and transformation processes. Renewable sources (like wind, sun but also biofuels, wood, etc.) are instead energy funds characterized by intrinsic regeneration processes that take place on infinitely shorter temporal scales and involve a series of variable interactions and extensive energy exchanges between the physical system where they can be localized and the external environment. Contrary to what happens for example with stocks of fossil fuels, renewable energy sources cannot generally be delimited spatially within fixed boundaries. Renewable energy sources like wind, solar radiation, biomasses, etc., cannot indeed be disjointed and conceived separately from their intensive and ever-changing interactions with an external environment, this external environment being represented by, e.g. the thermal sources whereby wind is generated, by the sun, by the ecosystem wherein biomasses are grown, etc.[16] The usually strong and highly variable energy coupling with the external environment that characterizes energy systems relying on renewable energy sources makes the dynamics observed within complex systems an everyday experience.[17] There is however another much more tangible reason why a massive transition[18] to renewable energy sources can reinforce the social

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[15] These points have been discussed by the author also in Labanca et al. (2015).

[16] It might be argued that all energy sources are ultimately generated through the energy coming from the sun and that also renewable energy sources are hence located within the practically closed and isolated system including the earth and the sun. The temporal and spatial scales which are relevant for existing energy supply systems require nevertheless that the boundaries of these systems cannot be enlarged to include all the actual sources of renewable energies.

[17] It may be worth pointing out that complex systems dynamics can certainly be observed also with non-renewable energy sources. The point made here is however that these types of dynamics do not necessarily play a relevant role when energy has to be generated from non-renewable sources, whilst they become a fundamental characteristic of supply systems relying on renewable energy sources like wind, sun, biomasses, etc. As previously mentioned, these dynamics do not follow the physical laws so far formulated and verified for physical systems that are in thermodynamic equilibrium with their external environment.

[18] It may be worth mentioning that the author does not intend to maintain here that renewable can completely substitute non-renewable energy sources in developed countries. Putting aside extremely important social constraints, important physical and economic constraints to this possibility are for example represented by the rates of power output to be guaranteed in these countries, by the

construction of complex systems. Present ways of life in so called developed countries require such huge amounts of final energy and renewable energy sources have such an high spatial distribution and low energy density that a very high interconnection among these sources will be necessary in order to allow that they can sustain a consistent part of present energy end-uses. More specifically, the type of transition at stake entails a large-scale transformation from uni-located to multi-located and interconnected energy production centres where these centres can also possibly play the role of energy consumption centres.[19] This transition can be characterized in terms of a *complexification*, as defined for example by Ruzzenenti and Basosi (2008a) and resulting from the necessity of creating hierarchical control systems at multiple levels in the energy supply network because of the presence of distributed geographical energy gradients[20] leading to an increase in the average distance from the points where energy is produced to the points where energy may be consumed. Moreover, it involves the creation of more interconnections and more frequent interactions (i.e. an increased *connectivity*) among the different energy production and consumption points of the energy network. The resulting networks exhibit a higher connectivity primarily because a large number of their nodes are both points where energy can be conveyed from other nodes in order to be consumed and points where energy is produced and redirected towards other network nodes (it is indeed obvious that the possibility of redirecting energy inputs determines more potential connections with other nodes).[21] This aspect contributes to confer on the end-users located at the nodes of these energy networks a higher degree of *flexibility* and possibility for *self-organization*. This possibility however depends ultimately on the creation of additional hierarchical control systems whereby decisions can be taken concerning, e.g. whether to redirect the energy produced to the network or to consume it locally, whether to exploit one type of energy source or another, etc. Overall, a complex character is indeed ultimately conferred on these energy networks by the establishment of these additional hierarchical control levels.[22]

(Footnote 18 continued)

significantly different amounts of energy from renewable and non-renewable energy sources that are needed to produce same amounts of energy carriers (see the concept of energy return on energy investment—EROI), by the impacts on land use, etc.

[19] When this transformation takes place, energy end-users can decide whether to use renewable energy sources for self-consumption or to sell the energy produced in the energy networks, so becoming prosumers.

[20] Geographical energy gradients are spatial regions where energy flows pass from a condition of higher concentration and intensity to a most likely arrangement made of more diffuse and less intensive flows.

[21] Compared to other energy networks, complex electricity networks fed by renewable energy may however show a higher connectivity also because energy generated from more diversified energy source types can be conveyed to their nodes.

[22] Additional links to the nodes of a network do not per se make this network more complex. On this point, see e.g. the distinction between *complication* and *complexification* formulated by Allen et al. (2003).

These networks can be more *adaptable* to changing conditions within and outside the energy network in so far as energy end-users located at their nodes can decide to switch from an energy source to another or can decide whether to consume or to input into the network the energy they can possibly produce. At the same time, however, they are also exposed to more uncontrollable and unpredictable factors (linked, e.g. to the decisions that can be taken at the different network nodes, or to changing conditions in the wider geographical area where the energy sources used to provide energy inputs are located) compared to centrally managed energy networks. Interestingly, the energy supply that can be provided through these complex energy networks can fluctuate unpredictably not only because of the intermittent availability of renewable energy sources possibly used, but just because of the complex character of the energy supply network. As complexity of the energy network depends on how the energy gradients whereby energy is provided are *spatially* distributed,[23] it can hence be concluded that the *spatial distribution* of energy can determine unpredictable conditions solely generated by complexity. A complexification of existing energy networks can hence to a certain extent be considered as the vehicle whereby the *space* dimension affects the *time* dimension of energy, this type of mutual interaction being enabled by information technologies. It should indeed not pass unnoticed how this complexification can be enabled by and represent a formidable push to exploit the available technical capabilities for the reconstruction and monitoring of huge amounts of information concerning the energy flows taking place within energy networks. At the same time, however, it should also not pass unnoticed how the construction of these networks can lead to an intensive manifestation of the previously described mutual reinforcement mechanisms between energy efficiency improvements and power capacity increases. This might happen in several ways. Whenever more energy end-use efficient technologies would be installed at one node of the network, the energy saved thanks to these technologies might for example be made available for other nodes so allowing performing additional activities. Or, it might happen that energy prosumers operating at the nodes of these networks are highly incentivised by existing market rules to produce more energy by installing additional and more efficient energy production plants in such a way that they can either sell more energy to the network or consume this extra energy by installing additional energy end-use technologies. Complex energy networks and energy markets potentially associable with them unfold plenty of possibilities to establish these mutually reinforcing mechanisms between energy efficiency improvements and augmented power capacity also because these mechanisms can represent a way to increase complex systems adaptability and possibilities of survival. As further discussed in the following chapter section, these considerations point to the fundamental role to be played by energy conservation policies for a sustainable evolution of these networks.

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[23] On this point see e.g. Ruzzenenti and Basosi (2008a).

Conclusions and Implications for the Design and Implementation of Policies for Sustainable Energy Transitions

Complex systems have been presented in the first two chapters of this book as the latest human artefacts resulting from a series of transformations concerning the way in which instrumentality has been socially intended. While doing so, the fundamental role played by science in their construction has been outlined and it has been discussed how this construction has been supported by a particular and fundamental misconception, i.e. the idea that the artefacts constructed through science are natural entities that have always existed and that can be experienced by people during everyday life. This endeavour has not certainly been undertaken to criticize the results achieved by scientists within their laboratories, or to contest the validity of the laws and the phenomenological principles they establish, or to deny the often extremely useful conceptual artefacts developed by science and their related technical applications. It has rather been undertaken to signal the important problems and negative implications of a particular attitude unfortunately often assumed and widely popularized by scientists as well as a series of relevant opportunities that can derive from its recognition. This attitude consists in pretending that the conceptual entities and experimental laws observed and verified under very restricted and controlled assumptions and conditions are eternal truths and guiding principles that can be used to interpret and act upon any society to hopefully improve its conditions. If this attitude is indeed somehow the necessary pre-condition for a massive multiplication of technical applications having often undeniable benefits, it also leads to forget the fundamental problems and alternatives represented by all those particular cases which escape categorizations and dynamics associated with the abstract and general principles which science must necessarily rely on and which are sometimes blindly applied anywhere, to anybody and at any time to explain how societies function and have functioned. The acknowledgment of this situation has made the adoption of a *two-faced* strategy necessary when presenting the social construction of complex systems. On the one hand it has indeed been necessary to try to understand the implications, the internal logic and the dynamics that can be expected from the enactment of complex systems dynamics. These dynamics are indeed what can be expected to be massively reproduced in the future also, but not only, because of the ongoing transition to renewable energies that is taking place in several parts of the world. On the other hand, however, it has been also necessary to highlight problematic aspects of and to hint to possible alternatives to what has been presented as an *artificial* generation of these dynamics. The best approach that could be conceived to prove this artificiality has consisted in the identification and description of the transformations that had to occur in some key concepts contributing to constitute the notion of instrumentality before the social construction of complex systems could become possible. These transformations have typically to be considered as the result of a non-linear and non-deterministic coevolution of material artefacts, ideas, discourses and technical skills emerging from a series of alternative evolution patterns that come to be discarded for reasons which are often contingent. The presence of these alternative evolution patterns is alone sufficient to legitimize the just mentioned two-faced analysis strategy and this strategy will be followed also in the remainder of this section to discuss the implications of the social construction of complex systems for policies that can be implemented to increase the sustainability of current energy transitions to renewables.

If complex systems will continue framing our social imaginary and will therefore continue to be massively constructed, it can reasonably be assumed that the phenomenological principles regulating their evolution will become more and more manifest and that a sustainable and healthy transition to renewables will be progressively identified by policy makers with the achievement of a proper balance between efficiency and power capacity improvements. A proper balance between these two complementary trends is what seems to have to be necessarily achieved by complex systems exhibiting a long term capability to withstand environmental challenges.[24] The possibility of a complex system break down can always be around the corner and nature has demonstrated that a long term survival capability can be identified with the capability of maintain this balance. A complex system that would increase the efficiency whereby some of its main inputs are transformed into outputs without maintaining a sufficient level of diversification and coupling among these outputs would be probably destined to collapse due to its scarce adaptability to possible changing conditions in the environment. Similarly, however, a system increasing its resilience through an augmented diversification and coupling among its outputs without a corresponding increase in the hierarchical organization and co-ordination among these outputs will probably be destined to collapse because of stagnation and lack of focus. The presence and the relevance of these phenomenological principles has been already acknowledged by scientists, policy makers and experts working in very different fields (e.g. ecology, energy sustainability, companies management, definition of national budget laws, etc.) and existing studies and literature hint already to a variety of policy approaches whereby such balance between efficiency and resilience can in principle be achieved. Goerner et al. (2015) have for example showed that factors like flexibility, diversity, small size and dense connectivity contribute to increase complex systems resilience, while factors like streamlining, large size and high capacity contribute to increase complex systems efficiency. When national economies are identified with complex networks converting resources and information into energy and products needed by societies, economies' resilience would entail a need for a diversity of options that can provide choice, competition and alternatives in case of failure by industrial activities. At the same time, however, economies' efficiency would be highly needed to generate robust flows, although the presence of extremely large, efficient and powerful organizations would tend to drain resources from smaller organizations so reducing an economies resilience and increasing brittleness. Interestingly, Goerner et al. (2015) deduce from the previously mentioned

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[24] See for example Chaisson (2001).

energy principles a series of measurable characteristics which are in clear contrast with current and widely applied neoliberal competitive principles and that have to be guaranteed to ensure that economic systems can develop in a healthy way within a transition to renewable energies. They infer for example that rather than by exports, resilience is enhanced in the long term by the presence of as many as possible self-feeding return loops whereby energy and material flows generated by an economy are constantly redirected back into this economy to maintain internal productive capacities and processes. The same resiliency principle would also indicate that healthy economies have to constitute intricate networks wherein human expertise, material infrastructures and cultural systems grow together and play a mutually supportive role. On the other hand, hierarchical organizations would be absolutely necessary to regulate societies and economies beyond a certain size, but these organizations would have to operate according to a "subsidiarity principle" because the degree of flexibility required by complexes societies cannot be achieved exclusively through top-down administration approaches.[25] Along a similar line of thought, Elinor Ostrom has formulated and empirically demonstrated the validity of a series of design principles whereby she has acknowledged, among others, the need for subsidiarity and for a proper balance between self-organized initiatives by local actors and hierarchical organization within the complex systems made of the cultural arrangements, the institutional arrangements and the physical environment whereby people produce and exchange their goods and services.[26]

Although described quite synthetically, the above mentioned aspects impose a radical change of gear to policy strategies currently adopted to ensure a more sustainable transition to renewable energy sources. The complexification linked to the on-ongoing transition to renewables obliges for example policy makers and researches operating in the field of environmental policies to increasingly pay attention to the temporal dimension and rhythms of energy consumption. They have now for example to deal with research questions like the following ones: if an increased speed in the circulation of energy and matter within densely interconnected energy systems is what can actually enhance systems health and possibilities of survival, how can then this condition be assessed and be reasonably achieved in a transition to renewable energies? Can renewable energies provide the same amount of power output produced through fossil fuels in all energy end-uses? To what extent can current energy end-uses expected to be flexible and adaptable to energy sources which are intermittently available? Which policies can be implemented to change the temporal profile of current energy demand? Which market rules can be established for a transition to renewable energies where power, rather the energy, could become the commodity mostly traded?

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[25] Interestingly, complex systems developments according to *fractal* patterns would represent a way in which a healthy balance between intricacy and hierarchical organization is achieved in nature. Fractal patterns could therefore be used to measure and assess complex systems health.

[26] The fundamental role that can be played by these principles and by community-based energy initiatives to ensure a sustainable low-carbon transition are just briefly discussed in the remainder of this section and will be the subject of a specific chapter of this book.

Another set of relevant policy research questions relates then, for example, to how to define and measure the balance to be maintained between energy efficiency and power output increases. How could indeed this balance be assessed in future renewable energy systems? On which temporal scale should it be established? Which are the parameters to be considered?

A further set of important questions comes then from the role played by self-organization in relation to hierarchies that have to be established across complex systems to ensure that they can endure un-expected environmental changes. How can indeed be guaranteed that a sufficient level of self-organization can be expressed and the necessary control hierarchies can be established? To what extent future renewable energy prosumers can be given the freedom to establish own governance systems whereby they establish own rules and sanction systems to administer energy and related infrastructures? How can these governance systems be integrated within a system of nested control hierarchies? Given the extremely high number of technical applications that in principle can be developed by anyone to exploit the extremely distributed and highly different types of possible renewable energy sources, how could a market of these applications be possibly regulated?

Changes induced in current policy strategies by all the above aspects are extremely relevant, especially when it is taken into account that these strategies are presently mostly implemented within competitive market settings and rely either on the stimulation of technical innovations capable of reducing energy inputs and/or CO_2 emissions of technologies or on initiatives aiming at changing individual behaviours. At the same time, it should not pass unnoticed how, contrary to what so far generally happened, energy efficiency improvement actions undertaken within complex systems cannot just be conceived as a means to reduce the energy consumption associated with human activities. Although continuing playing a fundamental role, energy efficiency improvements become indeed one part of a two-legged strategy where augmented power, diversification and coupling represent the other leg and a sustainable complex systems growth is the final objective to be achieved in order to guarantee systems survival. Rather than as a means to reduce energy consumption, energy efficiency becomes therefore a means whereby complex systems can continue growing and increase their survival possibilities by reallocating the energy saved for the production of given outputs to the production of the additional outputs that can increase their resilience. Complex systems survive indeed by using energy efficiency as a means to maintain and increase the density of their energy fluxes. They implicitly frame the problem of sustainability as a problem of sustainable *growth*.

All the above considerations apply in particular to existing electricity networks which are destined to expand and become densely interconnected within the ongoing transition to renewables energies. We are in a phase where the liberalization of the electricity market has separated the structures of production and distribution in many parts of the world and has made them more transparent. At the same time, however, this relatively new situation has certainly not managed to curb the increasing impact on existing resources by energy systems. If most of the electricity supply will have to rely on common resources like the sun, wind and water, then this further re-configuration implies that solutions to the new challenges determined by these energy sources cannot probably be provided by technical innovations operating within one of the two traditional and alternative institutional settings represented by a liberalized electricity market or by state regulated energy systems. As already mentioned, a series of studies has indeed already demonstrated that complex energy resource systems can be administered in a much more sustainable way when collaborative approaches, rather than competitive or authoritarian ones, are adopted.[27] Compared to institutional settings where resource systems and related technical equipment are owned individually (according to competitive market settings) or by a central authority (e.g. the state), commons-based institutional settings designed by establishing that these resource systems and technical equipment are owned in common by people can often achieve much better performances in terms of reduced environmental impacts and energy conservation. The reasons for this are quite intuitive. The self-interest of competing market agents can only achieve sub-optimal and short term solutions to solve the issues linked to the depletion of the energy sources possibly at stake, whereas centralised authorities can only rely on command-and-control and adopt unified and standardized solutions that do not fit optimally to all the local situations where they have to be applied. Local self-governing and self-organized institutions whereby equipments and resource systems are owned and managed in common by people could instead in principle exhibit the flexibility and adaptability required by the complexity of the problems at stake while being much more suitable to adopt strategies for long term sustainability.[28] The complexity of renewable electricity networks offer hence the opportunity to go beyond the conventional two binary usage structures based either on buyers and sellers (in case of competitive market settings) or on a central and unique owner and electricity customers (in case, e.g. of governmental settings). These structures can indeed in principle be replaced by a user community whose members are both electricity customers and electricity producers and can develop more suitable and flexible strategies to administer this resource. Lambing (2012) rightly mentions that the creation of these communities requires that consumers participate actively in the creation of rules and sanctions concerning electricity consumption and supply by taking into account local social, natural and technological conditions. Clearly, there are important barriers still hindering the establishment of these administration types. These barriers mostly include still too high costs associated with the installation of technologies and related infrastructures (e.g. windmills, PV panels, etc.) and negative impacts on a large circle of persons affected by the installation of these solutions (whose interests can however be integrated in the associated decision making processes). Lambing (2012), however, also mentions that the natural trend of electricity grids to aggregate and communalise electricity consumption (due to the fact that the larger the grid, the lower the additional power capacity needed to meet peaks in electricity

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[27] On this point see Chap. 6 of this book and e.g. Ostrom (1990).

[28] See Chap. 6 of this book and Ostrom (1990).

demand) may lead to very large grids that may be quite difficult to administer according to a commons-based approach.[29] These grids, like any other complex systems, have indeed to be hierarchically organized and the conciliation between commons-based approaches and hierarchies may be hard to achieve. Despite these barriers, the implementation of these governance systems looks nevertheless very promising. Due to the present situation of existing energy infrastructures, only hybrid solutions where common-based types of electricity supply coexist with a liberalized electricity market can however be realistically hypothesized and the first examples of these types of governance systems are represented by energy cooperatives.[30] Although most of these cooperatives deviate from a "pure" form of communalised electricity consumption (i.e. a model where the cooperative is owner and operator of the production plants and the power grid and where the cooperative includes all the electricity consumers and the decision makers on its electricity infrastructures), the ongoing multiplication of these types of undertakings can already highlight the huge economic interests at stake when citizens self-organization in the field of energy consumption and production becomes a reality.[31] In principle, it cannot be excluded that a further deployment of multi-located renewable energy sources within electricity networks and the associated diffusion of electricity communalisation can even trigger movements in the civil society for a re-appropriation of power industry. These, however, are just speculations. The governance options sketched above have been just briefly described to explain how complex systems dynamics may contribute to create new and interesting governance scenarios.

Either partly administered through local and self-organized institutional settings or not, complex systems remain hierarchical systems resulting from a social construction based on a particular and very abstract commodification of natural resources and human activities. This social construction relies on the assumption that functions accomplished by people within societies can be reproduced and sustained through an underlying network wherein energy, matter, information and monetary values circulate and it reflexively validates this assumption by

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[29] Very large grids could however still be managed based on a commons-based approach. Multistage control systems can indeed in principle be used to allow that overcapacity in one community compensate for demand peaks in other communities. This would certainly require the wide scale usage of smart grids and smart meters, but the resulting management system would be fundamentally different from the usually prospected solutions to the challenges posed by renewable electricity. These solutions propose indeed top-down management approaches mostly relying on price signals processed by automated systems regulating electricity usage in each consumption point.

[30] For a brief overview of existing energy cooperatives around the world, see e.g. ILO (2013).

[31] One important area where existing interests have started generating power conflicts concerns e.g. access rights to technologies for smart metering and smart grid management and access rights to personal data concerning consumption within households. Self-organized energy prosumerism relies e.g. on citizens sovereignty on data concerning their energy consumption and on the possibility of having free access to smart technologies. The actual realization of electricity commons will depend on the outcomes of existing and future conflicts in this area.

contributing to the materialization of this network. Societies can certainly be organized and policies can be designed and implemented based on the abstract principles regulating the evolution of this underlying network. Policies can, for example, be established to substitute given technologies with other technologies with reduced energy input and CO_2 emissions based on pre-established measurements and evaluations. Similarly, policies can for example be implemented to diversify and intensify activities for the production and exchange of goods and services in a given area and the optimal distribution and balance of these initiatives can be perhaps be assessed by using fractal branching patterns taken from complex systems theories. The usefulness of these methods cannot certain be denied and it would be probably insane to reject their adoption a priori based on some kind of ideological preconception. The point is, however, that these methods, when blindly applied to any social context without paying due attention to each specific case and circumstance, can produce serious damages and problems simply because they cannot take the effects they produce on every person and context into account. This problem is certainly not a minor issue and cannot certainly be solved or bypassed by Machiavellian considerations or by invoking the higher interests of the environment or of a not better specified collective with respect to individual persons. The current economic crisis is for example showing how a passive submission to the abstract principles and laws of the complex systems constituted by the international markets and monetary systems can escape any form of social control and be detrimental for millions of people. At the same time, however, what may seem to constitute an unfortunate impediment and obstacle to the application of abstract principles and laws to regulate societies is also what constitutes the lively force of these societies and the source of often more valid and alternative solutions to the problems at stake. The problem that is being delineated here is genuinely *political* and relates to how the blind and large-scale implementation of technical solutions can in some circumstances become a way to bypass people and aggravate the conditions that it should contribute to ameliorate. Policies cannot indeed be implemented exclusively based on abstract considerations related to reduction of energy inputs (or of associated polluting emissions) or multiplication of outputs. The experience that has been matured since the 70s of the last century with energy efficiency policies aiming at reducing the energy inputs of single technological instruments has for example showed how policies approaches exclusively fostering the diffusion of technologies with lower energy inputs can represent a way to bypass any political consideration concerning the actual utility of these technologies, how they often reduce the question of diminishing energy resource consumption into a mere question of individual choice (that can typically be influenced by economic considerations and incentives) and can actually end up reinforcing the need for these technologies without significantly reducing the associated energy consumption. To make an example, when the problem of reducing energy inputs and polluting emissions of private transportation in a city is primarily faced by implementing policies fostering the diffusion of more energy efficient and/or less polluting new vehicles, any political discussion concerning how urban mobility could be reorganized to reduce the amount of travelled kilometres by people is typically bypassed or is assumed to be of secondary importance compared to the diffusion of new technologies despite this reorganization could potentially result much more effective, more diversified and more tailored to the specific context at stake. Policies aiming at reducing energy *inputs* and polluting emissions by fostering the diffusion of more efficient and less polluting vehicles do not indeed call into question and may even stimulate a more intensive usage of vehicles, whilst the political decisions that people can effectively take around mobility relate to the reorganization of energy *outputs* and could for example concern the redistribution of shops and sales point in the different city areas, the implementation of solutions to reduce commuting, decisions concerning the need for new parking places nearby given sites, etc. In addition, the policy approach used as an example relies on private and economic decisions to be taken by the individuals supposed to purchase new and more environmental friendly vehicles, whilst the alternative approach being described relies on decisions to be taken by a community of people. Finally, the implementation of policies fostering the diffusion of specific new technologies results mainly from the active involvement of manufacturers supposed to produce these technologies, whilst the active involvement of so called end-users remain quite limited and the actual necessity of using these technologies (e.g. vehicles) is not put under discussion. This necessity is rather usually implicitly reinforced by the policy at stake and by all the activities that will lead to its implementation. For example, vehicle manufacturers are certainly interested in producing more environmental friendly solutions and will actively promote them, but will generally not be willing to put the necessity of using what they produce under discussion; at the same time all the forms of persuasion - including economic incentives - put in place to convince people to participate in the policy can reinforce the diffusion of vehicles and create lock-in effects that are very difficult to be eradicated.[32]

An important watershed lies between the two approaches just described. The former approach is designed by having measurable and reduced energy inputs and polluting emissions as primary and often exclusive objective. It is based on an hypothesis of calculability and measurability of its energy effects typically relying on the assumption that the policy being implemented will not produce any reorganization in the existing outputs.[33] Moreover, it is usually expected to produce

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[32] The radical monopoly that cars can for example exercise on mobility (i.e. the way in which their extensive diffusion can lead to the elimination of existing alternatives to mobility) by inducing a redesign of urban landscapes and the lock-in effects that can often generally be generated by the extensive diffusion of given technologies due to how they co-evolve with other material and conceptual artefacts in the environment where they start being widely used should never be underestimated while designing and implementing policies.

[33] The energy effects of the policies being discussed are typically calculated under a often questionable *ceteris paribus* condition consisting in assuming that these policies will not produce any other change than the expected reductions in the energy inputs. Put in other words, the outputs produced by the energy end-users participating in the policy initiative are generally supposed to not be changed by the policy itself (e.g. it is assumed that all end-users buying more energy efficient cars thanks to the economic incentives received through a given policy instrument will not change their travelling behaviours).

predetermined energy impacts through a process of homogenization associated with the diffusion of standardized solutions and its success depends on individual choices supposed to be typically taken within and be driven by competitive market settings. The latter approach takes instead the reorganization of energy outputs as the starting point to be considered for a possible reduction of associated energy inputs and polluting emissions. It consists of collective actions and decisions whose effects in terms of reduced energy consumption and emissions can be very relevant but cannot generally be easily quantified beforehand. Moreover, it typically can generate solutions which are highly diversified and can in this way better fit to the different necessities usually at stake.[34] The relevance and the nature of the characteristics associated with this latter approach (e.g. active involvement of people through collective actions, more diversity and adaption to specific contexts and conditions, potentially higher effectiveness, etc.) are alone sufficient to understand the consequences of disregarding the primacy of the role that it should play within policies and how, contrary to what usually happens, it can be socially relevant to find suitable ways to subordinate the former approach to the latter.

It might be objected that the above considerations do not hold in case of policies possibly informed by complex systems theories as these considerations mostly refer to energy efficiency policies mostly targeting single technological instruments and energy end-uses (as energy efficiency policies focused, e.g. on cars, refrigerators, air conditioners, etc.). This objection, however, is valid only to a limited extent. Complex systems certainly reframe the nature of the policy issues to be faced to increase the sustainability of human activities. As mentioned, they even allow better understanding the actual implications of energy efficiency improvements on single systems functions and allow adopting preventive strategies to cope with the problems that may be caused by the decreased diversification and systems' resilience that may be associated with these improvements. Nevertheless, they cannot certainly represent a way to bypass communities of people and subordinate their views and the solutions that they can elaborate based on the exertion of their practical knowledge to the large-scale application of technical solutions. Complex systems and policy informed thereby can certainly nowadays stimulate the diffusion of plenty of different individual options to perform given functions more sustainably thanks to the possibilities disclosed by new technologies to manage and organize huge amounts of information. The intensity and diversification of fluxes that can nowadays be generated and managed in relation to mobility are for example astonishing. An individual moving in some cities with a smart phone can nowadays detect the presence and decide to use a bike made available by a system of bike sharing for a segment of his journey, then he can leave the bike wherever he

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[34] In the above mentioned example of private transportation in a city, rather than causing that as many citizens as possible buy same types of new and more energy efficient vehicle, the political process whereby outputs are reorganized may for example cause that a consistent part of citizens will not have to use a vehicle anymore, while another part could be induced to use public transportation, another (hopefully minor) part could continue using inefficient vehicle because it cannot afford the usually more expensive energy efficient vehicles, etc.

wants and decide to take a bus, a tram, a train or a metro based on the information he finds within an online time table, then he can decide to take a car or to go by feet because his smart phone shows that this is the more convenient option to reach his final destination and can take him to this destination through an interactive map. It can be assumed that, in a hypothetical future, multitudes of persons and goods could be moved in this way and that these mobility practices could be extensively adopted within larger and larger geographical areas because of a series of associated advantages mostly linked to increased speed and convenience but also related to reduced emissions pollution by individuals. Thanks to the amount of information they can manage, individuals integrated within complex systems can indeed potentially identify plenty of alternative and optimized mobility options whereby the environmental impacts associated with their movements can be reduced. Nevertheless, it should not be forgotten that this multiplication of available options is alone responsible for an increased affluence and intensification of activities that overall may counterbalance the reduced impacts that can be associated with the mobility options adopted by single persons. Mobility systems organized as just mentioned are for example capable of generating and managing a density of fluxes that would have been impossible to imagine few decades ago.[35] Complex systems are naturally devoted to growth and, rather than the possibility to increase their efficiency, it is their growth and the increasing integration of people within them that constitutes a sustainability problem, either the outputs are generated by renewable or non-renewable energy inputs. Moreover, the multiplication and diversity of functions that they allow accomplishing is to a certain extent only apparent, as this diversification is generated through a progressive standardization and homogenization occurring at the level of the energy types, materials and information flows circulating in the underlying network supporting the generation of these functions. It should hence not be neglected how this increased homogenization, together with the increased extension and couplings existing among the nodes of the networks that are being constructed, makes these networks extremely vulnerable and exposed to breakdowns that may be caused by minimal and unpredictable perturbations occurring in some of their parts. Underneath the multitudes of people moving through their smart phones in the previous example there is a network that mostly works through electricity and electromagnetic fields which have invisibly colonized our public and private spaces and there are huge amounts of 0 and 1 s circulating through it. It is amazing to think of how a sneeze, a small accident and perturbation occurring in a remote part of a complex network can potentially and unpredictably put all people integrated into it in a kind of pneumatic vacuum without any point of reference. Recent cases of blackouts[36] already reveal how an increasing integration into complex electricity networks can put communities of people in very estranged and dangerous conditions due to the impossibility

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[35] Descriptions of mobility solutions informed by complex systems theory can be found for example in Newman et al. (2009).

[36] See for example RAENG (2016).

of accomplishing the most elementary activities in case of temporary interruptions in the supply of electricity. Taking just people mobility into consideration, it is probably not so unrealistic to assume that the increasing dependence on electricity and on the internet that can be expected in a near future can cause that, in case of temporary blackouts, most of the vehicles available in a city result inaccessible and plenty of people do not know which direction to take or how to reach their destinations. This might happen either because part of these vehicles might not function without electricity supplied by a network, or because the information system regulating their flow and/or providing information to end-users (e.g. within bus and train stations) could not be activated without electricity, or because most of the pumps whereby vehicles are refuelled might be electric pumps, or because electric lighting services might not be provided by night, or because communication devices like radios, cell phones, etc. might not work without electricity, or even because practical knowledge[37] of people related to how to move within and between cities might have been partly lost due to prolonged delegation of mobility related tasks to complex technical systems. The description of this extreme situation is not dictated by any kind of technophobia. It has been provided just to explain (a) how the diversity of options that can be identified within complex systems can be only apparent; (b) how these systems can potentially weaken the social tissue whereby people have always provided for their necessities and (c) how it can become politically relevant to ensure minimal conditions allowing that people can, at least temporarily, live disconnected from the increasing series of complex systems wherein they are being progressively embedded and can collectively identify own alternative spaces and ways of life. Despite it becomes more and more difficult to explain why these spaces are so important per se, it should not be difficult to understand how important it is that they can continue to exist at least as kind of backup reservoirs allowing that the system can be restarted after possible breakdowns.

The extension of the geographical areas and the number of persons that can be affected by unpredictable systemic accidents should alone be sufficient to understand how the presence of these spaces can become indispensable. Unfortunately, there is no control system that can completely secure from complex systems breakdowns. As already mentioned, complex systems dynamics are intrinsically affected by a deep uncertainty that cannot be dealt neither with deterministic, nor with statistical methods.[38] The role played by available information on the status of

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[37] This practical knowledge may concern orientation, creation of mental maps, memorization of streets names, etc., but may also concern capabilities related to the employment of possibly available alternative technical systems not relying on electricity consumption (e.g. paper maps, time sheets, railroad switches, hand pumps used to refuel vehicles, etc.).

[38] The application of deterministic methods produces indeed good results only within simple aggregates made of few parts interacting according to very simple mechanisms, whilst statistical methods can be applied to aggregates made of many parts with random and loose interactions. Complex systems are instead aggregates exhibiting organization and made of many and strongly coupled components. On this point, see, for example, Weaver (1948).

complex networks and their energy and matter flows, although still fundamental, becomes therefore sensibly weakened in the framework of whatever policy or strategy that can be designed to increase their security and sustainability. This information is indeed still highly necessary to identify a series of possible evolution patterns, but it will never be sufficient to establish ex-ante the actual evolution pattern, because this pattern is deeply affected by and extremely sensitive to how local interactions change. As a matter of principle, no model, no matter how detailed is the information available on the status of the system under investigation, can allow achieving this end. This conclusion has as a consequence that no underlying blueprint, no predetermined mechanism, no *planned* strategy can completely secure these networks from possible shocks. This is what has to be considered under a theoretical point of view when rules to administer the usage of equipment, resource systems and resource units consumed within complex systems have to be defined to increase their sustainability. Under the point of view of the actual implementation and enforcement of suitable control procedures, the situation is then further worsened by the fact that the extension and the complexity of the systems at stake, together with the presence of different types of economics constraints, typically obliges to delegate the implementation of these procedures to a myriad of different companies and actors, this situation causing that no-one can have the overall view of the status of system.[39]

Besides developing purely technical solutions and improving existing control procedures and risk assessment protocols to prevent situations of energy systems disruption, a good strategy to be further developed to cope with the situation of increased fragility that can be expected from future renewable energy systems is certainly that of learning from accidents and blackout already happened in the past[40] or to perform sociological studies in order to assess which solutions can be reasonably implemented to increase systems resilience and people flexibility and adaptation. These solutions typically range from purely technical ones to solutions generated by sociotechnical capacities of people, linked for example to possibilities of shifting the timing of their activities or moving to places where environmental conditions require less energy, etc.[41]

In relation to the aspects stressed in the last part of this section, it would however be a big mistake to assess the practices that people can autonomously generate to provide for themselves only in terms of the associated possibilities of increasing the resilience of the complex systems they depend on. This type of reductionist approach would indeed not consider, among other things, the presence of a huge diversity potential for increasing the sustainability of human activities existing within communitarian practices developed outside and in alternative to what dictated by these complex systems. Most probably, it is nowadays more than ever

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[39] For an accurate description of how these situations have actually occurred see, for example, Tainter and Patzek (2012).

[40] On this point, see, for example Trentmann (2009).

[41] See Chap. 13 of this book for further information.

necessary to acknowledge dignity and important sustainability potentials to alternative collective ways of life which manage to develop and remain outside the paradigm of growth enforced by current huge and complex monetary, energy and information systems. More than that, it is necessary to recognize in the ways of life conducted outside these complex systems an opportunity for recovering a sense of agency and a personal and more sustainable dimension within the relationships established with other people and with our environment in general.

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