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Methodological and Ideological Options

Energy, growth, and evolution: Towards a naturalistic ontology of economics

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ABSTRACT

In recent years new approaches to the integration of economics and thermodynamics have been developed which build on the physics of open non-equilibrium systems, the so-called 'Maximum Entropy Production Principle'. I review these contributions in the light of the implications for economic ontology, i.e. the question what the fundamental constituents of real world economic phenomena are. I argue in favor of the 'naturalization' of economic ontology, using the phenomenon of economic growth as my workhorse, and I explore the implications for the cross-disciplinary foundations of ecological economics. The paper shows how economic growth can be conceived as a 'natural' process that is driven by fundamental physical forces. The argument proceeds in three steps. After a short review of recent research on the linkage between energy and growth, I establish the connection with bioeconomic theories about evolution that allow restating the role of Lotka's Maximum Power Principle (MPP) as a property of open non-equilibrium flow systems with sufficient degrees of freedom of structural adaptation. The MPP is then related to the recent literature on Maximum Entropy Production (MEP), especially as deployed in the Earth Sciences. Economic growth can be seen as resulting from evolutionary adaptations of flow gradients in economic systems that increase throughputs of exergy and generation of work, and which thereby enhance the capacity of the Earth System to maximize entropy production. This framework offers fresh perspectives on a number of issues in research and policy, which I discuss in the conclusion.

> (…) the influence of man, as the most successful species in the competitive struggle, seems to have been to accelerate the circulation of matter through the life cycle, both by "enlarging the wheel," and by causing it to "spin faster." The question was raised whether, in this, man has been unconsciously fulfilling a law of nature, according to which some physical quantity in the system tends toward a maximum.Lotka (1922a: 149)

1. Introduction: Ontology, Disciplinary Boundaries and Ecological Economics

The question whether energy and growth are causally related phenomena has always been one of the core topics in ecological economics. This paper reviews most recent pertinent contributions, concentrating on new insights gained from the growing literature on the 'Maximum Entropy Production' approach in geophysics (with the landmark volume Kleidon and Lorenz, 2005). In putting some hitherto disconnected pieces in this review together, I also propose a new hypothesis about the nature and causes of economic growth. My focus is on methodological and conceptual issues, especially in the context of how economics relates to the other sciences, in particular physics and biology. Thus, this paper is about economic ontology (Mäki, 2001): What are the constituent phenomena of real-world economic processes such as growth? How can they be subsumed under more general categories by which we classify and analyze reality? What do such ontological choices imply for drawing disciplinary boundaries? How does ontology shape our heuristics in finding solutions to real-world problems? I approach ontology in strictly 'naturalistic' terms (Papineau, 2009), thus asking what recent developments in the sciences imply for the ontology of economics and the human sciences (thus following the track laid by Bunge, 1977, 1979).

In ecological economics, ontological issues come to the fore when we consider the dividing lines between the theory of growth, environmental economics and ecological economics (Spash, 2012). Especially in demarcating 'ecological economics', it is important whether and how economics can be integrated with the sciences, in particular physics and biology. This question came up with the seminal contributions by Georgescu-Roegen (1971, 1976) who claimed that thermodynamics must be recognized as an essential element of economic theories of growth and the environment. Although his contributions received a lot of skeptical and critical responses, they also played an important role in triggering the rise of ecological economics as a field of research

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separate from environmental and resource economics. What is the main difference, as established in early syntheses such as Martinez-Alier (1987)?

- Environmental economics treats the environment as a constraint of economic processes and growth in particular, which can be overcome by technological innovation, especially in the sense that technology is a close to perfect substitute for natural resources, energy included. Further, and most importantly, the goal of economic activity is to increase human welfare in terms of economic goods, hence value creation.
- Ecological economics treats the human economy and the natural environment as one integrated system, such that laws and regularities of the natural sciences are included in economic analysis (for example, material flows). Many contributions to ecological economics also question the priority of human goals and instead introduce goals related to the overall sustainability of the ecological system, that is, life on Earth (such as in 'deep ecology' thinking).

If we look at current discussions in ecological economics, these borderlines appear to be blurring, as many empirical contributions tend to use standard tools of environmental economics. This observation points towards the necessity of ontological reflection (Spash, 2013). There is a serious methodological issue here, as is most evident in the recent debates about the economics of climate change. Disturbingly, the standard economic approaches are close to useless and meaningless for giving appropriate guidelines for the design of climate policies (for a corresponding 'mainstream insider' assessment, see Pyndick, 2013). The root of these troubles is the principled arbitrariness of the relationship between variables that catch the physical and biological system properties on the one hand, and variables that reflect economic decisions on the other hand, as far as these are based on the standard notions of utility, choice and value. For example, there is no universally applicable criterion of how to fix the interest rate that is used for discounting future costs and benefits of climate change; thus, estimations of current costs remain indeterminate and fully depend on close to arbitrary choices by the researcher. This dilemma shows that in dealing with climate change, a systematic conceptual integration of economics and the sciences is indispensable. Preparing the ground for this is the task of economic ontology. The core question is whether the parameters of the phenomena covered by the sciences merely define constraints of the economic process and hence only find expression in economic variables such as prices, or whether there are 'natural' causal determinants of the economic process proper which have to be explicitly included into economic theory.

Going back to Georgescu-Roegen, there is one topic that allows developing a coherent ontological argument. This is the question of how energy relates to growth, and whether it is possible to approach growth as a 'natural' phenomenon. Is energy just a constraint of the economic process, or is energy a causal force or even a 'prime mover' in the economic process? Looking at recent contributions, there is a new argument unfolding that I will overview in this paper. The first step (Section 2) is to recognize the central role of energy in driving economic growth. This is by no means a new insight, but remains a disputed issue until today, although there is plenty of empirical evidence in favor of this idea. I will briefly summarize the state of the art, and then will simply take position: Let us assume that the empirical hypothesis is warranted stating that growth of energy throughputs and economic growth are two sides of one coin. What would that imply for economic ontology? This leads to the next step: Why does energy throughput grow? In principle, there are two responses to this question. One is that markets or, capitalism, create an endogenous dynamics by which the demand for energy throughputs is continuously increasing. This was mainly the response of Georgescu-Roegen and, for example, more recently, Binswanger (2013). This would imply that by means of an appropriate intervention into the market mechanisms one could possibly loosen the interdependence between energy and growth. This view still remains in the 'energy as constraint' paradigm; however, it adds the idea that certain economic systems generate the incentives exploiting energy intensively and overcoming the energy constraint by means of technological progress.

I will argue in favor of a much more radical view (following earlier programmatic statements such as Hall et al., 2001). This is that the energy–growth link reflects basic principles of evolution as a biological phenomenon (Section 3). Thus, energy would appear to be an essential causal element in an evolutionary approach to ecological economics. I think that in spite of the seminal contribution by Ayres (1994), energy theorists (and even Ayres himself) have later side-lined the necessity to ground their analysis on evolutionary theory as the necessary link between the economics and the physics of energy. For example, in Kümmel's (2013) magistral synthesis evolution and evolutionary theory are entirely blanked out, and hence biology as a disciplinary bridge between physics and economics; Ayres has concentrated his work on developing the industrial metabolism and material flows framework (Ayres and Ayres, 2002), and in his recent synthesis biology does not play a systematic role (Ayres and Warr, 2009). In contrast, my argument builds on the general ontological supposition that the human economy is a living system, hence an ecological system or integral part of a larger ecosystem, with the special feature of including technological artifacts and their evolution as 'extended phenotype' (Dawkins, 1982).

The idea that growth of energy throughputs is a generic property of evolution was first proposed by Lotka (1922a,b, 1945) in stating what was later labeled as his 'maximum power principle' (building on the earlier contributions of the German energy theorists, in particular Ostwald, for a survey see Martinez-Alier, 1987 and shorter Smil, 2008: 8ff). Although Georgescu-Roegen (1971: 307ff.) received Lotka's concept of 'exosomatic instruments' in interpreting human technology as an adaptive means (which easily fits with Dawkin's notion of 'extended phenotype'), he did not systematically refer to Lotka's theory of biological evolution. I think that this is a major reason why the field of energy and economics is still fragmented into diverse methodological approaches, and why we face troubles in interpreting what is still incomplete empirical evidence. There are certain recent developments in physics, biology and the ecological sciences which allow for restating Lotka's theorem as a principle in economics, too (and which go beyond what has been discussed in the earlier, already rich literature on the subject, surveyed by Buenstorf, 2000). I will briefly sketch the basic reasoning. This requires a creative synthesis, because the debate often manifests deep internal divisions among different schools of thought (such as between 'empower' theorists also claiming Lotka, Odum, 2008, and physicists such as Kümmel). I claim that these divisions can partly be overcome in the more general ontological analysis.

Once this step is done, I can proceed to the final argument (Section 4). If we treat energy as a part of economic ontology and hence as a causal factor, we can view economic growth as a direct manifestation of thermodynamic laws. In his original 'energy as constraint' approach, Georgescu-Roegen applied equilibrium thermodynamics in his argument. Today, we have new concepts for non-equilibrium thermodynamics. These new concepts directly tie up with Lotka's maximum power principle and have been introduced in the climate and Earth sciences recently (Kleidon, 2009). This more general framework is established by the Maximum Entropy Production (MEP) Principle. Then, evolution in general and economic evolution in particular can be approached as phenomena that directly express these more fundamental physical principles. In this view, economic growth is a direct manifestation of the more fundamental thermodynamic causalities. As a result, we achieve an ontological unification of physics, biology and economics.

In a nutshell, economic growth is not just operating under the constraint of the Second Law, but is the manifestation of the Second Law. This change of perspective has many important implications for policy issues of which I discuss a few in concluding the paper (Section 5).

The most essential ones are firstly, that markets cannot be seen as institutional means to overcome energy constraints by increasing efficiency and speeding up technological progress, but appear to be essential determinants of the degrees of freedom that are available to the more fundamental physical mechanisms of energetic dissipation. In other words, enhancing the scope of markets always and necessarily enhances and leverages the dissipation of energy. Thus, seeing markets as core elements of solutions to overcome energetic constraints is a fatal misperception resulting from a flawed economic ontology. Second, technological knowledge is a physical phenomenon, and hence we cannot approach technological progress independent from the question how far the production and the use of knowledge itself are part and parcel of energetic dissipation in the economy. Then, we cannot view technology as a substitute for energy, as this is typically assumed in environmental and resource economics. Thus, if neither markets nor technology are means to resolve the environmental challenges of today, those positions in ecological economics are vindicated which argue that fundamental changes of the values and institutions of capitalism are necessary to establish a sustainable global economic system.

2. Energy and Growth: Recent Evidence and Consequences for Economic Ontology

In this section, I will summarize recent contributions that support the hypothesis that economic growth is driven by the growth of energy throughputs. As is well known, growth theory does not pay special attention to energy as a production factor because empirically, the value added of the energy sector in the entire economic output is normally small, and because it is assumed that energy can be substituted by technology and capital, depending on relative factor prices. The latter point appears to be vindicated by the observation that in the advanced industrial economies, the ratio of energy and output has been declining over decades, thus reflecting efficiency improvements. However, this observation is not sufficient for refuting the opposing view that energy throughputs are the single necessary condition for growth, and that therefore the role of energy has to be made explicit in growth theories.

There are two major arguments in favor of positing the energy–growth causal linkage. The first one is historical and builds in the recent literature on the Industrial Revolution and hence the rise of modern economic growth, that is sustainable growth of GDP per capita. Whereas economists often tend to emphasize the role of institutions or culture (such as Acemoglu et al., 2002 or Landes, 2006), today leading historians highlight the essential role of energy (with seminal earlier approaches such as Debeir et al., 1991). This is interesting also for methodological reasons, because this simply amounts to an argument considering relative prices and resource endowments at the time of the Industrial Revolution, that is, leads us back to the economic fundamentals. However, the argument is also complex because it needs to demonstrate that explanations such as those referring to institutions remain secondary, that is, these only refer to additional enabling factors. In this discussion, a 'natural experimentum crucis' is of great significance: This is China. Hence, the entire discussion ties up with the specialist literature on Chinese social and economic history.

China is the 'experimentum crucis' precisely for the reason that there has been a strong revisionist movement in assessing her failure to industrialize, in spite of a substantial head start in economic development until the Middle Ages (this literature was launched by Elvin, 1973; for a survey, see Richardson, 1999: 6ff). We know today that during the times of the Industrial Revolution, China had all the necessary prerequisites for economic growth as far as institutional and cultural conditions are concerned, such as highly integrated markets, relatively secure property rights protected by the judicial system, a strong and economically active merchant class, and an open and fluid social structure (for example, Keller and Shiue, 2007; Zelin, 2004). Even more special arguments such as about the role of corporate legal forms have been refuted by recent research on functional equivalents, such as lineage corporations (Zelin, 2009). This is not the place for going into details, but suffices to state that this large and still growing revisionist literature supports an explanation of the Industrial Revolution in Europe that does not put the emphasis on these determinants anymore (however, the debate continues, see Brandt et al., 2014). So, what is left is a standard economic argument on relative scarcities of resource endowments. Here, energy plays the central role, thus vindicating Debeir et al.'s (1991) earlier approach to view institutions and economic processes in China as expressions of the more fundamental Chinese 'energy system'.

Allen (2009) has presented all the pertinent evidences which basically concur with lead contribution in revisionist China studies, in particular Pomeranz (2000). Allen's argument is simple, but adds a twist. The simple part is that relative prices of energy and labor diverged sharply between Britain and China, so that China was driven on the path of labor intensification, whereas in England there were strong incentives to substitute expensive labor for energy intensive capital. The twist is that in order to fully grasp the mechanisms, a local perspective is necessary, especially with regard to the role that the urbanization of London and the transport links to the coal mining areas. In China, the geography of coal deposits and urbanization was geared exactly to the opposite. Then, Allen shows that industrialization spread from England because of technological progress making the more expensive energy also available in the rest of Europe. So, the point is that once energy throughputs started to intensify in the English economy, this triggered market mechanisms that induced further technological change which in turn fostered energy intensification also elsewhere. In China, the introduction of railroad technology significantly reduced energy prices in the first part of the 20th century, which pushed industrialization (Rawski, 1989: 223ff).

In his authoritative literature review, Stern (2011) therefore concludes that the release of the initial constraints in energy intensification was the launching pad of modern economic growth (compare also Stern and Kander, 2011 on the example of Swedish industrialization). Then, during the 20th century, the energy constraint on growth became less binding because of technological innovation, such that the energy/GDP ratio has been declining continuously, manifesting increasing efficiency of energy use. However, this analysis cannot be interpreted as proving that energy is negligible in the sense that it would be sufficient to include only labor, capital and technology into the general conceptual framework for the theory of economic growth. This is the only question of interest from our ontological standpoint, because improvements in the efficiency of utilizing energy are not a proof of its inessentiality as a causal factor.

Turning to the second line of reasoning about energy and growth, we start with the simple argument that there are absolute limits to substitution. This is not merely a technological issue, but follows from the general definition of energy as a physical potential for change and, more specifically, as a capacity to generate work, given certain structural conditions (see Bunge, 1977: 240). The next is that common econometric techniques identifying the contribution of energy are misleading when they take the actual share of energy in GDP as indicators, thus presupposing the standard neoclassical assumptions about market structure and prices. Actually, alternative econometric approaches show that market prices and hence GDP shares undervalue the marginal productivity of energy, and that a higher share of energy would reduce the contribution of labor (Ayres et al., 2013). Further, Granger-causality analysis also shows that the relationship between energy and growth is complex and appears to be influenced by evolving constraints to substitutability between factors, turning the relationship non-linear (Stern and Enflo, 2013). The complex nature of the energy–growth link results in a large variety of econometric results, depending on which parameters are included (such as energy prices or energy quality), and which specific estimation technique is applied (Bruns et al., 2013).

Further, the question is how energy should be measured. From the viewpoint of physical theory, exergy is the relevant quantity as this is the form of energy that can be used to generate work (overview in

Buenstorf, 2004: 29ff). Then, as Ayres and Warr (2009) have demonstrated, growth theory would better use a measure of 'useful work' in order to identify the role of energy. That means, considering the transformation of energy in the economic process, one would look at the output of energy transformation, which is useful work, and not at the input, which is exergy. Then, improvements of the thermodynamic efficiency of transforming exergy into useful work can be identified as separate determinants of the energy–growth link. As a result, Ayres and Warr have shown that growth of useful work closely tracks GDP growth, combined with changes in the thermodynamic efficiency. The latter determinant appears to cover the role of 'technological progress', which is insignificant otherwise, in terms of Solow residuals or total factor productivity.

In this discussion, we should be aware of the fact that the energy–growth link is not only apparent in per-capita growth. If we consider the historical transition to agriculture, this can also be interpreted as a new way to harness the energetic potential of photosynthesis. In the past, this translated into population growth as another manifestation of economic growth in the energetic sense (Smil, 2008: 147ff; Gowdy and Krall, 2013). This is also important in assessing the case of China, as China experienced strong growth of her population in parallel with the European Industrial Revolution, yet based on traditional agriculture. In the global context, population growth continues to be a relevant modality of growth until today. It is important to recognize that in an interconnected world with ever growing international trade flows, analyzing the relationship between energy and growth is misleading as long as it is only done for single countries. This also applies for population growth. As we shall see, a crucial question in energetic analysis is where to draw the systems boundary. This can only be human civilization and the world economy in toto (Garrett, 2011).

This brief overview has shown that there are strong reasons to treat energy as an essential causal factor in economic growth, and not only as a constraint. This is by no means a new insight, but there is still a strong resistance against receiving this insight by 'mainstream' economics. One reason might be that energetic analysis has not yet been embedded into a fully-fledged alternative ontology of economics. By implication, this means that we also need to consider the role of the related physical notions, especially 'work', 'power' and the laws of thermodynamics. The question is whether this inclusion only results in taking a number of additional constraints of the economic process into consideration, or whether this also motivates us changing our fundamental assumptions on how the economic process actually works.

3. Power and Growth: The Evolutionary Perspective

Let us now push the argument onto the next level. If we take the Ayres and Warr analysis as the reference, we can pose the question why the output of useful work grows at all. On first sight, the response is competition and unlimited human wants, which incentivize the exploitation of energy for productive purposes (and, not to forget, military uses). Indeed, we must not leave human agency out of sight. This was also an essential methodological point in the debates over Georgescu-Roegen and more recent attempts at unifying physics and economics (for example, Khalil, 2004, or Scher and Koomey, 2011). However, if we ask for the function of useful work in the economic process, we need to recognize that this function is itself endogenous, which is the hallmark of an evolutionary process involving novelty and continuous change (Witt, 2005). In this case, we treat human agency as being shaped by evolutionary forces in the very long run, biologically and culturally, and hence aim at explaining its structure and content.

As is well known, the economic notion of competition was one of the building blocks that Darwin used to put his theory of evolution together. So we can ask whether economic competition and competition in living systems share certain generic properties that involve energetic transformations, thus resulting into a unified perspective on biology and economics. In the context of our discussion of growth, one recent contribution looms large, that is Vermeij's (2004) view on the economy of nature (which has been noticed in economics, see Mokyr, 2006).

Vermeij's theory is of particular relevance because he does not use the term 'economy' in the sense of applying economic methods on biology (see, for example, Noë et al., 2001), but in terms of the phenomenology of economics. That means, he uses generic terms such as scarcity or competition, but does not move on to the level of abstract economic models. This is congenial to our ontological analysis, because we can avoid the implicit ontological assumptions of those models (Rosenberg, 2001). In doing this, Vermeij formulates one general hypothesis about evolution that ties up with our previous discussion. This hypothesis is that evolutionary processes drive the growth of power output in living systems. 'Power' is the physical meaning here; that is flow of work per unit of time (Vermeij, 2004: 2, 22ff). He shows in meticulous detail how the evolution of more complex biological structures always works into the direction of increasing power flows, given structural constraints. The simple cause for this is the force of competition driving improvements on performing biological functions. These are mainly reproduction, competition against conspecifics and other species, and adaptation to the physical environment in the sense of harnessing the energetic supplies necessary to perform. If we consider the first two, these follow the 'Red Queen' logic, or result into an evolutionary arms race (compare Robson, 2005). In this arms race, evolutionary ratcheting occurs, such that performance improvements relative to ecological niches and competitors trigger corresponding adaptations of competitors, and vice versa.

Vermeij's (2004: 136ff, 252ff) theory relates the physical notion of power with a large number of structural and behavioral dimensions of performance (which often are also covered by the generic term of 'complexity', see seminally Bonner, 1988). For example, power flows increase with size increases and the corresponding metabolic changes, or with increasing range of mobility of organisms, or with the growth of communities that cooperate in harnessing energy resources ('ultrasociality'). That means, the argument operates in a stock-flow framework (compare Fath et al., 2001). This is crucial for my further reasoning: We need to distinguish between the structural evolution of living systems that in turn requires energetic investments, and the resulting changes of the power flows through these structures. Further, we need to consider the entire life cycles of living systems, especially also including decay and decomposition, in order to assess the complete energetic flows in the system (Salthe, 1993). Further, it is important to distinguish between the efficiency and the performance of living systems: Evolutionary arms races imply that structural evolution will not simply lead towards optimization in terms of efficiency, because this structure does not correspond to the capacity of maximum performance in terms of power output during a certain period of time, a fact well recognized in engineering (compare Odum, 2008: 36f). This argument shows that we cannot expect evolution to obey simple one-dimensional maximal principles because of the functional complexity of power flows resulting from selective pressures on both efficiency and maximum performance.

We can relate Vermeij's theory to one of the founding contributions to biophysics, Lotka's (1922a) Maximum Power Principle (MPP) (strangely, Vermeij does not mention Lotka, to my best knowledge). Lotka explicitly claimed that understanding evolution requires extending thermodynamics by adding principles that are peculiar to biological evolution. This argument runs as follows, matching with Vermeij's view. Biological evolution works via selection. Selection favors mechanisms that increase energetic throughputs that result into increasing power outputs in terms of performance. Evolution also involves the generation of novelties, however, so that this trend need not always become manifest. But the principle holds in the long run.

Now, in modern receptions of Lotka's theory this is treated in a more abstract way, which is however very useful when considering the unification of biology and economics. This starts out from the observation that classical thermodynamics is a theory about equilibrium states, whereas evolution obviously is a dynamic state far from equilibrium. Every organism is an open system that maintains its structures as a non-equilibrium state vis à vis the environment via energetic throughputs. In the context of classical thermodynamics, only the decomposed dead organism would be seen as staying 'in equilibrium'. So, the question is what principles might underlie non-equilibrium thermodynamics of living systems. Lotka's principle is a candidate. At this point it is important to notice, however, following Buenstorf's (2000) careful assessment, that this does not necessarily mean that the MPP is a causal theory. At this stage of the argument, it is a mere description of certain universal regularities of living systems conceived as non-equilibrium systems.

This directly connects with foundational ontological issues. In order to elaborate on this, we need to enhance our conceptual frame by referring to the physical notion of entropy explicitly, thus tying up with Georgescu-Roegen's thinking. Again, I concentrate on the bare bones of the theory. Then, we distinguish between energy, exergy as useful energy, power as useful output and the qualitative degradation of energy during the dissipation process. Entropy is the measure for this degradation. In the simplest thermodynamic cycle, this shows up in the absolute engineering constraint that a machine can only produce work based on energetic transmission in dissipating a certain amount of heat into a 'cooling' reservoir, i.e. the environment with lower temperature. For our current discussion, this most simple conceptualization of entropy suffices.

In the thermodynamic analysis of entropy production, on a most abstract level, we can distinguish between three types of systems (I follow Sciubba, 2011 here).

- The first is closed systems for which the laws of classical thermodynamics apply. Closed systems approach thermodynamic equilibrium and therefore cannot manifest growth and structural change. This is achieved in a state where entropy is at maximum, that is, all useful energy has been dissipated. The system cannot generate work anymore.
- The second is open and linear non-equilibrium systems which receive a constant throughput of energy flows. For these systems, Prigogine formulated a 'minimum entropy production principle' stating that systems will evolve so that dissipation and entropy production will converge to a minimum, while maintaining certain structures of non-equilibrium states. This can be called 'efficiency' in the economic sense.
- The third is open and non-linear non-equilibrium systems. Only these systems can manifest phenomena of sustainable growth. For them, Lotka's principle presumably holds if it is combined with the 'maximum entropy production principle'. This means that the system will undergo structural changes such that the rate of dissipation will increase with highest possible speed towards a maximum, given the constraints (compare also Lucia and Sciubba, 2013).

Considering these distinctions, and thinking in terms of general evolution, we can envisage trajectories in which systems move between the second and the third pattern, thus reflecting the functional complexity of power flows (Fath et al., 2001). For example, if there is a strong disturbance in terms of energetic impacts or because of the evolutionary emergence of new capacities to harness energetic resources, the system might first stay in scenario 3, and once it has moved near to equilibrium, it moves to scenario 2. Further, in order to maximize dissipation ultimately via maximizing power production, efficient states of subsystems can be a precondition for achieving maximum dissipation of the larger system, given the constraints on the systems architecture. This argument shows that the MPP should always be considered in terms of complete life cycle analyses, or complete evolutionary trajectories during which systems may oscillate between the states, and where we also include decay into the notion of production (compare Dewar, 2010).

This leads us to consider one essential question, which is where the boundary of the system has to be drawn (Vallino, 2010). There are temporal boundaries (such as defined by death and decay of an organism) and spatial boundaries, with the latter defining the distinction between throughput and output. For example, a plant may be defined by the boundaries of the plant, or we look at the ecological niche in which the plant is food to another organism, and then consider the plant as input to this organism. Maximum power production may only apply for more aggregate processes and more encompassing life cycles. Especially, we need to consider the possibility that subsystems may approach scenario 2, whereas the evolutionary dynamics of their interplay in the larger system approaches scenario 3. This matches with the fundamental sub-disciplinary distinction between functional biology and evolutionary biology.

There is another approach in the literature that also claims to be a major extension of standard equilibrium thermodynamics for non-equilibrium systems. This is Bejan's 'Constructal Law' (Bejan and Lorente, 2006, 2010). The Constructal Law states that evolving open flow systems will change their structure of flows in a way such that the scope, the number and the slope of gradients of flow dissipation will approach a state in which the flows tend towards a maximum. Evidently, this argument comes very close to Lotka's original formulations, but adds considerable theoretical detail on the architecture of flow systems in its implementation. This notion ties up with Vermeij's comprehensive perspective on power flows as mediated via different dimensions of size, scope and structural complexity. The Constructal Law adds a specific hypothesis about these structural changes. However, Bejan himself denies a direct relationship with any kind of thermodynamic maximum principles (see, for instance, Bejan, 2010). In my view, we can reconcile these apparently conflicting claims in treating the Constructal Law as a Meta-Law, as it is only formulated as a general principle without a particular mathematical formalism specifying the causalities in quantitative terms, as in the case of the different maximal principles. However, the advantage of the Constructal Law is that it reflects the functional complexity of power flows, which is precisely covered by the different maximal principles, as we have seen in the previous distinctions between systems scenarios.

This follows from the explicit inclusion of 'brakes', such as when organisms realize complex movements which ultimately come to halt (see Fig. 1); this notion refers to the ultimate functions and effects of power production. Power production will ultimately dissipate, too, such that MPP necessarily also increases the production of entropy. As Fath et al. (2001) have shown, considering flow systems of ecological networks, different optimization principles proposed in the literature actually converge, so that the oppositions in the literature fall together into one more fundamental principle.

The Constructal Law is important because it highlights the evolution of the structures of flow systems that drive power production and, ultimately, dissipation. The general idea is that there are proximate and ultimate functions of power flows, as analyzed by Vermeij, for example, and that these functions evolve in a way such that they support

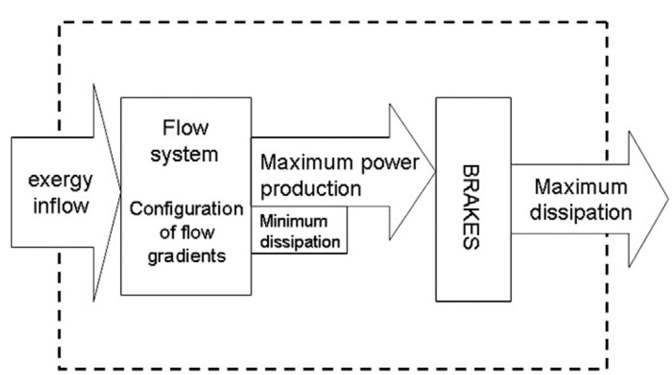

Fig. 1. The Constructal Law.
After Bejan and Lorente (2010: 24).

maximization of flows. Then, we would end up with the hypothesis that evolution of 'design' ultimately is driven by the physical forces that cause energetic dissipation and hence, entropy production (compare Bejan, 2014). This differs fundamentally from Schrödinger's (1944) famous characterization of life as a vessel of negative entropy and hence working against the Second Law. In the new view, life, in spite of being a form with lower entropy, is a means by which constraints against the enhancement and acceleration of entropy production are broken via evolution (for corresponding views in recent theorizing about origins of life, see Lahav et al., 2001; Michaelean, 2011). Evolution does not work against the Second Law, but leverages its physical manifestation. Or, in most general terms, the function of life is to maximize the production of entropy. In the Constructal Law framework, we can state this in pointing towards the role of physical constraints on energy flows which can be released by means of increasing the degrees of freedom in flow systems, which is achieved by the basic mechanism of evolution, variation, selection and retention.

4. Closing the Ontological Framework: Growth and Maximum Entropy Production

In order to clarify the relationship between proximate and ultimate functions of energetic flows in evolution, and hence the possible connection between the MPP and entropy production, we start with a brief reflection about the notion of 'work' (following Kauffman, 2000: 96ff). Obviously, the physical definition of work reflects the structural conditions that separate energetic flows which change macroscopic properties of the system and its environment from flows that merely dissipate exergy, which is producing heat. This difference is one between ordered and disordered movements of atoms on the microscopic level (Atkins, 2007: 31ff). This establishes the connection to human intentionality and design: We are able to change the environment of thermodynamic processes in such a way that work is generated. However, this also applies on evolution in general: In evolution, we observe the emergence of structural conditions for processes that feedback on the constraints that shape the dissipation of energy and thus produce work.

There is a particular class of feedback processes in chemistry which can be generalized over all kinds of living systems. This is autocatalysis (see already Lotka, 1922b: 153). In an autocatalytic process, some outputs lower the energetic thresholds that drive the dissipation of energy, hence speed up the chemical reactions. Autocatalytic circles connect a number of processes in the same fashion, with one process generating catalysts for the other, and so forth until the cycle is closed. This general principle can be applied on all levels of living systems, such as early molecular groups in origin of life theories, cell formation or ecological systems (Maynard Smith and Szathmáry, 1995: 51ff).

Autocatalytic cycles have certain properties which create tendencies to maximizing energetic throughputs and which are driven by competition (Ulanowicz, 1997: 46ff). This notion of competition even applies for chemical reactions: In a solution, the autocatalytic reactions will consume chemical inputs faster than alternative reaction pathways which are therefore crowded out. On an abstract level, autocatalytic circles are the most general concept of formation of structure via processes that impinge back on the process of structural formation and that are fed by energetic throughputs. Kauffman (2000: 61ff.) therefore defines an 'autonomous agent' (which corresponds to my use of 'living system') as being an entity that is able to reproduce itself by realizing a sequence of thermodynamic work cycles structured according to the logic of autocatalysis.

This framework allows showing up the relationship between thermodynamics and growth. I use a simple model proposed by Garrett (2011) recently in the context of climate sciences which can be applied on all levels of analysis, however. Garrett distinguishes between an entity and its environment, with the line of separation drawn by a permeable boundary such as a membrane (see Fig. 2). The system consisting of

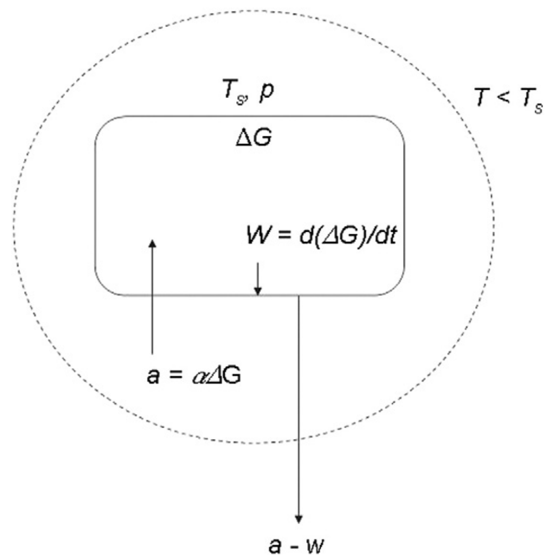

Fig. 2. Basic thermodynamic model of growth (Garrett, 2011).

the entity and its environment is embedded in surroundings with lower temperature $T < T_s$ such that heat can be exported. The interface between the entity x and its environment constitutes an energy potential ΔG. The available potential energy in the environment is transformed into unavailable forms by means of transfer of matter across the boundary, which can be measured at the rate $a = \alpha\Delta G$, where α is a system-specific coefficient which reflects the intrinsic physical characteristics of the system that influence the availability of energy throughputs (such as access to flows, or conductivity). The energy made available to the entity is transformed by its operations into either work output w or into heat dissipation $a - w$.

Work output is directed at creating, maintaining and expanding the energy potential ΔG, such that $a = \alpha\Delta G$ and $\mathrm{d}\Delta G / \mathrm{d}t = w$. The efficiency of the system is defined as $\varepsilon = w / a$. Garrett concludes that a system of this kind manifests a growth process, where a rate of return η can be defined as (Garrett, 2011, Eq. (2)):

$$\frac{da}{dt} = \alpha \frac{d(\Delta G)}{\mathrm{d}t} = \alpha \cdot w = \alpha \cdot \varepsilon \cdot a \equiv \eta \cdot a.$$

This system manifests continuous growth of energy throughputs, depending on the efficiency of the engine. Thus, the model identifies a simple, yet fundamental feedback mechanism between energy throughputs, growth and evolution which can be based on Kauffman's idea that the special aspect of work in evolution is that work is applied on the system itself.

Work, as applied on the system itself, also creates new degrees of freedom in changing the structure of the system. This is first, the condition for evolution and second, the condition for applying the Maximum Entropy Production (MEP) Principle as a final building block of our ontology. This hypothesis differs in one essential respect from applying the classical laws of thermodynamics directly on a system, because it is about the structural changes, i.e. the evolution of the gradients of dissipation, thus also matching with the Constructal Law hypothesis. Then, it states that open disequilibrium systems will evolve structurally into the direction of maximizing their entropy production, if there are sufficient degrees of freedom of adapting the gradients of the flows. Then, maximum power is a condition for maximum entropy in the sense that power generation and ultimately dissipation are the structural means to realize the tendency of MEP. Then, differing from Buenstorf's (2000) assessment, we can offer an explanation for MPP which combines two different perspectives: One is the analysis of ultimate functions in evolution, and the other is the physical principles driving evolution.

In the context of ecological economics, in particular, it is important to highlight the methodological difference between the MEP hypothesis and established approaches to thermodynamics and economics, which follow Georgescu-Roegen (1971) even when criticizing this approach (e.g. Kåberger and Månsson, 2001; Gillett, 2006). The standard views neglect the Statistical Mechanics approach to entropy, which had been eschewed by Georgescu-Roegen in the first place, too (resulting into harsh assessments of his work by leading physicists in the field, see Jaynes, 1982). In contrast, the MEP approach takes Statistical Mechanics as point of departure (Herrmann-Pillath, 2011). It has been firstly developed in the climate sciences. Here, it appeared in another shape, namely the Maximum Entropy (MaxEnt) approach. The MaxEnt approach is a methodological principle of analyzing complex systems and states that knowing the constraints under which a complex system operates, one can predict the direction of its change in assuming that the resulting state will be one of maximum entropy (Dewar, 2009). In other words, the most probable state will be attained. As such, this is a methodological principle underlying, for example, also maximum entropy estimation methods in econometrics (Golan, 2002). It was turned into a physical hypothesis in asking the question whether this realization of the most probable state is also driven by processes that maximize physical entropy production in the real world. There are today several theoretical frameworks by which this hypothesis can be systematically justified (for an overview, see Dewar et al., 2014).

One simple framework that can unify these different approaches is to think of a physical flow system in which different microscopic trajectories Γ are possible in the state space, with probabilities p_Γ. We consider trajectories and their reversal Γ*. Then, there is the quantity Ω which measures the dissipation in the system (often called dissipation function).

$$\Omega_\Gamma = \ln \frac{p_\Gamma}{p_{\Gamma*}}$$

In this approach, Ω is a measure of irreversibility. If it is equal to 0, this corresponds to thermodynamic equilibrium. The Second Law can then be formulated as:

$$\langle\Omega\rangle = \sum\nolimits_\Gamma p_\Gamma \ln \frac{p_\Gamma}{p_{\Gamma*}} \geq 0.$$

Maximum entropy production in any kind of physical flow system can be shown to be one of two possible states, depending on the constraints under which the system works: one is the state of minimum irreversibility and the other is the state of maximum entropy production, where entropy is defined as Kullback–Leibler relative entropy (see Dewar and Maritan, 2014; compare related approaches such as Niven, 2009):

$$\max H = \sum\nolimits_\Gamma p_\Gamma \ln \frac{p_\Gamma}{q_\Gamma}.$$

It is straightforward to understand this reasoning if we consider a system with sufficiently large degrees of freedom to adapt to continuous energy throughputs from the environment, and which is also large in the sense that we consider a large number of entities within the system that move statistically independent from each other. Then, as has been already stated by Lotka (1922a), such a system will adapt in such a way that this energy throughput will dissipate as fast as possible, under the given constraints. If the external observer wants to predict the end state, and only knows macroscopic properties of the system, she will assume that the system will tend towards the most probable state in which information entropy is maximal, relative to the observer. However, considering the underlying physical processes, this state will also be the state of maximal dissipation. In other words, the MEP approach posits that systems will approach the most probable state by means of dissipating maximal flows of energy. Again, we can compare this with the Schrödinger view: In this, growing complexity of life appears to be an improbable state; in the MEP approach, this complexity is the most probable state, given the constraints and causal forces shaping evolution as a process with large degrees of freedom (Whitfield, 2005, 2007).

Annila and co-authors (for example, Annila and Kuismanen, 2009, Annila and Salthe, 2010) have therefore integrated the Statistical Mechanics view and the classical thermodynamic view in considering systems with entities N_j which interact stochastically and which manifest differences in exergy potentials A_{jk}, that is energy flows among them that induce transformations of the entities (like in chemical reactions). Then, the Boltzmann statistical mechanics definition of entropy can be approximated as:

$$S = k_B \ln P = k_B \sum_j \ln P_j \approx k_B \sum_j N_j \left(1 - \sum_k A_{jk}/k_B T\right)$$

from which the authors conclude that the MEP principle results as:

$$\frac{dS}{dt} = -\sum_{j,k} \nu_j \frac{A_{jk}}{T} \geq 0$$

where the ν_j are the flows generated by the differences in energetic potentials and which are determined by structural constraints (such as conductivities). So, contra Georgescu-Roegen, it is the Statistical Mechanics view which only allows for connecting entropy and economic analysis, because this view offers an abstract principle for large scale stochastic flow systems, such as ecological or economic systems.

There are some important additional clarifications for applying this argument correctly, which we have partly mentioned already in other contexts but deserve renewed emphasis. The MEP principle depends on the proper identification of systems boundaries in both temporal and spatial terms (Vallino, 2010). This is especially true with regard to the life cycle of systems, because decay has to be regarded as a part of entropy production (for an early argument, see Salthe, 1993). The boundary issue is very complex because ultimately single systems need to be scrutinized in the context of ecological systems if they are part and parcel of their functioning. For example, large predators play an essential role in driving entire ecosystem productivity, hence energetic dissipation (Vermeij, 2004: 210ff): So, complexity increasing with size does not work against the Second Law, but reinforces its workings in the context of the larger system. Further, when dealing with actual systems, we should not expect that they have already arrived at a steady state, thus actually observing that the MEP state is realized. That might be true for the Earth climate, but less so for living systems and hence economic systems which are driven by a continuous flow of novelties. This refutes one of the most common critiques of the MEP approach, namely that it fails to describe actual states of systems: MEP can only hold empirically in a 'steady state' of entropy production (such as presumably in the Earth climate), but not in systems which are continuously disrupted by novelties. However, this does not imply that the physical forces do not work into the direction of MEP.

The MEP approach has been extended into a unified theory of the Earth System by Kleidon (2009, 2010, 2011). Here, we look at the thermodynamic side of the picture. The Earth System is conceived as a hierarchy of thermodynamic processes by which exergy inputs generate power flows which drive other processes out of thermodynamic equilibrium so that they develop the capacity of generating power, in turn, and so forth. Evolution plays an essential role in this system because it evolves novel mechanisms by which these potentials for generating work can be activated (such as by photosynthesis). That means, given an upper limit of energetic supplies set by solar radiation and geothermal processes, evolution will drive the processes towards the direction of increasing scope and speed of dissipation. In this system, generation of physical work and production of entropy are two sides of one coin. This view has important implications for locating the human economy into the context of the thermodynamic machinery of Plant Earth.

5. Discussion: Consequences for Ecological Economics

In the previous sections, I have arranged a number of recent advances in the theory of energy, evolution and thermodynamics into one overarching ontological framework. In this framework, the idea plays the pivotal role that living systems evolve into the direction of maximizing power throughputs and thereby the production of entropy in the context of the larger system of which they are a part. In this generic view, the growth of living systems is an expression of the Second Law and does not work against it. What does this ontology imply for ecological economics?

The shift from the equilibrium to the non-equilibrium open systems ontology relates with one of the influential conceptual frameworks in ecological economics, the Gaia hypothesis. The original Gaia hypothesis states that the Earth System is a tightly integrated complex system in which life evolves in a way to maintain the biogeochemical, climatic and other physical conditions that are the necessary conditions of its viability as a homeostatic system (e.g. Lovelock and Margulis, 1974; Lovelock, 1990). This idea has triggered a lot of controversies (for a critical review, see Smil, 2003: 230f.). In the MEP view, the biosphere also plays a central role in the Earth System, but it is conceived as a hierarchical system of different levels and mechanisms of entropy production. This implies that Gaia is not only seen as a steady state system out of equilibrium, but this steady state moves through time, such that the Earth System is driven further away from thermodynamic equilibrium continuously (Kleidon, 2011). So, whereas the standard use of the Gaia concept focuses on the steady state, the MEP approach analyzes the direction into which the steady state moves through time, and posits that this is MEP.

This substitution of the homeostasis hypothesis by the hypothesis of a steady state evolving farther away from equilibrium is of substantial interest for ecological economics, because the Gaia hypothesis is frequently invoked in stating positions of 'deep ecology', which see the economy as a subsystem of the ecological system that has disturbing effects on Gaia as a homeostatic system (e.g. Faber and Proops, 1998: 18; Šunde, 2008: 179; Eriksson and Andersson, 2010: 28). The MEP approach submits another hypothesis: It conceives the economy as part and parcel of the forces that drive the Earth System further away from homeostasis. To put it in drastic terms: Gaia manifests relentless forces of change, disruption and violent oscillations, if we adopt different temporal zooms, and the human economy is just part and parcel of this larger picture.

There are important empirical observations that support this viewpoint. Coming back to the 'experimentum crucis' of China, we clearly see how technological innovation in Britain resolved a 'hang up' in the thermodynamic mechanisms of entropy production, that is, overcame a constraint on MEP. This idea has been recently suggested by Haff (2014) who applies the Rayleigh–Bénard cell model in order to interpret economic processes from the MEP angle. In this model, there is a heat flow between two plates with different temperatures, and an interaction between advection across most of the distance between the plates and diffusion via the boundary layers of the plates. Whether the heat flow switches from conduction to convection depends on the Rayleigh number which is a measure and control parameter describing different physical conditions of the fluid. Haff proposes thinking of the economic system in a similar way as connecting a 'hot' spot, that is, a potential source of energy, with a 'cold' spot, the demand side. Markets and prices correspond to the role of the Rayleigh number in determining the flow of energy. Then, we can approach this process in terms of local energy flows. This is exactly what we observed about the comparison between China and Britain: Market conditions, technology and availability of coal played together in triggering a rapid 'convection' of energy flows, that is a collective and concerted transition to a new regime with a much enhanced rate of dissipation of energy and hence entropy production. This is a sudden release of a 'hang up' in entropy production in the Earth System and thus plays together with the general mechanisms of entropy production. We can generalize this observation in terms of the Constructal Law: The economy and its market mechanisms are means that enhance the degrees of freedom in the underlying physical flows and hence directly contribute to the realization of MEP mechanisms (compare Bejan and Lorente, 2013: 8ff).

Related to this, an important empirical issue in analyzing the relationship between energy and growth is the 'rebound effect' which goes back to Jevons' famous analysis of the 'Coal question'. Jevons' original argument was that there is a positive feedback mechanism between the price of coal and the demand for coal, mediated by technological innovation, such that improvements in the efficiency of coal usage would result into a continuous absolute growth of coal use. There is a substantial literature on the generality of this effect (reviewed by Sorrell, 2009; Sorrell et al., 2009). Broadly speaking, strong rebound effects may exist for a few single technologies, but in many cases they are much lower than one. On the other hand, the difficulty lies in assessing the general equilibrium effects in the context of the global economy: That means, the question looms large, again, where to draw the systems boundaries in order to properly assess rebound effects. For example, more efficient energy use in advanced economies may lead to lower prices, which induce more extensive energy use in developing economies, which export to the advanced economies (vide the tandem between US consumers and producers in China, driving CO_2 emissions in China). This question remains unresolved until today, but it is justified to adopt one possible interpretation of the evidence which would state that 'general purpose technologies' tend to manifest rebound effects larger than one, such as coal and steam in the past, or electricity more recently (Ayres and Warr, 2003). Then, we could match this with the MEP hypothesis: Technological evolution would lead to overall structural changes that maximize entropy production on Earth, and which show up in rebound effects on the systemic level for particular technologies that have systemic impacts. Proximately, rebound effects are manifestations of MPP and the MEP as ultimate causes.

In this context, information technology certainly is a candidate for a recently emerging general purpose technology. Here, the value of the 'ontological shift' is especially salient. In the past decades, there was much talk about the 'dematerialization' of advanced economies via the growth of the services and ITC sector. However, the empirical record on the contribution of structural change in the sectoral composition of the economy on energy flows is mixed, and the question is particularly important whether and how the increasing importance of information technology in services will affect its energy consumption, because it affects both the efficiency of energetic transformations and enhances the absolute throughput (Mulder et al., 2014). In almost all economic theories information is treated as a 'de-materialized' entity, such as 'ideas' (in growth theory, see for example Jones, 2002). There is the notion that Research and Development consume resources, but this does not relate to the information as such. But knowledge cannot impact on the economy without being mediated by material actions and artifacts (Witt, 2005). Today, one is information technology, where questions of energy use and environmental impact loom increasingly large. Generally, the opinion prevails that IT is contributing to increasing efficiency of energy use, but we have also opinions based on empirical analysis that these effects can be outweighed by the energetic costs of producing and using IT devices, for example, in developing economies (Sadorsky, 2012).

From the ontological point of view, this question is not only an empirical one, but reflects the necessity of conceiving information as a physical entity (Karnani et al., 2009). This is so far mostly done in the computer sciences, following Landauer's (1961) early work, showing that the energy consumption of IT results from the energetic costs of deleting information, for which an exact value in terms of bits can be given (Bérut et al., 2012). This means, however, that one cannot simply argue that 'knowledge' is a freely available means to overcome energetic constraints and the environmental impact. Also, one cannot treat 'knowledge' as something that is peculiar to the human domain: Information processing is a universal phenomenon, and the MEP ontology thus raises the question how this relates with entropy production in general. We can certainly raise the question, is modern information technology actually a force that can trigger further growth of energy throughputs, dissipation and entropy production? The research strategy resolving this question will be determined by the underlying ontological assumptions about the physical nature of knowledge and information. Then, we can venture the hypothesis that knowledge production and processing do not result into substitution of energy by technology, but is just another driver of energetic dissipation. Optimism about solving current environmental challenges by means of technological progress is not justified.

This argument also applies for the idea that markets and marketization are the ultimate means how to incentivize the actors in economic systems to resolve environmental challenges (such as is evident in favoring markets for pollution permits over Pigou taxes). I suggest that we have to see markets in a new light, following the track laid by discussing Haff's ideas, combined with Annila and Salthe's (2009) insights. Markets can be seen as one aspect of human networks in general and hence as a constituent part of the human 'living system' (such as in Gowdy and Krall's, 2013 view on human 'ultrasociality'). Interestingly, in their grand historical vision of the 'human web', the historians McNeill and McNeill (2003: 319ff.) adopt a thermodynamic framework in arguing that the creation and maintenance of this global network are driven by energetic flows and the human capacity to harness energy resources. This view goes beyond earlier network approaches in the historical study of energy (such as Debeir et al., 1991) which concentrate on the technological networks of energy systems (i.e. production and distribution). Just as the Constructal Law suggests, we can conceive of the entire network of economic human interactions as a flow system of gradients of energetic dissipation. Increasing connectivity and increasing rates of structural change imply the speeding up of rates of dissipation. Hence, if we see markets and the implied freedom of establishing connections between agents as drivers of network growth, the market itself can be interpreted in MEP terms, once we conceive of markets as material structures in the real world, a view that has been recently bolstered by research in economic sociology (see, for example, Pinch and Swedberg, 2008). I already referred to the Constructal Law previously in terms of the implications of market evolution for enhancing the degrees of freedom in flow systems. Then, even economic values and policies such as market liberalism can be seen as having physical implications, and, approaching markets from an evolutionary perspective, institutional evolution of markets can be analyzed along the lines of maximum power and maximum entropy (for a detailed and comprehensive analysis, see Herrmann-Pillath, 2013: Chapter 8).

For substantiating this point in brief, it is helpful adopting the geographic view on markets (as in Fujita et al., 1999): Then, urbanization and the related agglomeration of networks are the material manifestations of market evolution and can be seen as changing gradients of energetic dissipation, with urban structures, transport systems and so on materially representing them, as epitomized in the essential role of London in breaking up the 'hang up' of fossil energy in early industrialization (Allen, 2009). Again, we meet the conjunction of efficiency and increasing rates of dissipation, even on the micro-level, such as the walking speed of urbanites (Bettencourt et al., 2007). Interestingly, recently it has been demonstrated that observing urban lighting from space can serve as an accurate indicator of GDP of a country, thus directly proving the conjunction between urban growth, market dynamics in terms of GDP growth and energy (Henderson et al., 2012; related observations from the Constructal Law point of view are collected in Bejan and Lorente, 2013). So, the ontological shift of perspectives allows us to conceive markets as institutional complements of physical flow structures that drive the energetic transformations and ultimately entropy production.

One fundamental consequence of the ontology proposed here is that there can be a stark contradiction between most economists' conviction that the extension of markets will be conducive to higher efficiency and thereby will contribute to the solution of our environmental conundrums. In my view, the extension of markets speeds up growth and hence entropy production. So, there are actually two basic policy recommendations that follow. One is the standard one of changing the relative prices of energy and labor radically in order to properly reflect the role of energy in the growth process. However, this must be accompanied by a careful consideration of limits and limitations of markets. In ecological economics, this is already done in different contexts in the literature on 'degrowth' (see Kallis et al., 2012). This should be linked with the recent upsurge of debates about the ethical limits of markets, subsequent to Sandel's influential contributions (Sandel, 2013). In the MEP view, containing the scope of markets is a means of slowing down entropy production in the economy.

There is the optimistic version of applying thermodynamic ideas on economic growth which starts out from the observation that entropy generation by the human economy is minuscule as compared to entropy production of the Earth System (Kåberger and Månsson, 2001). Here, technological innovation in renewable energies would avert serious environmental consequences of continuing with the carbon economy that emerged in the Industrial Revolution. However, as Kleidon (2009) shows, the actual size of the energetic impact on the Earth System is already larger than the energetic flows of geological forces. This is also evident from the geological record of the material impact, which has led geologists to identify a new period in the geological history of the Earth, the 'anthropocene' (Crutzen, 2002; Zalasiewicz et al., 2008). Given the size of the impact today, one has to consider the possibility that the entire set of processes that deal with material transformations in human production systems (also including information, as sketched above), and especially, with the transformation of harmful wastes into non-hazardous matter, will ultimately consume increasing amounts of energy throughputs such that the so-called heat barrier will be reached within long-run time horizons that nevertheless count for the human society (Kümmel, 2013: 147ff). Then, climatic effects of the human economy will occur even without involving the greenhouse effect, just resulting from heat dissipation. This effect is already locally visible in the temperature differences between urban areas and the surrounding regions. So, entropy production matters in spite of the fact that human entropy production is only a minuscule share of entropy production of the Earth System which is, after all, exported to outer space.

That means, against the background of the MEP approach current climate change policies are misguided in concentrating on the CO_2 emissions issue. We have to design economic policies for the anthropocene (Gowdy and Krall, 2013), recognizing the integral role of the human economy in the thermodynamic processes of the Earth System. The MEP hypothesis states that economic growth is the expression of fundamental physical laws in the context of human institutions and behavior. That means, we cannot arbitrarily switch off these mechanisms, but we can manage their expressions, such as speed, direction or structural features. Focusing on single aspects such as CO_2 emissions follows the standard 'resources as constraints' viewpoint, which seriously misguides policy design. For example, as is well-known from EROI analysis, renewable energies may help to resolve the greenhouse issue in the short run, but will contribute to the further growth of energetic throughputs if only because they require increasing energy throughputs themselves (Murphy and Hall, 2010). This will speed up the convergence to the ultimate heat barrier of the thermodynamic processes in the Earth System. In the MEP view, we need a comprehensive approach to Earth System management of which the economy is only one part.

6. Conclusion

The gist of my argument is that we need to conceive human individuals as biological entities, and markets as part and parcel of ecological systems. Energy is reinstated as a foundational ontological category, together with the related thermodynamic notions. Such an ontological shift has many methodological implications. For example, the recent literature on energy and growth seems to have left the question undecided, from the viewpoint of standard growth theory. But against the background of the MEP hypothesis, it is theoretically plausible that historical periods with strong effects of energetic throughputs alternate with those where efficiency gains in energy use dominate; further, we have to consider the entire global economy as embedded into the Earth System in order to assess rebound effects, and so forth. In other words, ontology determines our evaluation of the empirical evidence which is still uncertain and limited, given the complexity of phenomena such as global climatic change. Without clarifying ontological issues based on scientific principles, we cannot properly interpret empirical knowledge, which therefore falls prey to competing political and ideological interpretations serving special interests.

In the naturalistic ontology that I have extracted from research across the different disciplines of physics, biology and economics, economic growth appears to be the expression of a fundamental physical law, mediated by evolutionary mechanisms, as has been envisaged by Lotka. This essential role of evolution has been neglected in the recent literature on energy and growth. Therefore, an important issue in economic ontology is the relationship between biological evolution and cultural evolution. There have been many important theoretical and empirical advances in this field of research which need to be integrated into economics in general and ecological economics in particular.

This naturalistic ontology of economics is strictly grounded in the sciences. The core insight from my review is that I do not see thermodynamics as defining the constraints of economic growth, but that economic growth is a direct manifestation of the Second Law in the context of open non-linear systems far from equilibrium. Growth is a natural process.

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