CHAIR ENERGY & PROSPERITY
Energy Transition Pathways and Financing

Working Paper

Energy capture, technological change, and economic growth: an evolutionary perspective

Victor Court[*]

August 17, 2018

Contact: Victor Court, victorcourt@free.fr

---

[*] CERES, École Normale Supérieure–PSL Research University, 24 rue Lhomond, 75005 Paris, France ; Chair Energy & Prosperity, Institut Louis Bachelier, 28 place de la Bourse, 75002 Paris, France.

La Chaire Energie et Prospérité

La chaire Energie et Prospérité a été créée en 2015 pour éclairer les décisions des acteurs publics et privés dans le pilotage de la transition énergétique. Les travaux de recherche conduits s'attachent aux impacts de la transition énergétique sur les économies (croissance, emploi, dette), sur les secteurs d'activité (transport, construction, production d'énergie, finance) et aux modes de financement associés. Hébergée par la Fondation du Risque, la chaire bénéficie du soutien de l'ADEME, d'Air Liquide, de l'Agence Française de Développement, de la Caisse des Dépôts, de Mirova, de Schneider Electric et de la SNCF.

Chair Energy and Prosperity

The Energy and Prosperity academic Chair was created in 2015 to inform decisions of public and private actors in managing the energy transition. The Chair research deals with the impacts of energy transition on national economies (growth, employment, debt), on specific sectors (transportation, construction, energy, finance) and with the associated financing issues. Hosted by the Risk Foundation, the chair has the support of ADEME, Air Liquide, the French Development Agency, the Caisse des Dépôts, Mirova, Schneider Electric, and SNCF.

Energy capture, technological change, and economic growth: an evolutionary perspective

Victor Court*

Abstract

After several decades of discussions, mainstream economics still does not recognize the crucial role that energy plays in the economic process. Hence, the purpose of this article is to reformulate a clear and in-depth state of knowledge provided by a thermo-evolutionary perspective of the economic system. First, definitions of essential concepts such as energy, exergy, entropy, self-organization, and dissipative structures are recalled, along with a statement of the laws of thermodynamics. The comprehension of such basics of thermodynamics allows an exploration of the meaning of thermodynamic extremal principles for the evolution of physical and biological systems. A theoretical thermo-evolutionary approach is then used to depict technological change and economic growth in relation to the capture of energy and its dissipation. This theoretical analysis is then placed in a historical context. It is shown that during the entirety of human history, energy has been central to direct the successive phases of technological change and economic development. In particular, energy is crucial to understanding the transition from foraging to farming societies on the one hand, and from farming to industrial societies on the other. Finally, the theoretical and historical insights previously described are used to discuss a possible origin of the economic slowdown of the most advanced economies for the last 40 years. The article concludes that conventional economic growth theories should finally acknowledge the central role that energy plays in the economic process.

Key Words: Energy capture; technological change; economic growth; evolution.

JEL Classification: B52, O44, Q43, Q57.

Published article, please cite as: Court, V. (2018). Energy capture, technological change, and economic growth: an evolutionary perspective. *BioPhysical Economics and Resource Quality*, 3(3): 12

---

*CERES, École Normale Supérieure – PSL Research University, 24 rue Lhomond, 75005 Paris, France; and Chair Energy & Prosperity, Institut Louis Bachelier, 28 place de la Bourse, 75002 Paris, France. Email: victorcourt@free.fr.

1 Introduction

1.1 Neo-Keynesian, ecological, and evolutionary views on production factors and growth mechanisms

Mainstream economists (i.e., proponents of the neoclassical-Keynesian synthesis), usually think of labor and capital (with land as a subcategory) as the primary factors of production, and goods such as fuels and materials as intermediate inputs. On the contrary, ecological/biophysical economists see labor and capital as intermediate inputs that are created and maintained by the use of the primary input of energy to transform materials. These different views on production factors translate into contrasting economic growth perspectives. Mainstream growth models focus on the accumulation of physical and human capital, their combination with routine labor and technology, and on the role of institutions to enable productivity increases (Acemoglu, 2009; Aghion and Howitt, 2009; Barro and Sala-i Martin, 2004; Jones and Vollrath, 2013). Mainstream growth models usually ignore energy, but sometimes acknowledge that a limited supply of energy (or a more general environmental asset) can generate a temporary constraint on growth that is ultimately relaxed the adaptation of market prices, or by technological progress. By contrast, the ecological economics literature posits a central role for energy use in driving growth and argues that limits to substitutability and energy-related technological change determine long-term growth prospects (Ayres and Warr, 2009; Daly, 1985; Georgescu-Roegen, 1971; Kümmel, 2011).

In evolutionary economics, the relative importance of capital, labor, technology, and natural resource inputs (energy and materials) tends to follow the mainstream approach. Therefore, evolutionary economics does not make energy central to its conceptual framework, despite several applications of evolutionary thinking to resource use and ecosystem management issues (van den Bergh, 2007). Furthermore, from the pioneering work of Nelson and Winter (1982), modern evolutionary economics has tended to be concerned with supply-side questions, posed at the firm or industry level.[1] This supply-side focus has been difficult to connect, both analytically and empirically, with macroeconomics. Indeed, many neo-Schumpeterian evolutionary economists refrain from drawing macroeconomic conclusions from their analyses because of the tendency for aggregation to wash out the interesting evolutionary dynamics (Foster, 2011). Nevertheless, there has been some notable recent attempts to tackle this problem (Boehm, 2008; Carlaw and Lipsey, 2011; Dosi et al., 2006; Saviotti and Pyka, 2008). These contributions provide useful insights but they are based on very different analytical frameworks and, as argued by Foster (2011), the absence of a common methodology has tended to place evolutionary macroeconomics at a competitive disadvantage in comparison to the relatively unified theoretical approach adopted by mainstream growth theorists.

1.2 Goal and organization of the paper

Similarly, the methodological pluralism of ecological economics created an opportunity for mainstream economics to gradually downplay the vigorous criticisms of the ecological field (Anderson and M'Gonigle, 2012). Plumecocq (2014) shows that since its inception in 1989, the discourse of articles published in *Ecological Economics* has converged towards mainstream environmental economics. As a corollary, it must be acknowledged that ecological economics has failed to make mainstream economics more aware of the crucial role that energy plays in the economic growth process. This is clear when one sees that the term 'energy' is not featured a single time in several textbooks presenting mainstream economic growth theories, namely Aghion and Howitt (1998), de La Croix and Michel (2002), Barro and Sala-i Martin (2004).[2] Similarly, energy is absent from the recent studies that seek to develop a *unified growth theory* (UGT), which could provide a unique analytical framework to study economic development over the entire course of human history (for a

---

[1] The birth of a coherent body of evolutionary economic thoughts is generally attributed to Nelson and Winter (1982). Nevertheless, Hodgson (1993) notes that economic evolutionary concepts can be found in the work of Marx, Veblen, Marshall, and Schumpeter; whereas van den Bergh (2007) highlights that similar evolutionary concepts are present in the work of the founding fathers of ecological economics such as Boulding and Georgescu-Roegen.

[2] In Acemoglu (2009) and Aghion and Howitt (2009) energy is mentioned in relation to just one econometric study that investigates innovation in energy sectors. The less mathematically formalized and more historically oriented book by Weil (2013) does a slightly better job than other economic growth textbooks, it does mention energy several times, essentially in the context of the Industrial Revolution. The third edition of Jones and Vollrath (2013)'s textbook dedicates a whole chapter to exhaustible resources that was not present in previous editions.

comprehensive review of UGT, see Galor, 2011). So far, unified growth models have focused on human capital, technological change, and the role of their feedback relationship in fostering sustained economic growth from an initial limited growth regime. As a consequence, these models are supposed to explain the Industrial Revolution without appealing to the role of energy, in particular the associated energy transition towards fossil fuels.[3] This is obviously confusing, to say the least, as it goes contrary to the work of many economic historians such as Pomeranz (2000), Fouquet (2008), Allen (2009), Kander et al. (2013), Malm (2016), and Wrigley (2016), who place a great emphasis on the role of coal to explain the early economic take-off of England towards sustained economic growth; whereas others, such as Debeir et al. (1991), Sieferle (2001), Crosby (2007), Morris (2010, 2015), and Smil (2017), go further and make energy central to their analysis of the entire history of human society.

Accordingly, there is still a need to highlight the crucial role of energy for the economic process. The correct integration of energy into economic models is indispensable to a good understanding of past, present, and future patterns of technological and economic changes. In order to achieve this goal, definitions of concepts such as energy, exergy, entropy, self-organization, and dissipative structures will be recalled in Section 2. Together with a presentation of the fundamental laws of thermodynamics, this section also deals with the meaning of thermodynamic extremal principles for the evolution of physical and biological systems. In Section 3, a theoretical thermo-evolutionary approach is adopted to depict technological change and economic growth in relation to the capture of energy and its dissipation. This section also provides several *theoretical propositions* and *research recommendations* that should contribute to conceptual and methodological convergences between mainstream, ecological, and evolutionary schools of thought. In Section 4, the theoretical thermo-evolutionary paradigm developed in the previous section is placed in a historical context. Such an analysis is necessary to show that energy has been central in directing the successive phases of technological change and economic development throughout human history. In particular, the thermo-evolutionary lens provided by Section 3 helps to understand the transition from foraging to farming societies on the one hand, the transition from farming to industrial societies on the other, and to discuss a possible origin of the economic slowdown of the most advanced economies for the last 40 years. Finally, a summary of the contributions to this article is given in Section 5.

2 Methods: basics of thermodynamics and the evolution of natural systems

In the first part of this section, fundamental concepts such as energy, exergy, and entropy are recalled. This is necessary to then understand the importance of the laws of thermodynamics initially formulated for natural equilibrium systems. In the second part of this section, the literature on thermodynamic extremal principles is reviewed to see how it can improve the understanding of the evolution of physical and biological non-equilibrium systems. The basics of thermodynamics given in this section are a prerequisite to understanding the role of energy for the economic system described theoretically in Section 3, and analyzed historically in Section 4.

2.1 Basics of thermodynamics: concepts and laws

2.1.1 Energy, exergy, and entropy

Energy is a prime concept of thermodynamics for which the following definition can be given.

Definition 1. *Energy, measured in joules, is the ability of a system to cause change.*[4] *Energy types include kinetic energy, which is the energy of motion; potential energy, which is the energy of a mass in a gravitational field, with coulomb energy as the potential energy of a charge in an electric field; electric and magnetic energies, which are related to coulomb energy by Maxwell's equation; photon energy, which is the energy of an electromagnetic wave such as light; and chemical energy, which is the internal energy of a system of many interacting particles.*

---

[3] Among more than thirty unified growth models that do not consider energy, Fröling (2011) is the only one exception.

[4] One joule (J) is defined as the quantity of mechanical work transferred to an object by moving it a distance of one meter (m) against a force of one newton (N), i.e. 1 J = 1 Nm. One newton is the force needed to accelerate one kilogram (kg) of mass at the rate of one meter per second (s) squared in the direction of the applied force, i.e. 1 N = 1 kg m/s^2. In the context of energy transfer as heat, 1 J = 0.2389 calorie, and one calorie represents the energy needed to raise the temperature of one gram of water by one degree Celsius at a pressure of one standard atmosphere (corresponding to 101,325 Pascal).

In the particular context of the economic process, it is crucial to distinguish between *primary*, *final*, and *useful* energy. Primary energy is present in the environment in the form of natural stocks (coal, oil, gas, uranium) or flows (sun, water, wind, geothermal, wave, and tide) that must be converted into secondary energy carriers in order to be usable. Such final energy vectors consist in heat flows, electricity, and solid, liquid, or gaseous refined products. Finally, end-use devices allow the conversion of final carriers into useful energy in the form of motion (i.e., mechanical drive), heat, and light.[5]

However, energy is not sufficient to understand real processes because, as well as varying in quantity, real processes also vary in quality. Indeed, from the beginning of the Industrial Revolution, scientists and entrepreneurs noticed that the fraction of energy that can be converted into mechanical work is not the same from one energy process to another. Scientists introduced the concept of *exergy* to account for the capacity of a given quantity of energy to be converted into mechanical work. Ayres (1998a) gives the following formal definition of exergy.[6]

Definition 2. *Exergy (measured in joules similarly to energy) is the maximum amount of work that can theoretically be recovered from a system as it approaches equilibrium with its surroundings reversibly, that is, infinitely slowly.*

Hence, the physical quality of a given quantity of energy changes according to its relative exergy content. Throughout any real process, energy is always conserved, but exergy is gradually destroyed because each step occurs with irreversibilities at the microscale, which are visible as friction and heat losses at the macroscale. These released heat outflows have higher temperatures than the wider environment, so they still contain some exergy. As the heat losses gradually mix with the surrounding environment, the temperature eventually equals the temperature of the environment. Accordingly, the exergy content (i.e., the capacity to do work) of these heat outflows gradually decreases to zero. Thus, in conversion processes, energy is conserved in quantity, but its quality degrades as it gradually loses all of its ability to perform work (Kümmel, 2011, p. 114).[7]

The gradual depreciation of the quality of energy, i.e., the progressive destruction of exergy, is part of an overwhelming tendency of all natural and technical systems to spread out their components as evenly as possible in space and over the states of motion (Kümmel, 2011, p. 114). In other words, systems move naturally towards their most disordered state in the absence of work available to maintain their energetic order. *Entropy*, noted S, is a concept that defines such a lack of energetic order.

Definition 3. *Entropy is the measure of energetic disorder, and all energy conversion processes produce entropy. Entropy is measured in energy unit (joules) per unit of absolute temperature (Kelvin), i.e., in J/K.*[8]

Entropy is not a 'thing' or a 'force' as it is formally the measure of the absence of exergy in a system. This means that when a system is in equilibrium with its surroundings, it cannot perform work (i.e., it contains no exergy) and consequently its entropy is at a maximum. Exergy increases and entropy decreases as the system is moved away from its equilibrium. That is why, in this sense, entropy is a measure of the energetic disorder, or even more formally the absence of energetic order, of a system.

The amount of entropy change, ΔS, of a given system is the energy reversibly transferred as heat, ΔQ_{rev}, divided by the absolute temperature, T, at which the transfer takes place: $\Delta S = \Delta Q_{rev}/T$. Atkins (2010, p. 48) provides a colorful metaphor to explain the concept of entropy and to see the importance of the temperature T at which the heat transfer ΔQ_{rev} takes place. Imagine a quiet library as a metaphor for a system at low temperature T_1 with little thermal motion. In such a context, if someone with a very bad cold

---

[5] It is important not to confuse useful energy with energy services. As put by Cullen and Allwood (2010), energy services (transport of passengers and goods, space heating, and illumination) are the outcomes of the interaction of useful energies (mechanical drive, heat, and light) with passive devices/infrastructures. Hence, all useful energy flows are measured in joules, whereas energy services take different units of measurement such as passenger-km or tonne-km for transport, and lumen for illumination.

[6] Earlier equivalent terms to name exergy are available work, available energy (or even availability), and free energy. For the sake of completeness and clarity, "Gibbs free energy" represents exergy in a particular process performed at constant temperature and pressure, whereas "Helmholtz free energy" represents exergy in a particular process performed at constant temperature and volume.

[7] As noted by one of the anonymous reviewers of this article, there is a tacit value judgment when using exergy instead of energy. Exergy values energy for its ability to produce mechanical work, whereas energy values the exact same flow for its ability to produce heat. There are applications in which exergy is more appropriate (manufacturing, transportation, etc.), whereas energy is more appropriate for other applications (home heating, for example).

[8] The absolute or thermodynamic temperature uses the Kelvin (K) scale and selects the triple point of water at 273.16 K (= 0.01°C) as the fundamental fixing point. Like the Celsius scale (but not the Fahrenheit scale), the Kelvin scale is a centigrade scale so that conversions between Kelvin and Celsius scales are simple: 0 K $\equiv$ -273°C, 273 K $\equiv$ 0°C.

sneezes suddenly, with ΔQ_{rev} representing the magnitude of the sneeze, it will be highly disruptive for the other people in the quiet library: there is a sudden large increase in disorder, i.e., a large increase in entropy $\Delta S_1 = \Delta Q_{rev}/T_1$. On the other hand, a busy street is a metaphor for a system at high temperature $T_2 > T_1$ with a lot of thermal motion. Now the exact same sneeze of magnitude ΔQ_{rev} will be almost unnoticed by the other people of the busy street: there is relatively little additional disorder, i.e., a small increase in entropy $\Delta S_2 = \Delta Q_{rev}/T_2$. In each case, the additional disorder, i.e., the increase in entropy ΔS_1 of the library and ΔS_2 of the street, is proportional to the magnitude of the sneeze, i.e., the quantity of energy transferred as heat ΔQ_{rev} in both cases, and inversely proportional to the initial agitation of the system, i.e., the temperature T_1 for the library and T_2 for the street.

Several entropy concepts have been derived, and therefore differ, from the original definition given above. From a molecular point of view, a statistical mechanics approach is needed to understand the concept of entropy as a measure of the number of ways in which a system may be arranged. In such a perspective, entropy is a measure, not of 'energetic disorder' as previously defined, but of the 'physical disorder' associated with the system structure.[9] By extension, the same term of entropy designates 'informational disorder' in information theory, with different definitions of the concepts of information, orderliness, and complexity among authors.[10] According to Ayres (1998a) and Corning (2002), using the same idiom of entropy for various concepts of orderliness (energetic, physical, and informational) has certainly led to misconceptions and to an overuse of such different concepts to try to understand the evolutionary dynamics of natural systems. The thermoeconomic research community is now more focused on exergy than on entropy. However, scientists that try to relate the evolution of physical and biological systems with the extremization of thermodynamic variables frequently use the concept of entropy. As a result, this paper will necessarily use both terms.

2.1.2 The laws of thermodynamics, self-organization, and dissipative structures

With all these concepts in mind, the laws of thermodynamics can be understood more easily. Based on Atkins (2010) and Kümmel (2011), the first and second laws of thermodynamics are reformulated as follows.[11]

LAW 1. *The first law of thermodynamics states that the total energy of an isolated system is constant, thus energy can be transformed from one form to another but cannot be created or destroyed.*

COROLLARY 1. *It is impossible to construct a perpetual motion machine of the first kind; that is, a machine that performs work without any input of energy.*

LAW 2. *The second law of thermodynamics states that the total entropy of an isolated system increases over time and exergy is necessarily degraded by spontaneous processes due to irreversibilities.*

COROLLARY 2. *It is impossible to construct a perpetual motion machine of the second kind; that is, a machine that does nothing other than extracting heat from a reservoir and performing work without an associated heat increase elsewhere.*

It is important to see the complementarity of the two laws of thermodynamics (Atkins, 2010, p. 51). The first law, with the help of the energy concept, identifies a *feasible* change among all conceivable changes: a process is feasible only if the total energy of the universe (system under study + surrounding environment) remains constant. The second law, with the help of the exergy and entropy concepts, identifies *spontaneous* changes among the feasible changes: a feasible process is spontaneous only if the total entropy of the universe increases. With this last point, it is crucial to stress that entropy can decrease locally for a given system, but the price of increasing local energetic order (local entropy decrease) is necessarily a higher increased

---

[9] For a given macrostate characterized by plainly observable average quantities of macroscopic variables such as temperature, pressure, and volume, entropy measures the degree to which the probability of the system is spread out over different possible microstates. In contrast to the macrostate, a microstate specifies all the molecular details about the system, including the position and velocity of every molecule. Hence, the higher the entropy, the higher the number of possible microscopic configurations of the individual atoms and molecules of the system (microstates) which could give rise to the observed macrostate of the system.

[10] For example, Shannon (1948) uses the term entropy to describe his measure of statistical uncertainty associated with the efficiency with which a message is communicated from a sender to a receiver. Hence, Shannon's entropy bears no direct relationship with the original energetic concept of entropy.

[11] There are a total of four laws of thermodynamics, but only the first and second are useful to understanding the economic process. The zeroth law of thermodynamics states that if two systems are in thermal equilibrium with a third system, they are in thermal equilibrium with each other. This law helps to define the notion of temperature. The third law of thermodynamics states that the entropy of a system approaches a constant value as the temperature approaches absolute zero, and with the exception of non-crystalline solids (glasses), the entropy of a system at absolute zero is typically close to zero.

energetic disorder (entropy increase) in the broader environment with an overall loss of energy quality (exergy destruction) during such a process (Kümmel, 2011, p. 114). As the above definitions make clear, the laws of thermodynamics have been formulated in the context of *isolated* thermodynamics systems, namely, systems that exchange neither energy nor matter with their encompassing environment. Except for the cosmic universe as a whole (as far as we can tell), such isolated systems do not exist in nature and can only be approximated in the laboratory. *Closed* thermodynamics systems that exchange energy but not matter with their surrounding environment are rare, but do exist in nature. Abstracting from meteoritic falls, the Earth can be considered as a closed system receiving a solar energy input that is re-emitted as an infrared heat output. *Open* thermodynamic systems exchanging both energy and matter with their encompassing environment represent the majority of physical, biological, and social systems.

Moreover, it is the non-equilibrium state of open systems that is relevant to this paper. Based on Sciubba (2011), a further distinction should be made between *linear near-equilibrium open systems* and *non-linear far-from-equilibrium open systems*.

Definition 4. *Linear near-equilibrium open systems are complicated systems operating in perturbed conditions with state functions (i.e., all the relevant variables influencing the system performance) remaining in a sufficiently small region of the solution space around their steady or even dynamic equilibrium state, such that perturbations of the state variables yield linear response.*

Definition 5. *Non-linear far-from-equilibrium open systems are complex systems that can undergo changes due to small perturbations involving bifurcation from one state to another, or states involving periodic variation in time and space. Accordingly, the time evolution (i.e., the future states and transitional dynamics towards such states) of such systems cannot be predicted solely using the three thermodynamics laws, even though these laws are also applicable during the system's evolution.*

Two other concepts that are of importance for the rest of this article are *self-organization* and *dissipative structures*, for which the work of Buenstorf (2000) is used to give the following definitions.

Definition 6. *Self-organization is the emergence of structures and properties at the system level (i.e., at a scale much larger than the individual system component), which are developed through interaction of system components without centralized control or coordination. In addition to non-linear far-from-equilibrium conditions, self-organization requires a system consisting of multiple elements in which non-linear relations of positive and negative feedback between the system's elements are present.*

Definition 7. *Dissipative structures are open systems that, through self-organization, convert a part of their available input energy into work to build internal structures. These are maintained (or further developed) insofar as input energy to the system is present (or increased).*

Prigogine et al. (1972a,b) show that near-equilibrium dissipative structures evolve towards a stationary state where energy dissipation and entropy production converge to a minimum compatible with the boundary conditions. However, it is important to note that such a *minimum entropy production principle*, as it was called, is valid only in a limited range close to a thermodynamic equilibrium where linear relations between variables hold. When the energy gradient between an open near-equilibrium system and its surrounding environment increases above a certain value (specific to the experiment's conditions), a bifurcation occurs, and the linearity of forces and flows breaks down so that the system becomes far-from-equilibrium. Prigogine and Stengers (1984) argues that in far-from-equilibrium thermodynamic systems, the minimum entropy production principle does not hold. In such conditions, Ziegler (1963) proposes that physical systems tend instead towards a state of *maximum entropy production*. Nevertheless, the concepts of dissipative structure and self-organization remain relevant to physical, biological, and economic systems since they maintain and further develop structures far-from-thermodynamic equilibrium through energy dissipation in the presence of input energy (Binswanger, 1993; Proops, 1983; Witt, 1997).

2.2 Thermodynamic extremal principles and the evolution of natural systems

2.2.1 Lotka Principles and Maximum Power Principle

Lotka (1922) was probably the first to suggest that the thermodynamic laws may have a link with biological evolution. He argues that "in the struggle for existence, the advantage must go to those organisms whose energy-capturing devices are most efficient in directing available energy into channels favorable to the preservation of the species" (*Ibid.*, p. 147). Well aware of the concept of natural selection set forth by Darwin (1859), Lotka sees two complementary, and possibly simultaneous, strategies for competing organisms: (i) energy efficiency gains, and (ii) innovative specialization to seize new energy opportunities. According to Lotka, in the case of significant contest among species for the same energy flows, natural selection favors organisms that can more efficiently harvest the contested resources compared to their competitors. However, in the presence of untapped energy flows, natural selection favors organisms that find new ways to utilize virgin energy resources for which no competition exists because other species are simply not capable of exploiting them. Accordingly, "the law of selection becomes also the law of evolution: Evolution, in these circumstances, proceeds in such direction as to make the total energy flux through the system a maximum compatible with the constraints" (Lotka, 1922, p. 149).

From the above *Lotka Principles*, several scholars have tried to derive general thermodynamic laws of evolution. Since Lotka (1922, p. 149) himself stresses that "the physical quantity in question is of the dimensions of power, or energy per unit time," Odum and Pinkerton (1955, p. 332) propose that natural "systems perform at an optimum efficiency for maximum power output, which is always less than the maximum efficiency." Hence, Odum and Pinkerton (1955, p. 332) assert that "under the appropriate conditions, maximum power output is the criterion for the survival of many kinds of systems, both living and non-living." In other words, they "are taking 'survival of the fittest' to mean persistence of those forms which can command the greatest useful energy per unit time (power output)." In addition to being invalidated on many scales by both models and empirical data (Mansson and McGlade, 1993), Odum's *Maximum Power Principle* loses the behavioral basis of the Lotka Principles, namely, the effect of competition and natural selection acting on individuals.

A sorting mechanism based on natural selection is also absent from Schneider and Kay's (1994) theory of life evolution based on a reformulation of the second law of thermodynamics. These authors state that "as systems are moved away from equilibrium they will take advantage of all available means to resist externally implied gradients" (*Ibid.*, p. 26). Based on this principle, Schneider and Kay (1994, p. 38) further argue that as "ecosystems develop or mature, they should increase their total dissipation, and should develop more complex structures with greater diversity and more hierarchical levels to abet energy degradation. Species which survive in ecosystems are those that funnel energy into their own production and reproduction and contribute to autocatalytic processes which increase the total dissipation of the ecosystem. In short, ecosystems develop in a way which systematically increases their ability to degrade the incoming solar energy."

To a varying degree, the absence of mechanisms for individual selection is also a characteristic of other formulation of general thermodynamic laws of life evolution based on the extremization (minimization or maximization) of thermodynamic variables. Moreover, most of these general thermodynamic laws of biological evolution, that we shall now review, are based on concepts of entropy that are often different from each other.

2.2.2 Maximum, Minimum, and Min-Max entropy production principles

As a precursor, Schrödinger (1945) thought that living systems were embodiments of negative entropy or *negentropy*, which organisms extract from the environment and feed upon to stay in a state of low entropy (high orderliness). More recently, the thermodynamics-life-evolution nexus has seen a resurgence of studies proposing a general law based on the pioneering work of Ziegler (1963). This theory has received different but strictly equivalent names, such as the *Law of Maximum Entropy Production* (LMEP) of Swenson (1989, 2010), the *Maximum Entropy Production Principle* (MEPP) of Martyushev and Seleznev (2006, 2014), and the *Principle of Maximum Entropy Production* (MEP) of Kleidon (2010, 2012). In these different studies, scholars stipulate that thermodynamic processes in far-from-equilibrium conditions tend towards steady states at which they dissipate energy and produce entropy at the maximum possible rate. Furthermore, Martyushev and Seleznev (2006) formally show that the principle of maximum entropy production of far-from-equilibrium systems and the minimum entropy production principle of near-equilibrium systems do not contradict each other as the latter is a consequence of the former.[12]

---

[12] Yen et al. (2014) provide a review of all thermodynamic extremal principles developed in the context of ecological systems. Apart from maximum entropy, alternatives include the maximum exergy storage of Jorgensen and Svirezhev (2004), the maximum ascendency of Ulanowicz (2003), the maximum 'E intensity' of Milewski and Mills (2010), and the maximum rate of cycling of Morowitz (1979). Furthermore, Yen et al. (2014) show that all these thermodynamic extremal principles are consistent with the maximum entropy production principle, including the maximum power principle of Odum and Pinkerton (1955), and the maximum rate of gradient

This general principle of maximum entropy production has recently received empirical support in physics, chemistry, climatology, oceanography, and biology. For instance, Kleidon (2012) applies it to explain the functioning of complex climate models. Dewar (2010) uses it to unify the different objective functions that plants optimize with respect to their environmental constraints. Moreover, del Jesus et al. (2012) uses the maximum entropy production principle to predict the spatial distribution of functional vegetation types at the scale of a river basin. Regarding the emergence and evolution of life, Swenson (2010) posits that self-organization is a process of selection governed by the law of maximum entropy production, and that consequently, natural selection is a special case where the components can replicate. Kleidon (2010, 2012) goes further in asserting that the principle of maximum entropy production underlies the whole evolution of the Earth system. More precisely, he argues that life should be viewed "as being the means to transform many aspects of planet Earth to states even further away from thermodynamic equilibrium than is possible by purely abiotic means. In this perspective pockets of low-entropy life emerge from the overall trend of the Earth system to increase the entropy of the universe at the fastest possible rate."

However, in analogy to ontogenic development, several authors have observed that energy throughput follows a particular pattern according to the development stage of ecosystems (Brooks and Wiley, 1986; Bruelisauer et al., 1996; Johnson, 1990; Schneider, 1988; Wicken, 1980). Energy throughput increases in the early stages of the development of ecosystems where resource limitations are not binding. However, in the latter stages of the development of ecosystems where resources are limited, the amount of biomass is still growing, but one can observe a decrease of the specific energy dissipation (i.e., energy dissipation per mass unit). Moreover, in ecological niches of mature ecosystems, natural selection seems to favor species with increasing efficiencies in resource use (Southwood, 1981). Hence, these authors argued for a maximum energy dissipation, or maximum entropy production principle, in the early stage of evolution of living systems (be it ontogenic, phylogenic, or ecological), followed in later stages of development by a minimum specific energy dissipation principle. In addition to empirical testing of this phenomenon on lakes and estuaries, Aoki (2006) label this phenomenon the *Min–Max Principle of Entropy Production with Time*.

2.2.3 Emergent optimality under constraints rather than extremization

Several scholars have argued against a general law of system evolution based on the extremization of a thermodynamic variable. In particular, Buenstorf (2000) argues that increasing energy flows and increasing energy efficiencies within ecosystems can be seen as the outcome of the self-organization of dissipative structures which emerge in systems characterized by competitive feedback between their elements. As a consequence, there is no need for an explicit underlying supra-law based on the extremization of a thermodynamic variable that deterministically governs life evolution. In addition, Buenstorf (2000) remarks that such a conceptual difference is far more in line with the original opinion of Lotka, who did not claim that observable patterns of increasing energy throughput should be seen as a general law of evolution: "It is *not* lawful to infer immediately that evolution tends thus to make this energy flux a maximum. For in evolution two kinds of influences are at work: selecting influences, and generating influences. The former select, the latter furnish the material for selection." (Lotka, 1922, p. 148, emphasis added). Batten et al. (2008) specify this last idea by a clear statement: self-organization proposes what selection subsequently disposes.[13]

Following these criticisms, Holdaway et al. (2010) suggest that the maximum entropy production principle may be interpreted as an emergent characteristic that is the result of natural selection pressures for maximizing the flux (and dissipation) of energy. In other words, the MEP principle provides the explicit criteria linking selection at the individual level with emergent and directional properties at higher levels of organization such as communities and ecosystems. Moreover, following the intuitions of studies already presented here, Holdaway et al. (2010) speculate that there are three different MEP selection pressures at work during the development of an ecosystem. The first maximizes the rate at which entropy production increases through successional time, which, initially at least, is achieved via rapid colonization of species with fast individual/population growth rates called '*r*-selected species.' The second selection component of MEP is for maximum sustained entropy production during maturity. This is achieved via maximizing biomass and structural complexity, which necessarily involves longer-lived, larger, slower-growing organisms named '*K*-

---

degradation of Schneider and Kay (1994).

[13] Weber et al. (1989) and Depew and Weber (1995) also provide comprehensive discussions on the interplay of Darwinian natural selection, self-organization, and the thermodynamic laws. In particular, they argued that a thermodynamic approach of living systems released Darwinism from its deterministic Newtonian anchoring because dissipative structures are characterized by tendencies towards spontaneous self-organization and non-deterministic bifurcations.

selected species.' The third selection component is for stress-tolerating species extending the effective mature phase and postponing retrogression of the ecosystem. Thus, given the existence of ecological disturbance in the landscape, the MEP theory leads to the prediction that there should be long-term co-existence of *r*- and *K*-selected species, a directional transition from *r*- to *K*-selected species during succession, and increasing predominance of *K*-selected species in ecosystems with longer disturbance return times.

With only minor changes to the work of Sciubba (2011), I provide in **Proposition 1** a synthesis for all previous ideas.

PROPOSITION 1. *Given N systems (e.g., species) interacting both among themselves and with a common environment at time t_0, and given that for $t > t_0$ the environment supplies a surplus of exergy, the $M < N$ systems that shall prevail (i.e., survive) for very large values of t are those that are capable of tapping the maximum exergy rate with the minimum exergy destruction (entropy generation), for each given conversion task (process) and under the boundary conditions (i.e. constraints) prevailing between t_0 and t.*

Such an attempt to reconcile the thermodynamic extremal principles with natural selection fall short on the more engaged criticism of Corning (2002, 2014). According to Corning, "the problem with various orthogenetic theories is that they invoke overriding deterministic influences, rather than recognizing that biological evolution is at once shaped by the laws of physics (and thermodynamics) and yet is also historically determined, context-specific and highly contingent. Biological evolution involves an open-ended, cumulative, opportunistic 'trial-and-success' (or failure) process—an 'economic' process in which local conditions and competitive forces play a key part" (Corning, 2014, p. 187). And indeed, for Corning (2002, p. 65), the role of energy in evolution can be best defined and understood in economic terms: "living systems do not simply absorb and utilize available energy without cost. They must 'capture' the energy required to build biomass and do work; they must invest energy in development, maintenance, reproduction and further evolution. To put it badly, life is a contingent and labor-intensive activity, and the energetic benefits must outweigh the costs (inclusive of entropy) if the system is to survive."[14]

3 Analysis: the economy in a thermo-evolutionary perspective

In this section, we use the definitions, laws, corollaries, and the Proposition 1 of Section 2 to explain the evolutionary relationship between energy capture, technological change and growth within the economic system. This theoretical analysis will then be placed in an historical context in Section 4.

3.1 The economy as an energy-dissipating system and the conditions for economic value creation

3.1.1 The misguided reasons for the omission of energy in conventional growth theories

Assigning a modest importance to energy in explaining growth is conventionally justified by its apparent small share in modern national income. Indeed, the so-called 'cost share theorem' implies that, if the function aggregating the production factors into a national product (GDP) is homogeneous of degree one, the output elasticities of production factors equal their income allocation in total GDP. Consequently, GDP elasticities with respect to labor and capital are generally set to 0.7 and 0.3 according to their respective empirical shares of GDP, while energy is neglected because its cost usually represents around 5% of the national income. Even when it is considered as a production factor, the output elasticity of energy is therefore set to 0.05 in standard growth models, such that labor and capital remain the most important production factors. However, it can be argued that this 'cost share theorem' is fallacious for several reasons.

---

[14] The *Constructal law*, which is supposed to be an encompassing formulation of all thermodynamics concepts and ideas, including the maximum entropy production principle, was intentionally not discussed in Section 2. Bejan (1997) formulates his Constructal law as follows: "For a finite-size flow system to persist in time (to live), its configuration must evolve in such a way that provides greater and greater access to the currents that flow through it." This supra-law is supposed to explain the dynamics of all physical, biological, or economic/cultural systems. However, when dealing with the economic process as in Bejan and Lorente (2011), the Constructal law seems to not bring anything new and to not be very useful. Basically, it says that energy is important for economic growth and that things happen the way they happen because it is the most logical/easiest way they can happen given existing constraints. The Constructal law gives the impression of being the modern reformulation of an old idea rather than a new path-breaking theory as claimed by its author. Hence, Spencer (1897, p. 249) already stated that "when we contemplate a society as an organism, and observe the direction of its growth, we find this direction to be that in which the average of opposing forces is the least. Its units have energies to be expended in self-maintenance and reproduction."

First of all, the cost share theorem results from an Euler–Lagrange optimization assuming that all perfectly competitive markets are at equilibrium for an economy only composed of small price-taking firms. Consequently, the cost share theorem is only true at the margin for a fictive economy, so that output elasticities with respect to a given input only follow the income cost share of those inputs for small shocks. Moreover, by construction, GDP is allocated exclusively to capital and labor payments. Accordingly, energy expenditure is itself only made of capital and labor payments (plus temporary market powers).[15]

But the fact that energy expenditures are relatively low in developed economies does not imply that energy *per se* is of no importance for economic growth. This fact was well illustrated by the first energy crisis of 1973, during which a 5% decrease in oil availability induced a 3% GDP loss in the US. A much greater effect than the mere 0.25% that the cost share theorem predicted. Reviewing how energy price shocks affect the US economy, Kilian (2008) asserts that rising energy prices cause both a reduction in aggregate demand, and a shift in consumer expenditures, which in turn create a ripple effect throughout the economy. The effects of energy price shocks on economic output are hence larger than suggested by the small share of energy in income. This means that the output elasticity of energy of 0.05 generally presupposed in standard macroeconomics is underestimated, whereas the output elasticities of capital and labor of 0.3 and 0.7, respectively, are overestimated.

Furthermore, energy expenditures used to account for up to 50–70% of national income in pre-industrial, low-growth economies, and it is probably only thanks to the use of previously untapped, concentrated—and consequently cheap—fossil fuels that this value gradually declined below 10% (Fizaine and Court, 2016). Kander et al. (2013, p. 7) indeed assert that the "decrease in the cost of energy, at the same time that much greater quantities of it could be supplied, has allowed vast reserves of capital to be employed, delivering other kinds of goods and services rather than covering only basic energetic needs" as was the case during pre-modern times. Hence, the small cost share of energy in modern economies is not a sign of its worthlessness, but on the contrary, it might indicate the crucial importance that concentrated fossil energy has on modern economic growth.

Finally, the ground breaking work of Kümmel and Lindenberger (2014) shows that whenever *hard* technological constraints—corresponding to "limits to automation" and "limits to capacity utilization"—are taken into account, shadow prices add up to usual factor costs, implying that the cost share theorem simply no longer holds.[16] In summary, pure financial expenditure accounting downplays the role of energy because it does not take into account the interrelation between energy and specific technological developments that have been crucial to generate an expansion of many sectors of the economy (e.g., the design of modern transport systems and the associated suburban habitat have been wholly dependent on the internal combustion engine (ICE) fueled by gasoline; similarly electric or gas-fired heating and cooling systems have made domestic and office life bearable in a variety of climates).

3.1.2 The economy as an energy-dissipating and material-transforming system

Economic growth theories in which energy is absent can be summarized as follows. Households provide routine labor and human capital to firms in exchange for wages and capital interests/rents (factor payments). An intermediation sector (banks) is in charge of households' savings and the creation of financial capital. Institutions shape the availability of private and public investments that allow firms to invest in physical capital. Institutions also influence the research and development (R&D) productivity, and the increase in human capital through education. Firms then combine the different factors of production (physical capital, routine labor, and human capital) to produce goods and services that households buy according to their utility function in return for consumption expenditure (Fig. 1a).

PROPOSITION 2. *In any theory of economic growth which omits the role of energy as a production factor or as a constraint, the economy is an isolated system in which cycles of factors-against-payments can occur indefinitely without the need for any energy input.*

COROLLARY 3. *In such a paradigm, the economic system is a perpetual motion machine of the first kind; that is, a conceptual artifact that cannot possibly exist in the real world.*

---

[15] For instance, the price of gasoline is constituted of capital interest, labor payment, and various taxes that are required to extract and refine the crude oil provided free-of-charge by nature.

[16] Besides, Ayres et al. (2013) argue that there are also some *soft* constraints—corresponding to social, financial, organizational, or legal restrictions—that determine additional limits to substitution possibilities between inputs over time.

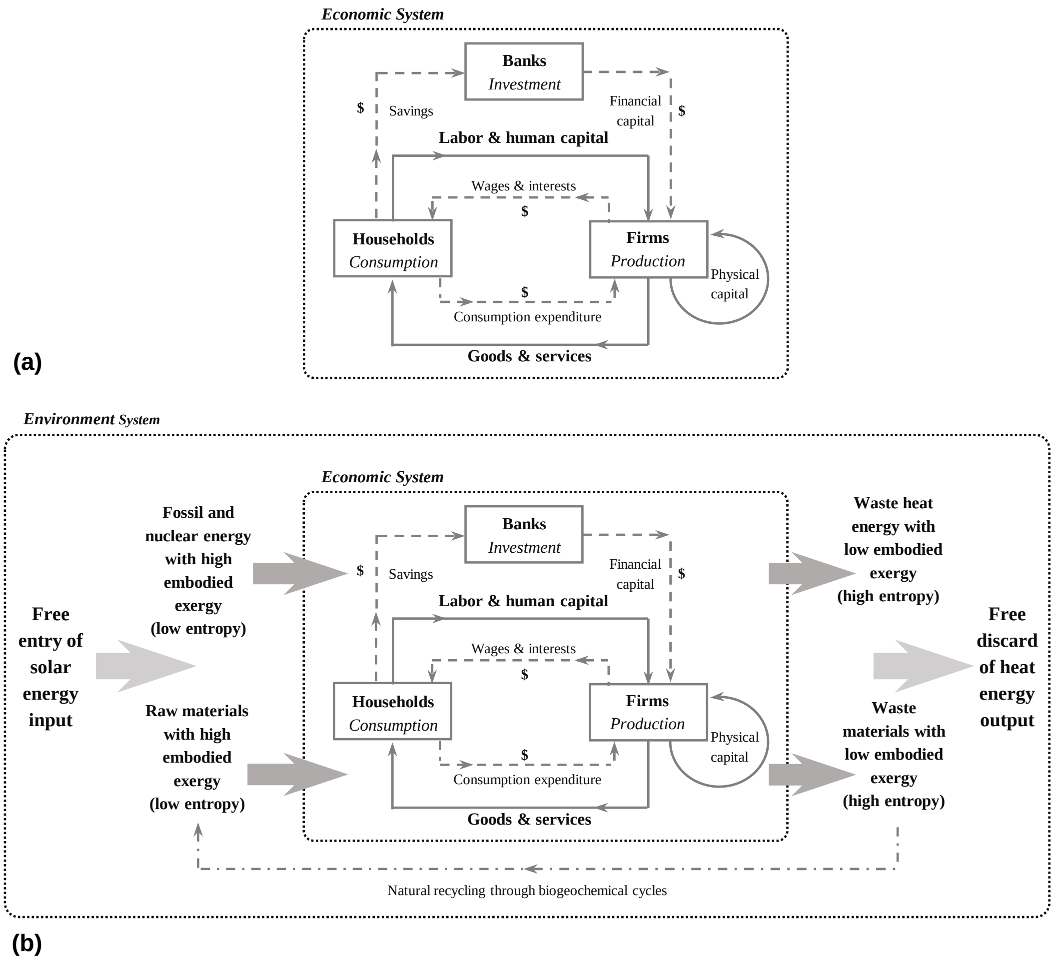

Figure 1: (a) Mainstream economics view of the economic system as a perpetual motion machine of the first kind versus (b) ecological economics view of the environment–economy system as a real motion machine (for graphical simplification, the role of the government as a tax-raiser, investor, and regulator is not shown in this figure).

The proof of **Proposition 2** is clear considering the brief introduction to thermodynamics given in Section 2.1. The pioneering works of Odum (1971), Georgescu-Roegen (1971), and Daly (1985) have shown that in order to comply with reality, the economic system described above should in fact be conceptualized as an open, far-from-equilibrium system enclosed in the surrounding environmental system. In such a perspective, a unidirectional throughput of material-energy is indispensable to allow for the continuous factors-against-payments cycling of the economic system. Within such a framework, the energy-dissipating/exergy-degrading/entropy-producing economic system respects the laws of thermodynamics which are otherwise violated by *abiophysical* growth theories that do not correctly take energy into account. Indeed, the second law of thermodynamics stipulates that exergy must be degraded through the functioning of the economic system since it is composed of multiple irreversible processes that each implies some entropy creation.

More precisely, the economic system converts low entropy/high exergy raw materials into relatively lower entropy/higher exergy products on the one hand, and high entropy/low exergy wastes on the other.[17] This non-spontaneous decrease in entropy (increase in order) from raw materials to products is only possible because of the much higher entropy production (decrease in order) that results from the degradation of the exergy embodied in the energy flow extracted from the environment and going through the economic system. Energy enters the economy as an input of high quality (high exergy content) in the form of direct

---

[17] On this last point, Kümmel (1989) and Ayres (1998a) have proposed to use entropy disturbance as a measure of pollution. The investigation of this idea is beyond the scope of the present article.

solar energy (biomass and water/wind flows) and indirect stored solar energy in the form of fossil fuels and nuclear energy in industrial stages. Those energy forms are ultimately dissipated into a lower-quality (lower exergy content) heat outputs that potentially contain no exergy (and thus zero ability to generate work) if their temperature is the same as the encompassing environment (Fig. 1b). The above biophysical description of the economic process calls for a first research recommendation.

RESEARCH RECOMMENDATION 1. *Exergy should always be present in macroeconomic models, either as a proper production factor, or as a constraint. Otherwise, the role of other factors in explaining macroeconomic phenomena will be overestimated. This could only result in misguided policy recommendations.*

The following question arises from the above research recommendation; which should be a production factor: primary exergy, final exergy, or useful exergy? To the author's mind, primary, final, and useful exergy represent the same production factor with varying levels of embodied technological progress. Hence, primary exergy could be considered as the "raw" estimate of exergy, and its evolution over time only measures the quantitative contribution of exergy to growth. Final and useful exergy flows have a lower absolute magnitude compared to primary exergy, but because they are usually "affected by" positive technological progress, they tend to increase more rapidly over time compared to primary exergy (when normalization is done for the same year). So the evolution of final and useful exergy also takes into account the qualitative contribution to growth of the technological progress that has specifically affected primary exergy refining. In the same way, routine labor is not a better production factor than human capital. They simply do not represent the same things.

Land, or rather its three-dimensional extension space (i.e., the bio-geosphere), is a production site but not an active factor as long as its capacity to absorb polluting emissions is not binding (Kümmel et al., 2010). In the same way, raw materials remain passive during the production process where their atoms or electrons are just rearranged by the combination of capital, labor, and exergy into the configurations required to generate a product (Kümmel et al., 2002). Hence, raw materials do not contribute actively to the generation of value added and can consequently be ignored, as long as their finite nature does not constrain growth. In summary, if both land and raw materials are not production factors, they must be seen as potential constraints.

3.1.3 The three conditions for economic value creation

Beinhocker (2006, pp. 302–315) defines three conditions that taken together summarize the biophysical description of the economic process given in the above section.

CONDITION 1. *All products and services with economic value are produced by thermodynamically irreversible transformations, including transactions between agents.*

The thermodynamic irreversibility of physical transformation is not in doubt, but one could argue that the irreversibility of transactions between agents is less obvious. Nevertheless, it surely takes energy to reverse a trade on the request of one (or both) of the involved parties if he considers that it was made on faulty information. Thermodynamic irreversibility is a necessary but not a sufficient condition for economic value creation. It is indeed not hard to imagine irreversible processes that are value destroying: hurricanes, explosions, and incompetent management teams all destroy value, and it surely takes energy to reverse such unfortunate events. So we obviously need a second condition.

CONDITION 2. *All value-creating economic transformations and transactions reduce entropy locally within the economic system, while increasing net entropy globally.*

This second condition enables a distinction to be made between an irreversible locally entropy-*in*creasing transformation that does not create value (i.e., throwing a rock through a window) and an irreversible locally entropy-*de*creasing transformation that does create value (i.e., repairing the broken window). As for irreversibility, local entropy decrease at the expense of global net entropy increase appears to be necessary for something to have economic value, but defining which kinds of order are valuable and which kinds are not is rather subjective and depends on peoples' preferences (formalized by a utility function is economics). Thus, in order to prevent the above two conditions from implying a value theory based on energy, a third condition is needed.

CONDITION 3. *Value-creating economic transformations and transactions produce artifacts or actions that are fit for a given human purpose (i.e. respond to a more or less explicit need).*

Explaining the origins of human preferences and their change over time is of course beyond the scope of the present article. Let us just state that evolutionary psychology claims that many of our behaviors are the way they are because they helped our ancestors survive and reproduce throughout the ages. In this process, genes express themselves to get to the next generation, but the environment also shapes behaviors.[18]

3.2 Definitions of technology and the unit of selection

3.2.1 Distinguishing physical and social technologies

The output resulting from the aggregation of labor, physical capital, and human capital in a production function is usually significantly lower than the historical GDP (Ayres and Warr, 2009, p. 189). Early observations have shown that such a gap, also called the *Solow residual*, between estimated and empirical GDP is increasing over time. This "measure of our ignorance" as put by Abramovitz (1956, p. 11) has been arbitrarily attributed to technological change, i.e., change in the productivity with which inputs units of physical capital, human capital, and routine labor are combined to produce an output unit. Hence, in the standard sense, technological change is a catch-all concept called total factor productivity (TFP) that includes the division and organization of labor, the skill improvements of laborers, the efficiency of other markets, the contribution of information and communication technologies, and also the beneficial effects of inclusive institutions (which, for example, protect private property rights and consequently incentivize innovation and R&D).[19]

In order to clarify the notion of technology, Nelson and Winter (1982) proposed to make a distinction between *physical* and *social technologies*. The definitions of these concepts reformulated by Beinhocker (2006, pp. 244 and 266, respectively) need only minor modifications (underlined for the sake of precision) to suit the thermo-evolutionary perspective of the present article.

DEFINITION 8. *Physical technologies are methods and designs for consuming exergy to transform matter, energy, and information from one state into another (or to change the geographic location of these elements) in pursuit of a goal.*

DEFINITION 9. *Social technologies are methods, designs, and rules for organizing people in pursuit of a goal.*

Under such definitions, physical technologies are characterized by the efficiency with which primary exergy contained in energy flows extracted from renewable sources (biomass, geothermal heat, water, wind, solar, tide, and wave) and non-renewable stocks (fossil fuels or fissile materials such as uranium) are first converted into final exergy forms (liquid fuels, gas, electricity) before suffering a second conversion into useful exergy (in the form of mechanical power, heat, and light). Depending on the physical scope under consideration, the measure of physical technological progress is thus a percentage, expressing the primary-to-final and final-to-useful exergy conversion efficiency. National estimates of the exergy conversion efficiencies of energy systems have been provided by several studies that will be discussed in Section 4.2. As it will be useful in the description of the historical role of energy for economic growth given in Section 4.1, it is worth highlighting here that physical technological change necessarily comes from the interaction of pure and applied knowledge. The former originates from fundamental scientific research, whereas the latter is derived from practical research and development (R&D).

Social technologies are logically less tangible than physical technologies. An emblematic but non-exhaustive list of examples include villages, armies, matrix organization in firms and industrial processes, paper money, the rule of law, and just-in-time inventory management. Accordingly, institutions, which many economists consider as the most important cause of economic development in the long run, can be considered as an important subclass of social technologies (Acemoglu and Robinson, 2012; North, 2005). More precisely, Nelson (2005) claims that under most conceptions of the term, institutions can be understood as generally employed relatively standardized social technologies (the way the game is played), or the forces that strongly mold and support the action pattern (the rules of the game). Another fundamental subclass of social technologies are *family systems*, the evolution of which has had a fundamental role on the determination of (i) political

---

[18] The co-evolution between genetic and cultural elements has been intensively explored since the 1980s, recent references include Richerson and Boyd (2005) and Jablonka and Lamb (2014). See also Vermeij (2009) on the fact that intentionality, preferences, and purposive utility are surely better developed in humans than in other living beings but are not unique to the former.

[19] Accordingly, if the aggregate production function is to match the historical GDP pattern more closely, a time-dependent multiplier (generally noted A) representing TFP must be added to take into account the technological progress of the economy. Moreover, in empirical growth studies, TFP contains desired components such as the effect of technical and institutional innovations, but it also includes unwanted elements such as measurement errors, omitted variables, aggregation bias, and model specifications.

regimes, as qualitatively argued by Todd (1985, 1990) and empirically supported by Mamadouh (1999) and Dilli (2016); and (ii) comparative economic performances, as qualitatively claimed by Todd (1987, 2017) and empirically supported by Duranton et al. (2008) and Le Bris (2016). The co-evolution of institutions and family systems is described by Greif (2006) and Todd (2017) among others.

Disentangling the respective role of physical and social technologies logically calls for a second research recommendation.

RESEARCH RECOMMENDATION 2. *As much as possible, a distinction between physical and social technological progress should be made in theoretical and empirical macroeconomic studies. Not performing such a distinction (i.e., assuming TFP instead) would result in spurious assessment of the relative importances over time of technological change and the increase in production factors, which could only lead to poor policy suggestions.*

3.2.2 Unit of selection and the universal algorithm of evolution

To give an evolutionary content to the thermodynamic perspective of the economic system given above, we must necessarily speak of the selection process and the unit it acts upon.[20] The concept of *routine* initially developed by Nelson and Winter (1982) has been extensively theorized as the unit of selection of the evolutionary economic process. Nevertheless, the literature review of Becker (2004) shows that the definitions of routine are plural so that a unique definition of this concept is necessarily incomplete. In order to provide the most accurate possible definition of the unit of selection, Beinhocker's (2006, pp. 283 and 235) concept of 'module of business plan' is slightly reframed into 'module of routine' to accommodate the widespread routine-related literature.[21]

DEFINITION 10. *A module is a component of routine that has provided in the past, or could provide in the future, a basis for differential selection between different organizations in a competitive environment.*

DEFINITION 11. *A routine is a schemata that can be formally written or simply exists in people's minds. It generally contains the description of an organization's purpose, its strategy for competing, its production plans and services, the types of physical and social technologies it requires.*

As summarized in **Proposition 3**, the economic system changes as the universal algorithm of evolution 'searches for' modules that best fit the prevailing external constraints through the process of variation, selection, and replication in the substrate of routines. Variation occurs as people continually invent, experiment with, and tinker with modules that ultimately generate new organizational routines. Selection works at multiple levels in the economy, causing some routines to succeed and others to fail. Replication occurs in economic systems as successful modules of routines are rewarded with more resources and are widely copied. This evolutionary algorithm of variation, selection, and replication works on three design spaces that, respec-

---

[20] This issue is the subject of an important debate among evolutionary economists. 'General Darwinism' supported by Hodgson (2002) and Knudsen (2002) is a core set of Darwinian principles that, along with auxiliary explanations specific to each scientific domain, is considered applicable to a wide range of phenomena. Hence, proponents of this theory argue that evolutionary aspects of the biological and the cultural spheres both involve the general Darwinian principles of variation, selection, and replication. On the contrary, the 'continuity hypothesis' of Witt (2003) and Cordes (2006) rejects the application of abstract principles derived from Darwinism to socio-economic evolution. According to this perspective, at some point in time Darwinian evolutionary theory lost its power to explain human behavior. This means that after a period of co-evolution with natural evolution, cultural evolution eventually allowed forms of human behavior to emerge that entailed a strong relative reproductive success, reducing selection pressure significantly and increasing behavioral variety. In particular, the 'continuity hypothesis' argues that human goal-directed behavior renders the functioning of the three mechanisms of selection, variation, and replication interdependent rather than independent as in the biological world. Moreover, purposeful human action, the deliberate choosing of certain entities, gives rise to 'directional' change in cultural evolution. By contrast, Darwinian natural selection is not carried out by intelligent agents who purposefully choose among design possibilities. As a result, the processes and criteria of economic/cultural selection are very different from natural Darwinian selection affecting biological organisms (Cordes, 2006, p. 538). 'Generalized Darwinism' is surely a framework of higher-level abstraction than the 'continuity hypothesis,' but rather than their opposition, future work will probably show the complementarity of these theories.

[21] For Kauffman (1993) an entity becomes individual-like, and therefore subject to selection and adaptation, when the rate of change among its components is less than the rate of sorting among like entities, that is, when the whole is intact long enough not to dissolve into chaos. According to Vermeij (2009), the criteria for entities as units of evolution are: the ability to multiply, inheritance of traits, and variation in these traits among individuals. Accordingly, organisms qualify as evolutionary units but larger and more intangible entities such as coalitions, species, coherent societies, languages, cultures, and even some ecosystems can also be understood as evolutionary units. In such circumstance, units of selection are diverse and change over the course of evolution, which complicate the overall analysis of this phenomenon. The definition of the unit of selection in the evolutionary economic process that I choose here as 'a module of routine' is so general that it circumvents this issue.

tively, contain the vast diversity of physical technologies, social technologies, and routines. The co-evolution of these three elements generates patterns of innovation, growth, and creative destruction.[22]

PROPOSITION 3. *Under prevailing, but surely changing, external constraints, economic evolution is the result of the co-evolution across three design spaces: physical technologies (designs and processes for degrading exergy to transform matter, energy, and information, or transport these elements, in pursuit of a goal); social technologies (designs, processes, and rules that humans use to organize themselves in pursuit of a goal); and finally routines that play the critical role of melding physical and social technologies together under a strategy, and then operationally expressing the resulting designs in the economic world.*

As already highlighted by Buenstorf (2000), economic systems do not intentionally seek to maximize useful exergy throughput and its associated entropy production, but as complex adaptive systems, such patterns emerge from the interaction of self-organization and selection. Combining **Condition 1**, **2**, and **3** with **Proposition 3** yields the following **Proposition 4** (adapted from Raine et al. (2006) by replacing the word 'Rules' by 'Routines' to better comply with the vocabulary of the present paper). **Corollary 4** and **5** are both original in the present article.

PROPOSITION 4. *As economic systems grow and develop, they should increase their total dissipation, develop more complex structures with greater energy flow, increase their cycling activity, develop higher diversity, and generate more hierarchic levels, all to abet energy degradation. Routines which survive in economic systems are those that funnel energy into their own production and reproduction and contribute to autocatalytic processes which increase the total dissipation of the system.*

COROLLARY 4. *The differential economic growth of nations depends on their evolving relative capacities to increase useful exergy throughput given (i) the respective external constraints set by their environment (notably in terms of exergy availability), and (ii) the internal history-dependent performances of their physical and social technologies, that also define their multilateral exchanges of raw materials, manufactured goods, and financial assets.*

COROLLARY 5. *A transition between economic growth regimes should be associated with a significant modification of energy systems and energy capture levels. Such a transition between different economic growth regimes would typically be preceded by changing external constraints and emerging internal factors.*

4 Discussion: energy, technology, and growth in history

The thermo-evolutionary description of the economic process given in Section 3 can now receive some historical context. The first part of this section focuses on the analysis of the transition from foraging to farming societies on the one hand, and from farming to industrial societies on the other. The second part of this section deals with the growth slowdown of the global economic engine after the 1970s. To carry out these discussions, we must first analyze the interaction between *General Purpose Technologies* (GPTs) and energy requirements.

4.1 The evolution from foraging to modern economies

4.1.1 General Purpose Technologies and energy requirements

Physical and social technologies that have a particularly significant influence on the economy have received different names [e.g., Baran and Sweezy's (1966) 'epoch-making innovations,' Georgescu-Roegen's (1986) 'Promethean techniques,' Mokyr's (1990) 'macro inventions,' and Gordon's (2016) 'great inventions'], but the term *General Purpose Technology* (GPT) is probably the most widely used now. According to Lipsey et al. (2005, p. 98), a GPT "is a single generic technology, recognizable as such over its whole lifetime, that initially has much scope for improvement and eventually comes to be widely used, to have many uses, and to have many spillover effects." Lipsey et al. (2005, p. 97) further stress that GPTs are typically use-radical but not

---

[22] It is interesting to note that Beinhocker (2006, p. 294) advocates market economies, not because they are the best method for allocating financial resources in a way that optimizes social welfare under conditions of equilibrium as neoclassical economics supposes it, but because they offer an evolutionary search mechanism that incentivizes deductive-tinkering leading to differentiation (of routines' module) and then provides a fitness function upon which economic selection can act.

technology-radical, meaning that GPTs do not stand out from other technologies because of a revolutionary technological basis, but rather because of outstanding adaptations and applications with other technologies and sectors of the economy. GPTs are typically not born in their final form, so they often start off as something we would never call a GPT, and then develop into something that transforms an entire economy. Hence, the considerable scope of improvement of GPTs is explored as their range and variety of use increases, which generates knowledge and practical spillovers to other technologies and organizational processes.

Table 1: Transforming GPTs, adapted from Lipsey et al. (2005, p. 132).

No.	GPT's name	Date of widespread use	Class
1	Stone, bone, and wood tools [a]	Before 200,000 BCE [b]	Material
2	Mastery of fire [a]	Before 200,000 BCE [b]	Energy
3	Domestication of plants	9000–8000 BCE	Energy
4	Domestication of animals	8500–7500 BCE	Energy/transport
5	Smelting of copper ore	8000–7000 BCE	Material
6	Wheel	4000–3000 BCE	Transport
7	Writing	3400–3200 BCE	Information
8	Bronze	2800 BCE	Material
9	Iron	1200 BCE	Material
10	Waterwheel	Early medieval period	Energy
11	Three-mastered sailing ship	Fifteenth century	Transport
12	Printing	Sixteenth century	Information
13	Steam engine	Late eighteenth to early nineteenth century	Energy
14	Factory system	Late eighteenth to early nineteenth century	Organization
15	Railway	Mid-nineteenth century	Transport
16	Iron steamship	Mid-nineteenth century	Transport
17	Internal combustion engine	Late nineteenth century	Energy
18	Electricity	Late nineteenth century	Energy
19	Petrochemistry [a]	Twentieth century	Material
20	Mass production (continuous process)	Twentieth century	Organization
21	Computer	Twentieth century	Information
22	Lean production	Twentieth century	Organization
23	Internet	Twentieth century	Information
24	Biotechnology [c]	Sometime in the twenty-first century	Material/information
25	Nanotechnology [c]	Sometime in the twenty-first century	Material/information

[a] Stone Age tools, mastery of fire, and petrochemistry are not mentioned in the original survey of Lipsey et al. (2005, p.132).

[b] 'Before 200,000 BCE' is used because defining a date of widespread use appears impossible for Stone Age tools and mastery of fire.

Those technologies were even used by hominids, such as *Homo habilis* and *Homo erectus*, who predated *Homo sapiens*.

[c] Of course, the GPT status of biotechnology and nanotechnology are for now purely speculative and have yet to be confirmed.

Table 1 gives a list of historical transforming GPTs adapted from Lipsey et al. (2005, p. 132). The most striking fact of this table is that, even if only seven out of the total twenty-five GPTs of this list are directly energy-related, all eighteen other GPTs are indirectly associated with energy. More precisely, energy-related GPTs are invariably associated with a new energy resource, and consequently, they imply a drastic change in the energy supply in terms of absolute quantities and relative shares of the different energy resources. On the contrary, all energy-unrelated GPTs (i.e., transport, material, organization, and information GPTs) depend on the extensive use of a preexisting energy source or carrier, and consequently, they generate a more progressive change of the energy supply. Moreover, if the seven energy-related GPTs are logically associated with a direct increasing energy consumption, the eighteen energy-unrelated GPTs also necessitate or imply an increasing energy consumption to deserve their GPT status. Hence, energy GPTs (mastery of fire, the domestication of plants and animals, the waterwheel, the steam engine, the internal combustion engine, and electricity) have directly implied an increase in the level of energy consumed by societies. Transport GPTs (animals, the wheel, sailing ships, railways, and iron steamships) were naturally used in combination with energy to propel people and goods. Material GPTs (Stone Age tools, iron and bronze smelting, and petrochemistry) inevitably required energy to be operationalized. The huge reshaping of the economic process brought by organizational GPTs (factory system, mass production, lean production) necessarily led to substantial increases in energy consumption. To an equal extent, the spread of informational GPTs (writing, printing, computing, and the internet) must be supported by increasing energy capture.

The fact that the level of development of societies in terms of technology, GPTs in particular, and standards of living is closely linked to their level of energy consumption has never been so well highlighted as in the graph of Cook (1971) reproduced in Figure 2.

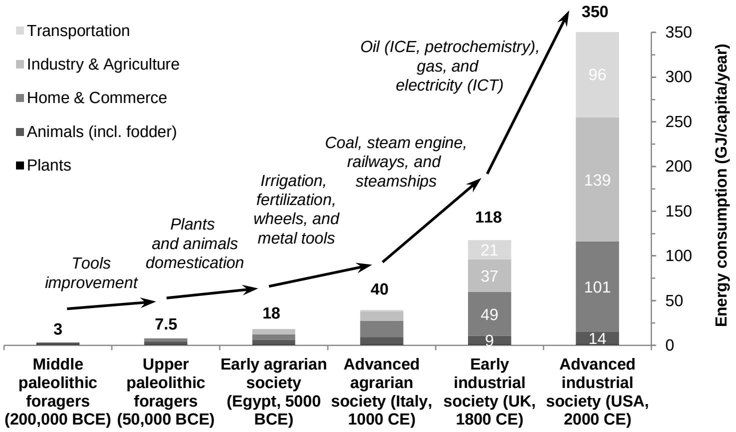

Figure 2: Energy consumption at different stages of societal development. Reproduced with permission from Cook (1971), originally, energy values were in kcal/day/capita, and associated technological breakthroughs were not mentioned.

4.1.2 Energy and technological developments from foraging to farming economies

For 94% of its history (200,000–10,000 BCE), humanity has been organized into highly egalitarian hunter-gatherer clans within which—depending on the performance of tools—each individual only consumed between 3 and 7.5 GJ/year,[23] mostly in the form of food and to a lesser extent woodfuel. Stone tools and the use of fire could not allow a greater energy capture, so material goods and occupations during this period were rather rudimentary compared to modern standards, which should not necessarily be interpreted as hunter-gatherers living in a mere subsistence economy. Indeed, Sahlins (1972, p. 2) argues that in foraging societies "human material wants are finite and few, and technical means unchanging but on the whole adequate," meaning that hunter-gatherers experience "affluence without abundance" (Sahlins, 1972, p. 11).[24]

The literature is unclear about why the transition from foraging to farming societies occurred during the so-called Neolithic Revolution, in particular because archaeological evidences indicate that early farmers faced a reduction in life expectancy and stature, an increase in infant mortality and infectious diseases, and multiple nutritional deficiencies, including vitamin deficiencies, iron deficiency (anemia), and mineral disorders affecting bones and teeth (Larsen, 2006). As for how the Neolithic Revolution happened, current thinking is that a preliminary step was increasing sedentism and social complexity, which was usually followed by the gradual adoption of plant and animal domestication. However, in some cases, plant domestication seem to have preceded sedentism, in particular in the New World (Lewin, 2009, p. 250). Nevertheless, to obtain an explanation of the transition from Paleolithic foraging societies to Neolithic farming societies that complies with the thermo-evolutionary theory of the economic process developed in Section 3, we shall mostly comply with **Corollary 5** and identify the changing constraints that might have incentivized individuals to test, fail, and sort novel strategies for extracting and using new exergy forms from their local environment. According to Lewin (2009, p.250), population pressure due to the saturation of space, and the ending of the last glacial period at the end of the Younger Dryas, have long vied as the most persuasive potential candidates for initiating sedentism and plant domestication. It is probably the combination of these two external changing constraints, possibly in association with internally increasing social complexity, that led to the gradual

---

[23] 1 gigajoule (GJ) $\equiv 10^9$J.

[24] Sahlins also adds that by foraging only for their immediate needs among plentiful resources, hunter-gatherers are able to increase the amount of leisure time available to them. So for Sahlins (1972, p. 2), the original affluent society is that of the hunter-gatherers, and not the Western modern one where "man's wants are great, not to say infinite, whereas his means are limited, although improvable" by productivity increases. Several criticisms have been developed against Sahlins' ideas, see Kaplan (2000) for a recent summary.

emergence of the domestication of plants and animals, two energy-related GPTs that drastically increased the possibilities for societal exergy control and aggregate technological changes as postulated in **Proposition 4**.

The domestication of plants and animals indeed induced an almost three-fold increase in the average energy consumption per capita (18 GJ/year), which came along with the establishment of permanent settlements and the premises of labor division and political hierarchization. Power delivered by draft animals (and fed with fodder, i.e., solar energy converted into biomass through photosynthesis) contributed substantially to this pattern. The gradual improvement of metal tools, the increasing use of organic fertilizers (manure), and the introduction of new farming technologies (irrigation, the wheel) induced a further two-fold increase in the average energy consumption per capita (40 GJ/year). Societal development at that stage was represented by bigger, more-connected, and increasingly militarized city-states and kingdoms, which, under special circumstances, could give rise to vast empires. Among other important developments, the waterwheel as an energy GPT, along with the windmill, had a particularly significant role in explaining the extraordinary effervescence in art, thought, economy, and technology that medieval Europe experienced from the beginning of the eleventh to the middle of the fourteenth centuries (Arnoux, 2012).

In total, the time for which energy capture by farming was representative of most of the global population represented 5.9% of humanity's history (10,000 BCE–1850 CE). During this entire period, land ownership gave economic and political power to its owners and land was considered as the most crucial factor of production. In fact, this supposed power was due to the photosynthetic collection of solar exergy operated free-of-charge by plants and that draft animals and people (often coerced as slaves or serfs) extracted and transformed into useful exergy. In such societies, income distribution and effective demand had a role, but economic growth depended mostly on the capacity to harness increasing primary exergy in the form of food, fodder, motion (from water and wind exergy flows, which ultimately derived from solar exergy), and woodfuel (here again indirect solar exergy), and on the ability to transform those primary exergy resources into useful exergy in the form of mechanical power, heat, and light. More precisely, in agrarian societies of the past, the possibilities for capturing and converting the primary solar exergy flow into useful exergy were ultimately constrained by the forces that organic structures such as animal/human muscles and wood fibers could take and exert. Hence, past agrarian economies were in essence limited in their growth possibilities because of thermodynamic constraints.

4.1.3 Energy and technological developments from farming to industrial economies

Wrigley (2013, pp. 9–10) gives the best summary of the central role that fossil energy played in the transition from farming to industrial societies. For him, "a necessary condition for the move from a world where growth was at best asymptotic to one in that it could be, at least for a period, exponential was dependent upon the discovery and exploitation of a vast reservoir of energy that had remained untapped in organic economies. Only by adding the products of plant photosynthesis accumulated over a geological age to the annual cycle of photosynthesis, which had previously been the source of almost all the energy available for human use, could the energy barrier that had constrained growth so severely in the past be overcome."[25]

In the same line of thought, and after a comparison of the role of energy in Europe and other parts of the world over the last five centuries, Kander et al. (2013, p. 366) conclude that it is hard to imagine anything like modern economic growth occurring without the adoption of fossil fuels, first of all coal. They further emphasize that they "view the transition to fossil fuels both as a necessary condition, and an enabling factor *leading* to modern growth" (italic emphasis present in original). As others, such as Sorrell (2010), have argued before, Kander et al. (2013, pp. 367–368) assert that coal was crucial for the British Industrial Revolution not solely as source of heat, but mostly for its high complementarity with the steam engine and iron industries to deliver unprecedented amounts of power that vastly reshaped industrializing societies. Indeed, Kander et al. (2013, pp. 367–368) argue that "the steam engine is one of the most important innovations in the history of mankind. For the first time in history it was possible to reliably and in a controlled form convert heat to motion, equipping people with inanimate 'energy slaves' (machines). Steam engines saved labor, and initiated a capital-deepening growth path.[...] This capital-deepening growth was

---

[25] The idea of a ceiling imposed by the organic energy supply on the capacity of development of pre-modern economies should be clarified in two ways. First, this limit was not determined at a fixed value as it could move upward (respectively downward) in the case of physical and social technological progress (respect. regress). Second, changing climatic and disease conditions implied a fluctuation of both the energy supply and standards of living per capita in the pre-modern world. Accordingly, medium-term oscillations around decreasing or increasing long-term trends characterized pre-modern economies, whereas a smoother upward long-term trend is more representative of the modern fossil regime.

almost wholly reliant on fossil fuels and eventually, although by no means instantly, led not just to increased incomes, but set in motion a dynamic that has continued to raise incomes." Appendix 1 gives estimates of land- and labor-savings achieved in the UK thanks to the use of the steam engine fueled by coal, whereas Appendix 2 details the 'energy slave' concept and its quantification.

The Industrial Revolution is another critical period where the thermo-evolutionary theory of the economic process given in Section 3 must correctly apply. As for the Neolithic Revolution that saw the transition from foraging to farming societies, we must comply with **Corollary 5** and identify the emerging internal factors and changing external constraints that set in motion the Industrial Revolution and the associated transition from farming to industrial societies. Regarding the evolution of internal factors, eminent scholars, such as Jacob (1997), Goldstone (2009), and Mokyr (2011), attribute much of the credit for the burst of innovations, and accelerated diffusion of best practices after 1750, to the scientific culture of Western Europe and in particular Britain. They argue that Western European societies were particularly dynamic and inclined to see a technological breakthrough in the eighteenth century thanks to the increase, or propagation during the previous two hundred years, of printing books, publishers, scientific societies, university networks, relatively accessible public lectures, and growing day-to-day exchanges between scientists, engineers, and craftsmen. More precisely, these authors use changes in the intellectual, social, and institutional background environment to explain the success of the British Industrial Revolution. These changes crystallized in the emergence of a modern science capable of fostering the conversion of ideas and inventions—whatever their geographical origin—into workable innovations that were rapidly transformed into useful technologies able to yield profits to their developers.[26]

Moreover, from the sixteenth century onward, the extensive use of slaves to extract natural resources (sugar, tea, tobacco, coffee, fur, and more specifically guano, wood, and cotton) from the New World implied an Atlantic Trade that flooded Western European markets with new exotic products. This expansion of European markets, and the institutional changes that accompanied it, have been important in leading several Western European countries to an *Industrious Revolution* that consisted of households-size handicraft manufacturing (de Vries, 1994). In particular, for two Western European proto-industrial nations, Britain and the Netherlands, wages broadly increased from the sixteenth to the eighteenth centuries compared to other European Nations and development cores in other parts of the world. This so-called *Little Divergence* within Europe implied that incentives for labor-saving technologies were more important in Britain and the Netherlands compared to other European nations, while non-existent in China, Japan, or India where labor remained relatively cheap. Simultaneously, because proto-industry relied heavily on wood fuel, critical levels of wood scarcity, visible both in quantity shortages and price increases, were recurrent in most of Western Europe, and especially in Britain (Pomeranz, 2000, pp. 220–223). Allen (2009) comprehensively argues that the relative prices of production factors, and the existence of coal deposits close to urban centers, have been crucial in directing and fostering sustained technological change. In other words, for Allen (2009), the British Industrial Revolution originated in the willingness of its people to apply knowledge brought by science to tap their favorable coal endowment thanks to financial incentives represented in high prices of labor and wood compared to the relatively low prices of capital and coal. In summary, emerging internal factors (proto-industrialization, increasing scientific knowledge, and new inclusive institutions) and changing external constraints in terms of exergy availability (wood scarcity and accessible coal) explain how the evolutionary algorithm of variation, selection, and replication worked upon the design spaces of physical technologies, social technologies, and routines to enable an early transition from farming to industrial societies in Western Europe, and more precisely in Britain.

---

[26] It is important to understand that all these scholars do not denigrate the many scientific breakthroughs that episodically originated in China and Islamic countries. They rather highlight the earliness of Britain in creating a scientific culture able to transpose useful knowledge into technological change thanks to a favorable institutional environment. Similarly, Lipsey et al. (2005, pp. 225–289) argued that Islam is an occasionalist doctrine in which the state of the world at any one moment in time is contingent on the particular will of God. On the contrary, the doctrine of Christian naturalism posits that God created the world according to natural laws and then endowed humans with free will to determine their own affairs. For Lipsey et al. (2005, pp. 225–289), this difference was decisive to see the apparition of science in early modern Europe, whereas Islam developed hostility against free inquiry and mechanistic science. Moreover, according to the same authors, the incapacity of China to develop an original version of modern science on its own has more to do with the absence of institutions that would save and organize cumulative knowledge, whereas on the contrary Europe elaborated an early institutionalization of scientific research through universities and scientific societies.

4.1.4 Energy and technological developments in modern economies

Proposition 4 clearly applies to the last 0.1% (1850 CE–2018 CE) of human history during which the most significant changes in societal development have been associated with (and in fact largely caused/allowed by) the opportunity for humans to tap into fossilized solar energy in the form of coal, oil, and gas. As shown in Fig. 2, the average US citizen now controls 350 GJ/year, a seven-fold increase compared to any pre-1800 proto-industrial individual. The extent of this modern energy pattern enables the transformation and transport of materials and information in quantities and qualities that translates in levels of standard of living that have no precedent in human history. Figure 3 specifies the global evolution of the use of the 'Grand Chain of Energy' by the 'industrial man' as coined by Morris (2010). Rather clearly, the pre-industrial global energy consumption mix has been altered dramatically since the Industrial Revolution. In a first step, coal largely replaced woodfuel for heat and supplanted water for rotary motion through the widespread use of steam engines in various industries such as textile, railways, and steamships. On the eve of World War I, coal reached its maximum share of 50% of the global primary energy consumption mix. In a second step, engineers found for crude oil even more applications with progressive efficiency gains and cost reductions. One of the most famous examples of this fact is the decision made by Winston Churchill to convert the entire British fleet from coal to oil in 1914, which gave to Britain the fastest navy in the world and a consequent decisive advantage over Germany during the war. Together, electricity and oil (and its associated GPT, the internal combustion engine) have enabled economic growth to reach unprecedented levels from the end of World War II to the beginning of the 1970s. After the two oil crises of the 1970s, various countries tried to reduce their dependence on crude oil, so gas production, nuclear electricity, and hydropower increased considerably. The so-called clean technologies (wind turbines, solar panels, tidal, and wave electricity) which many experts see as the energy future of humanity, currently represent 1% of the global primary energy supply (and 10% of its renewable part, woodfuel, and crop residues still contribute for 70%, and hydro the remaining 20%).

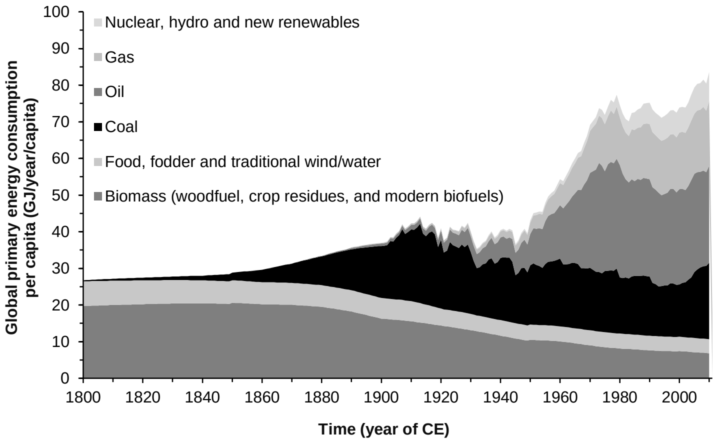

Figure 3: Global primary energy consumption per capita, 1800–2014. Reproduced with permission from Court (2016, p. 214).

During the last two centuries, animal and human labors have been gradually replaced by exergy-activated machines. In terms of relative prices, fossil exergy expenditure as a percentage of GDP has gradually declined (Fizaine and Court, 2016; King, 2015). This decrease has also driven down the cost of goods and services (in terms of the number of working hours required to buy such products), and has consequently increased demand and production on markets. In currently developed countries, this long-term substitution seems to have been the dominant driver of economic growth since the Industrial Revolution (Ayres and Warr, 2009, p. 168). More recently, transistors powered by electricity have started to reduce biological limitations further as they assist the human brain in processing and storing huge quantities of information. Hence, in modern industrialized societies, it is "exergy that drives the machines in mines and on drilling sites, in power stations, factories, and office buildings, on rails, road and farms, in the air, and on the sea. In short, it activates the wealth-creating production process of industrial economies" (Kümmel, 2011, p. 37).[27] For the sake of brevity,

---

[27] Ayres and Warr (2009, pp. 52–53) highlight that modern technological change at the macro level is ultimately defined by the

econometric contributions to the energy-growth nexus are discussed in Appendix 3.

4.2 Explaining the economic growth slowdown of the last 40 years

4.2.1 A slowdown or a return to normal?

Figure 4 shows that the average annual growth rate of the real Gross World Product (GWP, measured in 2011 US$) per capita increased from 0.07% per year in 1500–1820 to 0.7% per year in 1820–1870. As explained in Section 4.1.3, the rapid growth in the middle of the nineteenth century is associated with the Industrial Revolution, based on the energy transition towards fossil fuels. With the increasing services provided by crude oil and electricity, the global dynamics of development accelerated between 1870 and 1913 where GWP per capita grew at 1.5% per year. The two world wars have undoubtedly hampered this growth trajectory (GWP per capita grew at 0.8% per year from 1913 to 1950), but global growth regained its vigor afterward, to the extent that the global economy grew at the astonishing growth rate of 3.0% per year between 1950 and 1970. In developed countries, this 1945–1970s period is remembered as an age of economic miracle.[28] During the next twenty years (1970–1990), the average annual growth rate of per capita GWP was only 1.65% per year, and it slightly increased to 2.3% during the 1990–2010 period, before slightly decreasing again to 2.0% between 2010 and 2016. Some may see the economic slowdown of the last 40 years as an unexplained deceptive performance compared to the 1950–1970s period. But others may argue that we are currently following a logical return to low growth in the long run, such that the 1950–1970s period should be seen as a singular past event. Either way, there is no consensus among economists on the causes of this macroeconomic dynamic that more clearly manifests in advanced countries compared to developing countries.

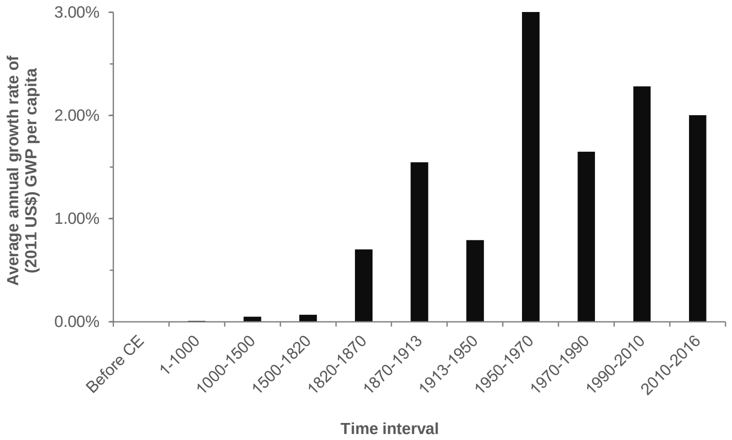

Figure 4: Average annual growth rate of real (2011 US$) GWP per capita, 1–2016 CE. Data reproduced with permission from Bolt et al. (2018).

An argument that is of particular interest in the context of this paper is the analysis of Gordon (2016). Focusing on the US, Gordon claims that some inventions are more important than others and that the revolutionary century after the Civil War (which ended in 1865) was made possible by a unique clustering that the author calls the 'Great Inventions.' Principal among them are the internal combustion engine (ICE) and electricity. Moreover, the second important idea of Gordon (2016) is that advances since the 1970s have tended to be channeled into a narrow sphere of human activity involving entertainment, communication, and the collection and processing of information. The author argues that the narrower scope of the post-1970 inventions has implied a diminished impact of innovation, which together with a stagnant level of education, explains the economic growth slowdown of the US in the last 40 years.

---

limiting efficiency of all metallurgical, chemical, and electronic processes at micro levels, which in turn depend essentially on the properties of structural materials. Indeed, some technologies, such as prime movers and many metallurgical reduction and synthesis processes, depend on the temperatures, and in some cases, pressures, achievable in a confined space. These are limited by the strength and corrosion resistance (chemical inertness) of structural materials at elevated temperatures. In the same way, turbines' efficiencies also depend on the precision with which blades, piston rings, gears, and bearings can be manufactured, which depends in turn on the properties of materials being shaped and the properties of the ultra-hard materials used in the cutting and shaping of tools.

[28] In France, it is even remembered with nostalgia as the 'Glorious Thirty.'

4.2.2 A thermoeconomic perspective to Gordon's analysis

Gordon's (2016) explanation is perfectly in line with the thermoeconomic perspective adopted in the present article. First of all, the ICE and electricity are the two inventions that have brought the most drastic economic changes during the twentieth century, because these General Purpose Technologies (GPTs) are associated with tremendous changes in the energy and material supply of the economy. The ICE make use of crude oil, which is the most concentrated energy form that humans can find in their environment other than nuclear isotopes. The widespread use of electricity in many appliances has radically changed how final energy is converted into useful energy. These two energy GPTs have completely reshaped the productive basis of the economy, along with its internal organization. On the contrary, most recent GPTs, namely, the computer and the internet, have increased electricity needs but they have not revolutionized the energy supply of the economy. As a consequence, new information/organization GPTs have certainly had an impact on communication, entertainment, and information processing, but they have not fundamentally changed the most primordial aspects of the economic system, and in particular, the physical infrastructures that provide people's standard of living. Indeed, despite the increasing prevalence of portable communication technology, people still eat food produced in mechanized farms, commute to work by car or public transport, work and live in buildings made of steel, concrete, and glass, and more generally they enjoy the services of tangible goods made of various materials. These physical aspects constitute the reality of everyday life and, despite valuable qualitative improvements, it must be recognized that they did not significantly change since the mid-1970s.

The thermoeconomic perspective described in Section 3 brings two other related explanations to the phenomenon of global economic slowdown. First, Fig. 3 shows that global primary energy consumption per capita increased remarkably from 1945 to the 1970s, but after the second oil crisis, the annual growth rate of crude oil consumption decreased substantially, and the overall per capita primary energy supply did the same. *Ceteris Paribus*, a lower exergy supply necessarily implies a lower achievable potential product for the economy. However, precisely, one thing that did not remain the same over time is the efficiency with which primary exergy is converted into useful exergy. This efficiency of primary-to-useful exergy conversion, representing the aggregate physical technology *level* of the economy, can be estimated because exergy efficiencies of all major exergy conversion processes, and the exergy quantities passing through them, can be assessed. Building on Ayres (1998b), Warr et al. (2010) provide estimates of the aggregate primary-to-useful exergy conversion efficiency for the USA, UK, Austria, and Japan from 1900 to 2000, with updated values proposed for Austria from 1900 to 2012 by Eisenmenger et al. (2017). Brockway et al. (2014) also propose updated values for the US and UK primary-to-useful exergy conversion efficiencies from 1960 to 2010. Despite several differences in methodologies,[29] I used the trends from Brockway et al. (2014) to extend the data for the USA and UK from Warr et al. (2010) from 2000 to 2010. De Stercke (2014) performs the same assessment of the aggregate primary-to-useful exergy conversion efficiency for the world economy from 1900 to 2014. The primary-to-useful exergy conversion efficiency of these four industrialized countries, as well as the world, have a similar S-shaped form over time, and technological *change* of these economies is formally given by the instantaneous rate of growth of their respective curves. Figure 5 shows that gains in the efficiency of primary-to-useful exergy conversions were rather slow from 1900 to 1945 and then increased considerably up to the 1970s. Since then, gains in the aggregate efficiencies of primary-to-useful exergy conversion have stagnated or declined for these four countries and for the whole world. Hence, rather clearly, periods of highest rate of primary-to-useful efficiency growth correspond to the periods of highest economic growth.

It should be recalled that aggregate primary-to-useful exergy conversion efficiencies such as the ones displayed in Fig. 5 result from the quantity-weighted aggregation of the efficiencies of all primary-to-final exergy converting infrastructures (refineries, power plants, etc.) with the efficiencies of all final-to-useful exergy converting devices (internal combustion engines of cars and trucks, electrical, and electronic appliances such as light bulbs, TV sets, and so on). Figure 6a shows that the average efficiency of the US thermal power generation rose from 4% in 1900 to 13.6% by 1925, and then almost doubled to 23.9% by 1950. The US nationwide mean surpassed 30% by 1960, but it has stagnated since and has never exceeded 33%. From a

---

[29] Differences lie in (i) the fact that Brockway et al. (2014) only take into account the above-basal-need food intake needed for heavy labor, while Warr et al. (2010) consider the entire food intake of people; (ii) a higher assumption for food conversion efficiency into muscle work in Brockway et al. (2014) compared to Warr et al. (2010); (iii) a higher mechanical drive efficiency in Brockway et al. (2014) compared to that from Warr et al. (2010) (e.g., 11% vs. 8%, respectively, in 1960); and (iv) a higher heat efficiency in Brockway et al. (2014) as more heat is allocated to Low Temperature Heat end-use in Warr et al.'s (2010) analysis (e.g., 12% vs. 7%, respectively, in 1960).

physical point of view, thermal efficiency is of course not equivalent to a primary-to-final exergy conversion efficiency, but it is a good approximation. Hence, Fig. 6a indicates that an important aspect of the efficiency of primary-to-final exergy conversion appears to have stagnated since the 1960–1970s in the US and hence in other industrialized countries too.[30] Regarding final-to-useful exergy conversion efficiencies, Figure 6b is again more indicative than demonstrative. It shows not only that the efficiency of successive generations of light bulbs in terms of lumen emitted per (dissipated) watt has increased, but also that each generation of technology seems to have an inherent limit that is ultimately approached. In summary, the perspective adopted in the present article enlightens Gordon's (2016) work on economic slowdown by providing a thermodynamic rationale to his hypothesis of technological stagnation : physical technological change has been slowing down since the mid-1970s because *ultimate* limits to exergy conversion efficiency are progressively approached. Again, it is important to assert that any exergy conversion process has an intrinsic ultimate efficiency that cannot be exceeded (see Cullen and Allwood (2010) for estimates).

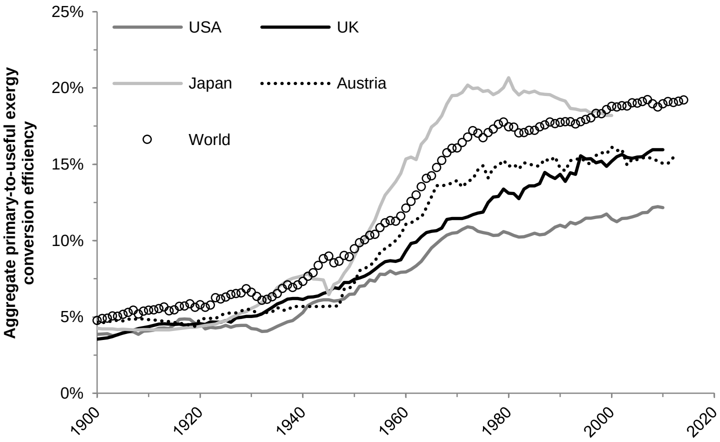

Figure 5: Aggregate primary-to-useful exergy conversion efficiency of the USA (1900–2010), UK (1900–2010), Austria (1900–2012), Japan (1900–2000), and the world (1900–2014). Data reproduced with permission from Warr et al. (2010), Brockway et al. (2014), De Stercke (2014), Eisenmenger et al. (2017).

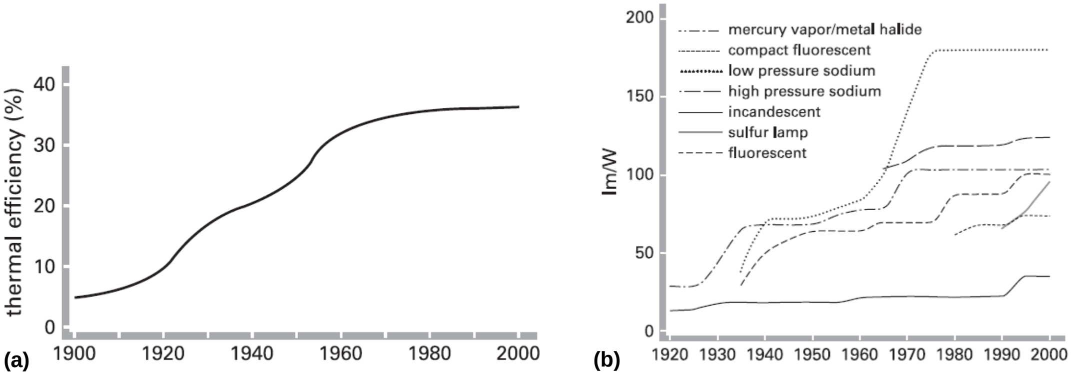

Figure 6: Reaching technological limits in energy efficiencies. (a) US average thermal generation efficiency. (b) Efficiencies of electric lighting. Reproduced with permission from Smil (2008, p. 237 and 267, respectively).

---

[30] As noted by one of the anonymous reviewers of this article, power plants could operate at a higher efficiency, but in doing so they would produce less power and would consequently generate less revenue. So the stagnation of the average US thermal power generation efficiency around 33% shown in Fig. 6a is not strictly due to thermodynamic limits. Rather, the emergence of this optimal efficiency is caused by the interaction of thermodynamic and economic constraints.

5 Summary

This article started by defining essential concepts such as energy, exergy, entropy, self-organization, and dissipative structures to explain that the first and second laws of thermodynamics always apply to open far-from-equilibrium systems such as living organisms and economies. Then, it was shown that general laws based on the extremization of thermodynamic variables are helpful but incomplete to explain life evolution. Such laws cannot completely rule out natural selection as an explanatory mechanism. Hence, self-organization driven by thermodynamic laws works in combination with the general algorithm of evolution (variation, selection, and replication) to explain the emergent dynamics of complex adaptive systems such as living organisms, ecosystems, and even economic systems.

Applying the laws of thermodynamics to economic systems demonstrates that in economic growth theories omitting energy, the economy is a perpetual motion machine of the first kind, that is, a machine that performs endless cycles of factors-against-payments without any input of energy. As recalled by the laws of thermodynamics, such a conception of the economic system is a conceptual artifact that cannot exist in the real world. Energy makes up a small share of total production costs not because it is less important than capital or labor as a production factor, but rather because the biosphere and geosphere generate the physical work that we use abundantly and free-of-charge. As put by Atkins (2010, p. 22), if the first law of thermodynamics was found to be false, “wealth—and untold benefits to humanity–would accrue to an untold extent.” In reality, the economic system is an open far-from-equilibrium system that extracts and converts low entropy matter-energy into even lower-entropy products and gives off high entropy wastes that are freely discarded in the environment. The unspontaneous decrease in entropy associated with the increasing order of matter from raw to refined materials in the forms of goods is only possible because an even higher amount of entropy production is associated with the degradation of exergy extracted from the environment.

Moreover, systems of energy capture and knowledge expressed in cultural organization and institutions also seem to follow a co-evolutionary path. On this point, it is important to stress that “it is not that individuals are caused to adopt values by their society’s mode of energy capture. Rather, over the course of long stretches of history, and as a result of innumerable social experiments by inventive humans, the societies that are best organized to exploit available modes of energy capture-–by their social structures, economic and political institutions, culture and values-–will tend to prevail over and displace other societies that are less well organized. Social forms and the associated values that are ill-adapted to human survival and comfort, given available technologies, will give way to more effective institutions and values” (Morris, 2015, p. XIX).

Hence, economic growth results from the co-evolution of knowledge, social organization, and the physical means to capture and process energy. Production and income are allocated on markets, and the legal framework determines their division, but it is energy conversion and exergy degradation set by physical constraints that determine the growth of production and income. Organizational routines which survive in economic systems are those that funnel energy into their own production and reproduction and contribute to autocatalytic processes which increase the total dissipation of the system. Accordingly, the differential economic growth of nations depends on their evolving relative capacities to increase useful exergy throughput given (i) the respective external constraints set by their environment (notably in terms of exergy availability), and (ii) the internal history-dependent performances of their physical and social technologies, that also define their multilateral exchanges of raw materials, manufactured goods, and financial assets. Similarly to biological organisms, economic systems do not intentionally seek to maximize useful exergy throughput and its associated entropy production, but as complex adaptive systems, such patterns emerge from the interaction of self-organization and selection.

Energy is central to explaining long-term patterns of technological changes and economic developments. In particular, fossil fuels used in heat engines drastically changed the previously constrained organic economies. Tapping into the most favorable store of fossilized solar exergy accumulated more than 200 million years ago in the form of coal, oil, and gas allowed the cheap production of metals from which heat engines and many other machines were invented. This positive feedback loop between fossil exergy and raw material extraction greatly expanded the amount of available natural resources. Most importantly, heat engines converted the chemical exergy of coal, oil, and gas into work beyond the limitations of human and animal bodies. Hence, from the first use of heat engines, the level of exergy consumption per capita has been mostly extended through *exosomatic* exergy, i.e., exergy that is external to the human body, as opposed to *endosomatic* exergy, i.e., exergy that is derived from food and is internal to the human body.

Furthermore, the thermo-evolutionary perspective adopted in this paper provides an explanation for the economic growth slowdown encountered by the most developed countries since the mid-1970s. Contrary to energy GPTs that have powered the extraordinary growth of the 1945–1970s, most recent GPTs (namely the computer and the internet) do not imply a similar revolution of the energy supply. Additionally, these information/organization GPTs certainly have an impact on communication, entertainment, and information processing, but they do not fundamentally change the most primordial aspects of the economy, and in particular, the physical infrastructures that still provide the necessary standards of living. Moreover, it seems rather clear that the combined patterns of declining primary exergy consumption per capita and stagnating efficiency of primary-to-useful exergy conversion could partially explain that growth rates of industrialized economies were significantly higher between the end of World War II and the mid-1970s than in the last 40 years (mid-1970s–2018).

As summarized by Kümmel (2011, pp. 19–20) translating Sieferle (1997): “universal history can be subdivided into three parts. Each part is characterized by a certain energy system [based on foraging, farming, fossil fuel burning]. This energy system establishes the general framework, within which the structures of society, economy, and culture form. Thus, energy is not just one factor acting among many. Rather, it is possible, in principle, to determine the basic formal structures of a society from the pertaining energetic system conditions.” Hence, far from being negligible, the amount of energy per capita dissipated by any economic system provides the first-order description of its level of complexity, and it is time to see such a fact acknowledged in standard economic growth theories.

Appendices

Appendix 1: Labor- and land-savings thanks to coal use

To quantify the importance of coal as a source of both heat and mechanical power in the transition from limited to sustained economic growth, Malanima (2016, pp. 95–99) follows the seminal contribution of Wrigley (1962) in order to estimate land- and labor-savings due to coal use in England and Wales on the period 1560–1913.[31] The results presented in Fig. 7 exhibit two distinct historical phases. During the first one, that lasted from the end of the sixteenth century until about 1830, the use of coal was mainly land-saving. It is only during the second phase (from 1830 to 1900) that coal was really both land and labor-saving. Covering both phases from 1800 to 1900, the land-related (resp. labor-related) social savings grew from 1 to 14 times the extent of the entire country, that is 15 million hectares (resp. from 1 million to almost 300 million workers when the English population was 32 million and the labor force 13–14 million in 1900). These estimates strongly support Wrigley’s (2016, pp. 2–4) claim that “the energy required to produce, say, iron and steel on a large scale or to construct and operate a railway system implied that it was idle to expect that it could be secured from the annual *flow* of energy derived from plant photosynthesis” (italic emphasis in original). As a corollary, “an Industrial Revolution could not be accomplished as long as mechanical energy continued to be provided principally by human and animal muscle.”

Appendix 2: The ‘energy slave’ concept and its quantification

Focusing on the ‘energy slave’ concept, Kümmel (2011, p. 16) delivers a vivid analysis of the fundamental role that fossil fuels played in the transition towards modernity. He asserts that the human rights, as proclaimed by the *United States Declaration of Independence* in 1776, and market economics, as established the same year by *The Wealth of Nations* of Smith (1776), would not have become ruling principles of societies aspiring to freedom, had not the steam engines and more advanced heat engines provided the services that created the preconditions for toil relief. A sobering way to understand these assertions is to calculate the number of energy slaves in an economy. “This number is given by the average amount of energy fed per day into the energy conversion devices of the economy divided by the human daily work-calorie requirement of 2500 kcal (equivalent to 2.9 kWh or 10.5 MJ)[32] for a very heavy workload. In this sense, an energy slave, via an energy-conversion device, does physical work that is numerically equivalent to that of a hard-laboring human. Dividing the number of energy slaves by the number of people in the economy yields the number of energy

---

[31] As noticed by Malanima (2016, pp. 95–99), usual social savings calculations based on relative costs of old and alternative technologies appear quite impossible here because it would require to compute counter-factual wood prices and labor wages in a theoretical British economy where coal would have been absent.

[32] kWh refers to kilowatt hour, a derived unit of energy equal to 3.6 MJ, and 1 megajoule (MJ) $\equiv 10^6$J.

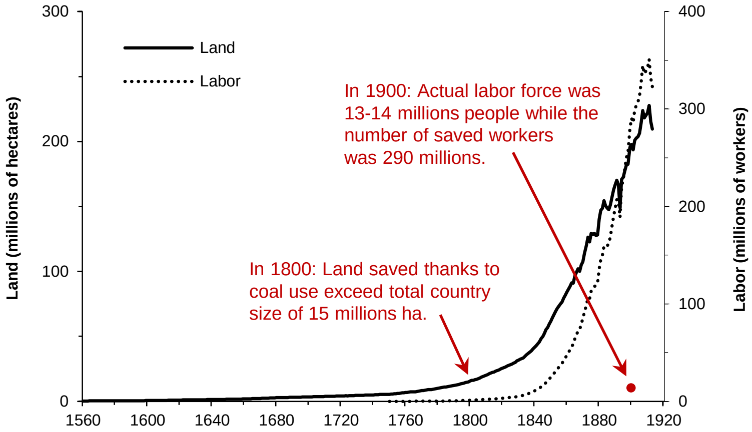

Figure 7: Land (millions of hectares, left vertical axis) and workers (millions, right vertical axis) saved by the use of coal in England and Wales, 1560–1913. Source: Malanima (2016).

slaves per capita.” Broadly speaking, the number of energy slaves at the service of a person has increased from one throughout the Paleolithic, to roughly ten in medieval Western Europe, to between 40 and 100 in modern Europe and North America. “And, of course, modern energy slaves work much more efficiently than medieval ones. It is also interesting that Jefferson’s original draft of the Declaration of Independence included a denunciation of the slave trade, which was later edited out by Congress. Only after industrialization had provided enough energy slaves could the noble words of the Declaration of Independence be finally put into practice—albeit not without the sufferings of the Civil War,” followed by decades of segregation and bigotry.[33] Mouhot (2011) extends the above analysis by arguing that both slave societies and developed countries externalize(d) labor and both slaves and modern machines free(d) their owners from daily chores. Consequently, modern societies are as dependent on fossil fuels as slave societies were dependent on bonded labor. Mouhot (2011) also suggests that, in different ways, suffering resulting (directly) from slavery and (indirectly) from the excessive burning of fossil fuels are now morally comparable.

Appendix 3: Econometrics of the en/exergy-growth nexus

The crucial role of en/exergy in modern economies is supported by different econometric studies well summarized by Stern (2011). In addition to the work of Kümmel et al. (2010, 2002) on the controversial Linex production function (that shall not be further discussed here for the sake of brevity), Santos et al. (2018) have recently provided a new perspective on the question of the relative importance of production factors in an attempt to reconcile the ecological and neo-Keynesian approaches. Focusing on the particular case of Portugal over the last one hundred years, they find that production functions estimated from models where energy is absent from the cointegration space provide the worst fits. On the other hand, the best-estimated fit to past economic trends (and lowest total factor productivity component in growth accounting) is a two-input Cobb–Douglas function with quality-adjusted labor and capital, but with capital being a reconstructed variable as a function of useful exergy and labor and not the historical estimates retrieved from conventional data. In such a case, useful exergy is primordial to defining the actual utilization of capital in production, and estimated values of constant output elasticities for capital and labor are very similar to the average values for historically observed cost shares associated with these factors.

Finally, a word is needed on econometric studies that try to assess the direction of causality between energy and economic growth. Four assumptions are possible: (i) a relation of cause-and-effect running from energy consumption to economic growth, (ii) a causal relation running in the other direction from economic growth to energy consumption, (iii) a feedback relation between energy consumption and economic growth, and (iv) the absence of any causal relationship between energy consumption and economic growth. Unfortu-

---

[33] Bloch (1935) questions the direction of causality between technological improvements related to energy capture (e.g., water mill, horse collar) and the progressive status change of European slaves into serfs from the Early (fifth to tenth centuries) and High Middle Ages (eleventh to thirteenth centuries). He does not use the word ‘co-evolution’ but his description of the process is in line with this concept.

nately, after more than 40 years of research, and despite the increasing sophistication of econometric studies, this area of study has not led so far to a general methodological agreement or a preference for any of the four assumptions. More specifically, three independent literature reviews (Chen et al., 2012; Kalimeris et al., 2014; Omri, 2014), covering respectively 39, 48, and 158 studies, have shown that no particular consensus has emerged from this empirical literature, and that the share of each assumption ranges from 20 to 30% of the total.[34] Nevertheless, both Stern (2011) and Santos et al. (2018) seem to indicate that when misspecification of early studies are avoided (e.g., choosing multivariate models instead of bi-variate) and if a quality-adjusted energy index is employed (e.g., based on exergy), energy is found to Granger cause GDP.[35]

Acknowledgments

This work benefited from the support of the Chair Energy & Prosperity. I thank Adrien Nguyen-Huu and David Le Bris for their helpful comments on earlier versions of this article. I am also grateful to two anonymous referees for their fruitful comments and suggestions. All remaining errors are mine.

Compliance with ethical standards

The author declares that he has no conflict of interest.

References

Abramovitz, M. (1956). Resource and Output Trends in the U.S. since 1870. *American Economic Review*, 46(2):5–23.

Acemoglu, D. (2009). *Introduction to Modern Economic Growth*. Princeton University Press, Princeton, NJ.

Acemoglu, D. and Robinson, J. (2012). *Why Nations Fail: The Origins of Power, Prosperity, and Poverty*. Crown Publishers, New York, NY.

Aghion, P. and Howitt, P. (1998). *Endogenous Growth Theory*. MIT Press, Cambridge, MA.

Aghion, P. and Howitt, P. (2009). *The Economics of Growth*. MIT Press, Cambridge, MA.

Allen, R. C. (2009). *The British Industrial Revolution in Global Perspective*. Cambridge University Press, Cambridge, UK.

Anderson, B. and M'Gonigle, M. (2012). Does ecological economics have a future?: Contradiction and reinvention in the age of climate change. *Ecological Economics*, 84:37–48.

Aoki, I. (2006). Min-Max principle of entropy production with time in aquatic communities. *Ecological Complexity*, 3(1):56–63.

Arnoux, M. (2012). *Le Temps des Laboureurs : Travail, Ordre Social et Croissance en Europe (XIè-XIVè siècle)*. Albin Michel, Paris, FR.

Atkins, P. W. (2010). *The Laws of Thermodynamics: A Very Short Introduction*. Oxford University Press, Oxford, UK.

Ayres, R. U. (1998a). Eco-thermodynamics: economics and the second law. *Ecological Economics*, 26:189–209.

Ayres, R. U. (1998b). Technological Progress: A proposed Measure. *Technological Forecasting and Social Change*, 59(3):213–233.

Ayres, R. U., van den Bergh, J. C., Lindenberger, D., and Warr, B. (2013). The underestimated contribution of energy to economic growth. *Structural Change and Economic Dynamics*, 27:79–88.

Ayres, R. U. and Warr, B. (2009). *The Economic Growth Engine: How Energy and Work Drive Material Prosperity*. Edward Elgar Publishing, Cheltenham, UK.

Baran, P. A. and Sweezy, P. M. (1966). *Monopoly Capital*. Monthly Review Press, New York, NY.

---

[34] Various explanations can be suggested for these mixed results, including the period under study, the countries in question (the level of development affecting the results), the level of disaggregation of the data (GDP or sectorial levels), the type of energy investigated (total energy, oil, renewable, nuclear, primary, final or useful energy, energy vs. exergy), the econometric method applied (OLS, cointegration framework, VAR, VECM, time series, panel, or cross-sectional analysis), the type of causality tests (Granger, Sims, Toda and Yamamoto, or Pedroni tests), and the number of variables included in the model (uni-, bi-, or multivariate model). As proposed by one of the anonymous reviewers of this article, another possible explanation for the inconclusiveness of causality studies could come from their sensitivity to changing constraints. If that is true, and if economies oscillate among energy, materials, capital, and labor being the binding constraint over the period studied, causality test will be inconclusive. No one factor will appear to drive growth, because each is the dominant constraint at different times.

[35] There are many causality tests based on different definitions of causality. The main idea of the Granger causality test is to verify that adding past data of variable X to past data of variable Y enhances the prediction of the present value of variable Y. If the residuals generated from a model with variable Y and its past only, are significantly different from another model with the past of variable Y and the past of variable X, we can reject the assumption of non-causality from X to Y and accept the assumption of a causality running from X to Y.

Barro, R. J. and Sala-i Martin, X. (2004). *Economic Growth*. MIT Press, Cambridge, MA, 2nd ed. edition.

Batten, D., Salthe, S., and Boschetti, F. (2008). Visions of Evolution: Self-organization Proposes What Natural Selection Disposes. *Biological Theory*, 3(1):17–29.

Becker, M. C. (2004). Organizational routines: a review of the literature. *Industrial and Corporate Change*, 13(4):643–678.

Beinhocker, E. D. (2006). *The Origin of Wealth: Evolution, Complexity, and the Radical Remaking of Economics*. Harvard Business School Press, Cambridge, MA.

Bejan, A. (1997). Constructal-theory network of conducting paths for cooling a heat generating volume. *International Journal of Heat and Mass Transfer*, 40(4):799–816.

Bejan, A. and Lorente, S. (2011). The constructal law and the evolution of design in nature. *Physics of Life Reviews*, 8(3):209–240.

Binswanger, M. (1993). From microscopic to macroscopic theories: entropic aspects of ecological and economic processes. *Ecological Economics*, 8(3):209–233.

Bloch, M. (1935). Les “inventions” médiévales. *Annales d’histoire économique et sociale*, 7:634–643.

Boehm, B. (2008). Traverses of economic growth. An econometric investigation. *Journal of Evolutionary Economics*, 18(2):233–247.

Bolt, J., Inklaar, R., de Jong, H., and van Zanden, J. L. (2018). *Maddison Project Database*. https://www.rug.nl/ggdc/historicaldevelopment/maddison/releases/maddison-project-database-2018.

Brockway, P. E., Barrett, J. R., Foxon, T. J., and Steinberger, J. K. (2014). Divergence of Trends in US and UK Aggregate Exergy Efficiencies 1960–2010. *Environmental Science & Technology*, 48(16):9874–9881.

Brooks, D. R. and Wiley, E. O. (1986). *Evolution as Entropy: Toward a Unified Theory of Biology*. University of Chicago Press, 2nd edition.

Bruelisauer, R., Bradfield, G. E., and Maze, J. (1996). A thermodynamic interpretation of succession. *Coenoses*, 11(2):73–76.

Buenstorf, G. (2000). Self-organization and sustainability: energetics of evolution and implications for ecological economics. *Ecological Economics*, 33(1):119–134.

Carlaw, K. I. and Lipsey, R. G. (2011). Sustained endogenous growth driven by structured and evolving general purpose technologies. *Journal of Evolutionary Economics*, 21(4):563–593.

Chen, P.-Y., Chen, S.-T., and Chen, C.-C. (2012). Energy consumption and economic growth—New evidence from meta analysis. *Energy Policy*, 44:245–255.

Cook, E. (1971). The Flow of Energy in an Industrial Society. *Scientific American*, 225(3):134–144.

Cordes, C. (2006). Darwinism in economics: from analogy to continuity. *Journal of Evolutionary Economics*, 16(5):529–541.

Corning, P. A. (2002). Thermoeconomics: Beyond the Second Law. *Journal of Bioeconomics*, 4(1):57–88.

Corning, P. A. (2014). Systems theory and the role of synergy in the evolution of living systems. *Systems Research and Behavioral Science*, 31(2):181–196.

Court, V. (2016). *Energy, EROI, and Economic Growth in a Long-Term Perspective*. Ph.D. thesis in economics, Université Paris Nanterre, FR.

Crosby, A. W. (2007). *Children of the Sun: A History of Humanity’s Unappeasable Appetite for Energy*. W.W. Norton & Company, New York, NY.

Cullen, J. M. and Allwood, J. M. (2010). Theoretical efficiency limits for energy conversion devices. *Energy*, 35(5):2059–2069.

Daly, H. E. (1985). The Circular Flow of Exchange Value and the Linear Throughput of Matter-Energy: A Case of Misplaced Concreteness. *Review of Social Economy*, 43(3):279–297.

Darwin, C. (1859). *On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life*. John Murray, London, UK.

de La Croix, D. and Michel, P. (2002). *A Theory of Economic Growth: Dynamics and Policy in Overlapping Generations*. Cambridge University Press, Cambridge, UK.

De Stercke, S. (2014). Dynamics of Energy Systems: A Useful Perspective. Technical report, International Institute for Applied Systems Analysis (IR-14-013)., Schloss Laxenburg, AT.

de Vries, J. (1994). The Industrial Revolution and the Industrious Revolution. *Journal of Economic History*, 54(2):249–270.

Debeir, J.-C., Deleage, J.-P., and Hemery, D. (1991). *In the Servitude of Power: Energy and Civilisation Through the Ages*. Zed Books, London, UK.

del Jesus, M., Foti, R., Rinaldo, A., and Rodriguez-Iturbe, I. (2012). Maximum entropy production, carbon assimilation, and the spatial organization of vegetation in river basins. *Proceedings of the National Academy of Sciences*, 109(51):20837–20841.

Depew, D. and Weber, B. (1995). *Darwinism Evolving*. MIT Press, Cambridge, MA.

Dewar, R. C. (2010). Maximum entropy production and plant optimization theories. *Philosophical Transactions of the Royal Society. Series B: Biological sciences*, 365(1545):1429–35.

Dilli, S. (2016). Family Systems and the Historical Roots of Global Gaps in Democracy. *Economic History of Developing Regions*, 31(1):82–135.

Dosi, G., Fagiolo, G., and Roventini, A. (2006). An Evolutionary Model of Endogenous Business Cycles. *Computational Economics*, 27(1):3–34.

Duranton, G., Rodríguez-Pose, A., and Sandall, R. (2008). Family Types and the Persistence of Regional Disparities in Europe. *Economic Geography*, 85(1):23–47.

Eisenmenger, N., Warr, B., and Magerl, A. (2017). Trends in Austrian Resource Efficiency: An Exergy and Useful Work Analysis in Comparison to Material Use, CO2 Emissions, and Land Use. *Journal of Industrial Ecology*, 21(5):1250–1261.

Fizaine, F. and Court, V. (2016). Energy expenditure, economic growth, and the minimum EROI of society. *Energy Policy*, 95:172–186.

Foster, J. (2011). Evolutionary macroeconomics: a research agenda. *Journal of Evolutionary Economics*, 21(1):5–28.

Fouquet, R. (2008). *Heat, Power and Light: Revolutions in Energy Services*. Edward Elgar Publishing, Cheltenham, UK.

Fröling, M. (2011). Energy use, population and growth, 1800–1970. *Journal of Population Economics*, 24(3):1133–1163.

Galor, O. (2011). *Unified Growth Theory*. Princeton University Press, Princeton, NJ.

Georgescu-Roegen, N. (1971). *The Entropy Law and the Economic Process*. Harvard University Press, Cambridge, MA.

Georgescu-Roegen, N. (1986). The Entropy Law and the Economic Process in Retrospect. *Eastern Economic Journal*, 12(1):3–25.

Goldstone, J. A. (2009). *Why Europe? The Rise of the West in World History, 1500-1850*. McGraw-Hill Higher Education, Boston, MA.

Gordon, R. J. (2016). *The Rise and Fall of American growth: the U.S. Standard of Living Since the Civil War*. Princeton University Press, Princeton, NJ.

Greif, A. (2006). *Institutions and the Path to the Modern Economy: Lessons from Medieval Trade*. Cambridge University Press, Cambridge, UK.

Hodgson, G. M. (1993). *Economics and Evolution: Bringing Life Back Into Economics*. University of Michigan Press, Ann Arbor, MI.

Hodgson, G. M. (2002). Darwinism in economics: from analogy to ontology. *Journal of Evolutionary Economics*, 12(3):259–281.

Holdaway, R. J., Sparrow, A. D., and Coomes, D. A. (2010). Trends in entropy production during ecosystem development in the Amazon Basin. *Philosophical Transactions of the Royal Society. Series B: Biological sciences*, 365(1545):1437–1447.

Jablonka, E. and Lamb, M. J. (2014). *Evolution in Four Dimensions: Genetic, Epigenetic, Behavioral, and Symbolic Variation in the History of Life*. MIT Press, Boston, MA, 2nd edition.

Jacob, M. C. (1997). *Scientific Culture and the Making of the Industrial West*. Oxford University Press, New York, NY, 2nd edition.

Johnson, L. (1990). The thermodynamics of ecosystems. In Hutzinger, O., editor, *Handbook of Environmental Chemistry, vol. 1. Part E*, page 1–47. Springer, Heidelberg, DE.

Jones, C. I. and Vollrath, D. (2013). *Introduction to Economic Growth*. W.W. Norton & Company, New York, NY, 3rd edition.

Jorgensen, S. E. and Svirezhev, Y. M. (2004). *Towards a Thermodynamic Theory for Ecological Systems*. Elsevier Ltd., Amsterdam, NL.

Kalimeris, P., Richardson, C., and Bithas, K. (2014). A meta-analysis investigation of the direction of the energy-GDP causal relationship: implications for the growth-degrowth dialogue. *Journal of Cleaner Production*, 67:1–13.

Kander, A., Malanima, P., and Warde, P. (2013). *Power to the People: Energy in Europe Over the Last Five Centuries*. Princeton University Press, Princeton, NJ.

Kaplan, D. (2000). The Darker Side of the "Original Affluent Society". *Journal of Anthropological Research*, 56(3):301–324.

Kauffman, S. A. (1993). *The Origins of Order: Self-Organization and Selection in Evolution*. Oxford University Press, New York, NY.

Kilian, L. (2008). The Economic Effects of Energy Price Shocks. *Journal of Economic Literature*, 46(4):871–909.

King, C. (2015). Comparing World Economic and Net Energy Metrics, Part 3: Macroeconomic Historical and Future Perspectives. *Energies*, 8(12):12997–13020.

Kleidon, A. (2010). Life, hierarchy, and the thermodynamic machinery of planet Earth. *Physics of Life Reviews*, 7(4):424–460.

Kleidon, A. (2012). How does the Earth system generate and maintain thermodynamic disequilibrium and what does it imply for the future of the planet? *Philosophical Transactions of the Royal Society. Series A: Mathematical, physical, and engineering sciences*, 370(1962):1012–40.

Knudsen, T. (2002). Economic selection theory. *Journal of Evolutionary Economics*, 12(4):443–470.

Kümmel, R. (1989). Energy as a Factor of Production and Entropy as a Pollution Indicator in Macroeconomic Modelling. *Ecological Economics*, 1(2):161–180.

Kümmel, R. (2011). *The Second Law of Economics: Energy, Entropy, and the Origins of Wealth*. Springer, New York, NY.

Kümmel, R., Ayres, R. U., and Lindenberger, D. (2010). Thermodynamic Laws, Economic Methods and the Productive Power of Energy. *Journal of Non-Equilibrium Thermodynamics*, 35:145–179.

Kümmel, R., Henn, J., and Lindenberger, D. (2002). Capital, labor, energy and creativity: modeling innovation diffusion. *Structural Change and Economic Dynamics*, 13(4):415–433.

Kümmel, R. and Lindenberger, D. (2014). How energy conversion drives economic growth far from the equilibrium of neoclassical economics. *New Journal of Physics*, 16(12):125008.

Larsen, C. S. (2006). The agricultural revolution as environmental catastrophe: Implications for health and lifestyle in the Holocene. *Quaternary International*, 150(1):12–20.

Le Bris, D. (2016). Family Characteristics and Economic Development. *Toulouse Business School Working Paper*.

Lewin, R. (2009). *Human Evolution: An Illustrated Introduction*. Malden, MA, 5 ed. edition.

Lipsey, R. G., Carlaw, K., and Bekar, C. (2005). *Economic Transformations: General Purpose Technologies and Long-Term Economic Growth*. Oxford University Press, Oxford, UK.

Lotka, A. J. (1922). Contribution to the Energetics of Evolution. *Proceedings of the National Academy of Sciences*, 8(6):151–154.

Malanima, P. (2016). Energy consumption in England and Italy, 1560-1913. Two pathways toward energy transition. *Economic History Review*, 69(1):78–103.

Malm, A. (2016). *Fossil Capital: The Rise of Steam Power and the Roots of Global Warming*. Verso, London, UK.

Mamadouh, V. (1999). A political-cultural map of Europe. Family structures and the origins of differences between national political cultures in the European Union. *GeoJournal*, 47(3):477–486.

Mansson, B. A. and McGlade, J. M. (1993). Ecology, thermodynamics and H.T. Odum's conjectures. *Oecologia*, 93(4):582–596.

Martyushev, L. M. and Seleznev, V. D. (2006). Maximum entropy production principle in physics, chemistry and biology. *Physics Reports*, 426(1):1–45.

Martyushev, L. M. and Seleznev, V. D. (2014). The restrictions of the maximum entropy production principle. *Physica A: Statistical Mechanics and its Applications*, 410:17–21.

Milewski, A. V. and Mills, A. J. (2010). Does life consistently maximise energy intensity? *Biological Reviews*, 85(4):859–879.

Mokyr, J. (1990). *The Lever of Riches: Technological Creativity and Economic Progress*. Oxford University Press, New York, NY.

Mokyr, J. (2011). *The Enlightened Economy: Britain and the Industrial Revolution, 1700-1850*. Penguin Books, London, UK.

Morowitz, H. J. (1979). *Energy Flow in Biology: Biological Organization as a Problem in Thermal Physics*. Ox Bow Press, Woodbridge, CT.

Morris, I. (2010). *Why the West Rules For Now: The Patterns of History, and What They Reveal About the Future*. Farrar, Straus and Giroux, New York, NY.

Morris, I. (2015). *Foragers, Farmers, and Fossil Fuels: How Human Values Evolve*. Princeton University Press, Princeton, NJ.

Mouhot, J.-F. (2011). Past connections and present similarities in slave ownership and fossil fuel usage. *Climatic Change*, 105(1-2):329–355.

Nelson, R. R. (2005). *Technology, Institutions, and Economic Growth*. Harvard University Press, Cambridge, MA.

Nelson, R. R. and Winter, S. G. (1982). *An Evolutionary Theory of Economic Change*. Harvard University Press, Cambridge, MA.

North, D. C. (2005). *Understanding the Process of Economic Change*. Princeton University Press, Princeton, NJ.

Odum, H. T. (1971). *Environment, Power, and Society*. Wiley-Interscience, New York, NY.

Odum, H. T. and Pinkerton, R. C. (1955). Time's speed regulator: The optimum efficiency for maximum output in physical and biological systems. *American Scientist*, 43(2):331–343.

Omri, A. (2014). An international literature survey on energy-economic growth nexus: Evidence from country-specific studies. *Renewable and Sustainable Energy Reviews*, 38:951–959.

Plumecocq, G. (2014). The second generation of ecological economics: How far has the apple fallen from the tree? *Ecological Economics*, 107:457–468.

Pomeranz, K. (2000). *The Great Divergence: China, Europe, and the Making of the Modern World Economy*. Princeton University Press, Princeton, NJ.

Prigogine, I., Nicolis, G., and Babloyantz, A. (1972a). Thermodynamics of evolution. *Physics Today*, 25(11):23–28.

Prigogine, I., Nicolis, G., and Babloyantz, A. (1972b). Thermodynamics of evolution. *Physics Today*, 25(12):38–44.

Prigogine, I. and Stengers, I. (1984). *Order out of Chaos*. New Science Library, Boulder, CO.

Proops, J. L. R. (1983). Organisation and dissipation in economic systems. *Journal of Social and Biological Structures*, 6(4):353–366.

Raine, A., Foster, J., and Potts, J. (2006). The new entropy law and the economic process. *Ecological Complexity*, 3(4):354–360.

Richerson, P. J. and Boyd, R. (2005). *Not by Genes Alone: How Culture Transformed Human Evolution*. University of Chicago Press, Chicago, IL.

Sahlins, M. (1972). *Stone Age Economics*. Aldine-Atherton, Chicago, IL.

Santos, J., Domingos, T., Sousa, T., and St. Aubyn, M. (2018). Useful Exergy Is Key in Obtaining Plausible Aggregate Production Functions and Recognizing the Role of Energy in Economic Growth: Portugal 1960–2009. *Ecological Economics*, 148:103–120.

Saviotti, P. P. and Pyka, A. (2008). Product variety, competition and economic growth. *Journal of Evolutionary Economics*, 18:323–347.

Schneider, E. and Kay, J. (1994). Life as a manifestation of the second law of thermodynamics. *Mathematical and Computer Modelling*, 19(6-8):25–48.

Schneider, E. D. (1988). Thermodynamics, ecological succession, and natural selection: a common thread. In Weber, B., Depew, D., and Smith, J., editors, *Entropy, Information, and Evolution*, pages 107–138. MIT Press, Cambridge, MA.

Schrödinger, E. (1945). *What is Life?* Cambridge University Press, Cambridge, UK.

Sciubba, E. (2011). What did Lotka really say? A critical reassessment of the "maximum power principle". *Ecological Modelling*, 222(8):1347–1353.

Shannon, C. E. (1948). A Mathematical Theory of Communication. *Bell System Technical Journal*, 27(3):379–423.

Sieferle, R. P. (1997). Das vorindustrielle Solarenergiesystem. In Brauch, H. G., editor, *Energiepolitik*. Springer, Berlin, DE.

Sieferle, R. P. (2001). *The Subterranean Forest: Energy Systems and the Industrial Revolution*. White Horse Press, Winwick, UK.

Smil, V. (2008). *Energy in Nature and Society: General Energetics of Complex Systems*. MIT Press, Cambridge, MA.

Smil, V. (2017). *Energy and Civilization: A History*. MIT Press, Cambridge, MA.

Smith, A. (1776). *An Inquiry into the Nature and Causes of the Wealth of Nations*. W. Strahan, T.Cadell, London, UK.

Sorrell, S. (2010). Energy, Economic Growth and Environmental Sustainability: Five Propositions. *Sustainability*, 2(6):1784–1809.

Southwood, T. (1981). Bionomic strategies and population parameters. In May, R. M., editor, *Theoretical Ecology*, pages 30–52. Blackwell Publishers Ltd., Oxford, UK.

Spencer, H. (1897). *First Principles*. D. Appleton & Company, New York, NY.

Stern, D. I. (2011). The role of energy in economic growth. *Annals of the New York Academy of Sciences*, 1219(1):26–51.

Swenson, R. (1989). Emergent attractors and the law of maximum entropy production: Foundations to a theory of general evolution. *Systems Research*, 6(3):187–197.

Swenson, R. (2010). Selection Is Entailed by Self-Organization and Natural Selection Is a Special Case. *Biological Theory*, 5(2):167–181.

Todd, E. (1985). *The Explanation of Ideology: Family Structure and Social Systems*. Blackwell Publishers Ltd., New York, NY.

Todd, E. (1987). *The Causes of Progress: Culture, Authority, and Change*. Blackwell Publishers Ltd., New York, NY.

Todd, E. (1990). *L'Invention de l'Europe*. Seuil, Paris, FR.

Todd, E. (2017). *Ou en Sommes-Nous ? Une Esquisse de l'Histoire Humaine*. Seuil, Paris, FR.

Ulanowicz, R. E. (2003). Some steps toward a central theory of ecosystem dynamics. *Computational Biology and Chemistry*, 27(6):523–30.

van den Bergh, J. C. J. M. (2007). Evolutionary thinking in environmental economics. *Journal of Evolutionary Economics*, 17(5):521–549.

Vermeij, G. J. (2009). Comparative economics: evolution and the modern economy. *Journal of Bioeconomics*, 11(2):105–134.

Warr, B., Ayres, R., Eisenmenger, N., Krausmann, F., and Schandl, H. (2010). Energy use and economic development: A comparative analysis of useful work supply in Austria, Japan, the United Kingdom and the US during 100 years of economic growth. *Ecological Economics*, 69(10):1904–1917.

Weber, B. H., Depew, D. J., Dyke, C., Salthe, S. N., Schneider, E. D., Ulanowicz, R. E., and Wicken, J. S. (1989). Evolution in thermodynamic perspective: An ecological approach. *Biology and Philosophy*, 4(4):373–405.

Weil, D. N. (2013). *Economic Growth*. Pearson Education, Harlow, UK, 3rd edition.

Wicken, J. S. (1980). A thermodynamic theory of evolution. *Journal of Theoretical Biology*, 87(1):9–23.

Witt, U. (1997). Self-organization and economics—what is new? *Structural Change and Economic Dynamics*, 8(4):489–507.

Witt, U. (2003). *The Evolving Economy: Essays on the Evolutionary Approach to Economics*. Edward Elgar Pub, Cheltenham, UK.

Wrigley, E. (1962). The Supply of Raw Materials in the Industrial Revolution. *Economic History Review*, 15(1):1–16.

Wrigley, E. A. (2013). Energy and the English Industrial Revolution. *Philosophical Transactions of the Royal Society. Series A: Mathematical, physical, and engineering sciences*, 371:1–10.

Wrigley, E. A. (2016). *The Path to Sustained Growth: England's Transition from an Organic Economy to an Industrial Revolution*. Cambridge University Press, Cambridge, UK.

Yen, J. D. L., Paganin, D. M., Thomson, J. R., and Mac Nally, R. (2014). Thermodynamic extremization principles and their relevance to ecology. *Austral Ecology*, 39(6):619–632.

Ziegler, H. (1963). Some extremum principles in irreversible thermodynamics. In Sneddon, I. N. and Hill, R., editors, *Progress in Solid Mechanics*, pages 91–193. Elsevier, Amsterdam, NL.