Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 97 (2016) 51 – 58

Energy Procedia

European Geosciences Union General Assembly 2016, EGU
Division Energy, Resources & Environment, ERE

Exergy and the economic process

Georgios Karakatsanis[a]*

[a]*Department of Water Resources and Environmental Engineering, National Technical University of Athens, Heroon Plytechneiou 9, 15870*

Abstract

Physical work generation requires the existence of a *heat gradient*, according to the universal notion of the *Carnot Heat Engine*; also the corner stone of the *exergy* concept. Heat gradient availabilities fundamentally drive systems' evolution. However, exergy is consumed irreversibly, via its gradual transformation to *entropy*. Extending Roegen's postulations [16], it is argued that exergy consumption founds *economic scarcity*, via: **(a)** human difficulty to produce large heat gradients on the Earth and **(b)** irreversible depletion of existing ones. Additionally, in the emerging *Anthropocene* epoch, exergy upgrades to a core concept for interpreting thermodynamically natural resource *degradation* and energy paradigm *transitions*.

Peer-review under responsibility of the organizing committee of the General Assembly of the European Geosciences Union (EGU)

Keywords: Physical work; heat gradient; Carnot Heat Engine; exergy; entropy; economic scarcity; Anthropocene; degradation; transition

1. Introduction

The Second Law of Thermodynamics (from now called 2nd Law) dictates that introduction/abduction of physical work in/from a system requires the existence of a heat gradient, according to the universal notion of the Carnot Heat Engine. This concept is the corner stone for the notion of exergy as well, as exergy is *the potential of physical work generation across the process of equilibration of a number of unified systems with different thermodynamic states.*

As energy concerns the *abstract ability* of work output, exergy concerns the *specific ability* of work output, due to the requirement for specifying a *reference environment* -in relation to which the thermodynamic equilibration takes place. Consequently, while (the) *energy is always conserved*, (the) *exergy is always consumed*. From that aspect, the

* Corresponding author. Tel.: +30-210772-2845; fax: +30-210772-2831.
E-mail address: georgios@itia.ntua.gr

Peer-review under responsibility of the organizing committee of the General Assembly of the European Geosciences Union (EGU)
doi:10.1016/j.egypro.2016.10.018

availability of heat gradients is what fundamentally drives the evolution of economic systems [1,3,4]. In addition, the consumption of exergy is irreversible, through the gradual transformation of useful physical work to *entropy*; hence, reducing its future economic availability. The paper discusses the utility of the exergy concept for the generalization of Roegen's approach [16] for all systems that are subject to mass and energy fluxes. It is argued that economic and ecological systems are highly coupled; with the irreversible exhaustion of available planetary exergy stocks [10,20], comprising the fundamental cause of *economic scarcity* –as the core concept of economic science. Specifically, we may consider that economic scarcity is founded in two major physically-based pressures. The first, is the allocation difficulty of very large heat gradients -within the Earth System- that would potentially make humanity's heat engines highly efficient. However, as it will be discussed in a later section, this was an inevitable cost of the Earth System's evolution process. The second, is the irreversible depletion of the existing heat gradients due to the validity of the 2nd Law; which is entropy production. Depletion of exergy (and production of entropy) occurs at the microscopic scale –as generation of *information* across the reordering of energy states- that -in turn- manifests at the macroscopic scale –as unavailability of useful work. This establishes the exergy concept's consistency for explaining economic scarcity from the molecular level. In addition, special issues of the exergy concept are discussed; the most important being the use of exergy in the emerging *Anthropocene* epoch -in which the integrated examination of social and ecological systems is vital for addressing adequately global environmental issues- with focus on interpreting *natural resource degradation* in thermodynamic terms and modelling the general process of *energy paradigm transitions*.

Nomenclature

η	Carnot Heat Engine Efficiency, $\eta \in (0,1)$
T	Temperature (for statistical mechanical or general use)
T_H	Temperature of the *Hot Tank* (in K)
ΔT_H	Temperature Change of the *Hot Tank* (in K)
T_C	Temperature of the *Cold Tank* (in K)
S	Entropy (in J/K)
ΔS	Entropy Change (in J/K)
$\theta^2 S$	Rate of Entropy Change ΔS
Q	Energy Flux (in J)
p_i	Probability of a Kinetic Energy State i
ε_i	Kinetic Energy State i
k	Boltzmann Constant
M	Number of Maximum Possible Configurations (or a distribution's bin width)
H	Shannon Entropy (Information) (in bits), $H \geq 0$
B	Chemical Reaction Rate
A	Kinetic Frequency Factor
E_A	Activation Energy
R	Universal Gas Constant
λ	Frequency of Individual Reaction
K	Rating at the Kardashev Scale, $K \geq 0$
t	Time Step (for general use)
$E_i(t)$	Exergy Consumption per Fuel Type i at Time Step t
$E_T(t)$	Total Exergy Consumption (of all fuel types) at Time Step t
C_i	Scale Factor of Exergy Use per Fuel Type i, $C \geq 1$
a	Parameter of Intrinsic Growth Rate of Use of Fuel Type i, $a \geq 1$
b	Parameter of Intrinsic Reduction Rate (eg. due to substitution) of Fuel Type i, $b \geq 0$
$N_i(t)$	Remaining Deposit of Fuel Type i at Time Step t, $N_i(t) \geq 0$

2. Heat Engines: A universal concept

Sadi Carnot (1796-1832) formulated (in 1824) parsimoniously the mechanism for physical work generation; also establishing the concept that became known as the *Carnot Heat Engine*. The concept suggests that physical work is generated from the equilibration process of heat gradients of a number of connected heat reservoirs with different thermodynamic states (here for the sake of generalization only differences in temperature will be considered and not in pressure). The magnitude of these heat gradients determines the efficiency of the heat engine as following:

$$\eta = 1 - \left(T_C \;/\; T_H \right) \tag{1}$$

The above short equation condenses numerous properties of a set of connected thermodynamic systems; the most significant being the setting of an *upper boundary* for *physical work generation* as a function of the systems' relative states. This systematization is universal and applies to every scale. For instance, the extreme temperature differences between the stars (eg. our Sun emitting radiation at ~5500 K) and background radiation of space (~3 K on average) comprise a heat engine of 99,9% overall efficiency, as far as the radiation that reaches the outer atmosphere of the Earth is concerned. Similarly, the Earth emits radiation at ~255 K to space, which makes an efficiency of 98,8% for this heat engine. In contrast, within the Earth System, as well as in human-made internal combustion engines, heat gradients are much lower. If somehow we could transcend the boundaries of space and time within the Earth and intervene a heat engine between the places in which the lowest and the highest temperatures were ever recorded ($T_H = 366{,}9\ K$; 15/07/1972; Furnace Creek; CA; USA; $T_C = 183{,}8\ K$; 21/07/1983; Lake Vostok; Antarctica), we would achieve a heat engine efficiency of only 49,9%. Respectively, the heat engine efficiency of a conventional fission reactor reaches 30%, while for a coal-fired plant 36%. Below, the proper use of the exergy concept is discussed.

2.1. Energy, environment and physical work

The frequently encountered terms *high energy*, *low energy* etc., comprise only intuitive or –in the best case- only empirical estimations. A reference to an object's *high energy* actually concerns the object's ability to produce a large amount of work. Hence, the first fair question that comes in mind after this observation is *in comparison to what*? Although the observer has already defined the object of comparison intuitively, this will not suffice for a complete scientific clause. To make the clause complete we must first define the *cause* for which an object can generate work. According to the 2nd Law, work can be produced only due to the existence of a thermodynamic gradient (either in temperature or pressure) in relation to a *well-defined reference environment*. Hence, the *exact* ability of the object to generate work fundamentally depends on *pre-defining* an environment, of which the object is a part, so that it's clear if the latter satisfies the above *necessary condition*. If –in contrast- the object is examined completely isolated from its environment, it can be easily realized that no conclusion can be derived on its ability to generate work. In simple terms, when an observer examines an object at T = 300 ^oC, he realizes high work generation ability as he empirically compares this temperature to a temperature that he is used to (eg. room temperature at 15 ^oC). Although the object within an environment of 300 ^oC contains kinetic (internal) energy embodied in its molecules, how much of this energy can it utilize to generate work? The answer is zero. An alternative statement is that the ability of work output in this object-environment system exists in *latent state*; only if the whole system is attached to another environment with different temperature, can then work be produced. *Ceteris paribus*, the above system contains exergy for any temperature other than 300 ^oC. This same object within an environment of –say- -90 ^oC could generate even more work than in the environment of 15 ^oC. Hence, the major utility of the Carnot Heat Engine (and exergy as its directly derived concept) is setting the proper scientific statement for the conditions under which physical work generation can be achieved. Hence, when there is reference to *high* or *low* energy, what is actually meant is high or low ability of work generation (exergy). For analysts who study integrated economic and ecological systems, exergy comprises a concept of high utility and importance [10,20] as it highlights the need of designing optimal processes across the (inevitable) degradation of physical work generation ability [7].

Consequently, it can be postulated that the existence of temperatures above absolute zero (0 K) concerns the *per se* existence of energy (as motion, irrespective of its ability to generate work), while the existence of thermodynamic gradients concerns the ability of physical work generation. Scientifically though, the concept of energy alone cannot cover all the range of these possible events, as anything above 0 K contains energy with a *theoretical* ability of work generation. For the *precise* ability of work generation, a complementary concept is needed; the concept of exergy. At this point we may generalize the above findings by setting one *necessary* and one *sufficient* condition for work generation *to* or *from* an object. The necessary (universal) condition is the existence of a temperature above absolute zero (0 K) and the sufficient condition is the existence of a different temperature from its well-defined environment of reference. While for the definition of energy only the first condition is required, for the definition of exergy both of them are required, which signifies the higher specialization of the latter concept.

3. Exergy consumption and entropy production

Exergy is directly related to the concept of *Entropy*, as it can alternatively be considered the potential of entropy production across heat gradient equilibration. In an *isolated* system, the entropy is the amount of work that has been inserted and transformed into random molecular motion. By definition, without any ability of heat abduction (eg. via convection), at that state -called *equilibrium state*- the properties of the distribution (eg. average, standard deviation) of the energy states of molecules do not change any further per unit time. Although individual permutations of the molecular energy states take place continuously, the *per unit time* state of the molecular ensemble remains constant; hence its distribution is *stationary*. In an isolated system this is the *maximum entropy state*, at which the potential of physical work generation –as organized molecular motion- is fully exhausted and exergy is fully consumed.

3.1. Entropy in the microscopic scale: Information generation

From the heat gradient equilibration process, derives a feature that is remarkable due to the natural asymmetry it creates; *irreversibility* of exergy consumption (and entropy production). Irreversibility manifests at the microscopic scale as *information generation* –on the energy states' population- and emerges at the macroscopic as *unavailability of work*. More specifically, irreversibility concerns the inability to return two thermodynamically connected systems –from which there are no losses to an exterior environment- at exactly their initial condition before the equilibration process took place, using exactly the same amount of energy that was initially in the system. The distribution of the energy states of molecules with the ensemble at equilibrium is expressed by the *Maxwell-Boltzmann Distribution* as:

$$p_i = \left(e^{-\varepsilon_i / k \cdot T}\right) / \sum_{j=1}^{M} e^{-\varepsilon_i / k \cdot T} \tag{2}$$

Equation (2) expresses the probability to find a molecule at a specific kinetic state. In Figure 1 (a), a schematic depiction of Boltzmann Distributions for each equilibrium state is (hot, cold and unified tanks) is designed.

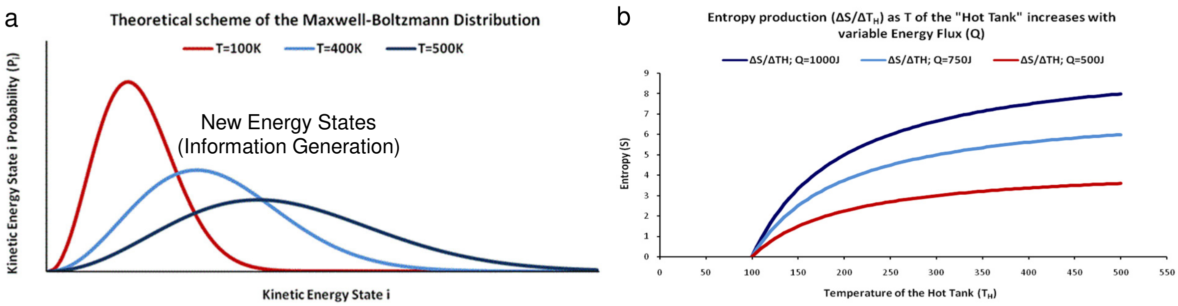

Fig. 1. (a) Each tank (cold at 100 K and hot at 500 K) is at equilibrium before their unification. After that, a new distribution (at 400 K) is formed. A part is common to each of the initial distributions, while a new part contains energy states that were recently populated, denoting *information generation*; (b) Classical entropy increases with both the heat gradient and the energy flux; although at diminishing rate ($\Delta S/\Delta T_H>0$; $\theta^2 S/\theta T_H^2<0$).

It is obvious that each of the three probability distributions depends primarily on the ensemble's temperature (as average kinetic energy). Hence, the energy states of the hot tank concentrate to higher values and of the cold tank to lower ones. The denominator in Eq. (2) contains the *Partition Function*, which is actually a normalization factor of the distribution, concerning the relation between the ensemble's number of molecules and their possible energy state combinations. For a given number of combinations, entropy is a positive function of the number of molecules. After the unification of the two ensembles -at the new equilibrium- the new distribution populates new energy states, of which each of the initial distributions had no memory; generating *information*. *Shannon's Entropy* [18] is a measure of the amount of information generated (new states) after the new equilibrium has been reached.

$$H = -\sum_{i=1}^{M} p_i \cdot ln\, p_i \tag{3}$$

According to Shannon's formula, the information grows along with the distribution's dispersal; meaning that the more energy states are populated the higher is the information generation. Indeed, in the above schematic, it is clear that the initial distributions are generally concentrated towards low or high energy states; leaving intermediate states less populated. However, after their unification, energy transfers from the hot molecules to the colder ones lead the new ensemble to an intermediate distribution form. New states are actually the irreversibility's cause, as they signify the consumption of exergy at the microscopic level that manifests at the macroscopic level as unavailability of work.

3.2. Entropy in the macroscopic scale: Physical work unavailability

What the increasing population of intermediate energy states -at the molecular level- impacts, is the constantly reducing ability of net work transfer from the hotter molecules to the colder ones. As both of the initial systems had no prior memory of these intermediate energy states, it is impossible to return the system to its initial parts only by using the same energy contained in the initial distributions. Some hot molecules continue to lose energy, while some cold molecules continue to gain energy, but this concerns only permutations; *on average* all energy state changes are immediately compensated so that the population of every energy state remains constant. At the macroscopic level the entropy change of the new ensemble is expressed by the following equation:

$$\Delta S = Q / T \Rightarrow \Delta S = Q / T_C - Q / T_H \tag{4}$$

The macroscopic expression of entropy change is based on the classical *Clausius* definition [7]. According to Eq. (4) and an explanation from the same authors [7], if we considered again the two heat tanks *C* and *H* with $T_C=100K$, $T_H=500K$ with a thermal energy flux $Q=2000kJ$ from $H \rightarrow C$, then based on the 2nd Law we have an entropy change $\Delta S_C = Q_C/T_C = 2000\ kJ/100\ K = 20\ kJ/K$; $\Delta S_H = -Q_H/T_H = -2000\ kJ/500\ K = -4\ kJ/K$, while the total entropy change is $\Delta S_T = \Delta S_C + \Delta S_H = 20\text{-}4 = 16\ kJ/K$. Expected symmetries –observed in *Newtonian Mechanics* so that $\Delta S_T=0$- do not apply. The unified system demonstrates preference towards an energy asymmetry and the incorporation of a part of the generated work into the molecules as random motion and not as organized motion that would be mechanically utilizable. If we attempted to return the system to its initial state, we would realize that for every *K* there is a deficit of *16 kJ* of the initial available work. As it is also shown in Fig. 1 (b), *the higher is the heat gradient the less is the cost in terms of entropy increase*. Alternatively, we could reinstate the tanks to their initial condition, however only by using additional work from some external source that would -in turn- increase the entropy in another part of the universe, being constantly consistent to what has been defined as the *universal increase of entropy*. This facilitates thermodynamic depletion of fuels and the need for discovering new exergy resources and deposits.

4. Exergy and ecological evolution

Planetary evolution could also be explained via the exergy concept. The *Earth System* operates daily at an exergy consumption intensity of ~1700TW, accounting for only 1% of the total incoming cosmic exergy intensity [5]. From that quantity a ~98% (1690TW) is associated with the Earth's radiation processes [~82% (1410TW) is scattered as atmospheric radiation and ~16% (280TW) as surface radiation], while only ~2,5% (45TW) is consumed for crustal processes. Reaching the current level of crustal exergy consumption was a matter of increasing harnessing of solar exergy across ecological diversification and growth. In short, the Sun emits short-wave radiation, consisting of high exergy photons. The Earth System consumes this exergy for global biogeochemical processes and emits long-wave radiation -of lower exergy- photons to space. The Hadean Earth (4,6-4Ga) emitted radiation at the near-infrared at T~513K; including radiation from heavy elements that still existed in abundance at the surface, as the distribution of elements -from the crust to the core- was under gravitational organization. With the transition to chemosynthetic life (4-3,5Ga) the Earth radiated at the near-infrared at ~423K, holding only partial control of incoming solar exergy and fragmented regional biogeochemical cycles. Since the transition to photosynthetic life (3,5Ga-to date), the Earth has been emitting infrared radiation at T~298K, along with rapid global biomass growth that consumes large amounts of solar exergy, integrating biogeochemical cycles and controlling nutrient fluxes for the global ecological metabolism.

5. Exergy and social evolution

The relation between energy use and social evolution is usually analyzed under the concept of *social complexity*. Taking as criterion the *energy paradigm* -defined as *the dominant pattern of energy harvesting from the environment* [11]- human social organization could historically be classified in three (3) major categories: **(a)** *Primitive societies* (hunter-gatherers), based on individual body engines **(b)** *Agricultural civilizations*, based on secondary solar exergy -in the form of chemical exergy of crops- and **(c)** *Fossil-fuelled civilizations*, based on secondary solar exergy -in the form of fossil fuels deposited in geological formations. Irrespective of the age examined, energy has always been a crucial evolutionary factor. For instance, in primitive human societies a typical diet ranged from 2kWh/d (gatherers) to 6kWh/d (4kWh for hunters without fire and 6kWh with fire). Some researchers [6,8,17] argue that the use of fire was the factor that drove –via improved metabolic brain processes- the evolution from primitive to agrarian societies and the consequent production of surpluses that –in turn- established trade. The agricultural age contains the largest part of social evolution, in which per capita energy use ranged from 20-30kWh/d via the utilization of animals. With the entrance to the *Industrial Revolution* (late 18th century), energy use per capita climbed to ~112kWh/d [13].

In every age, the increase of exergy availability is equivalent to labour substitution and creation of *social degrees of freedom* that leads to structural reconfiguration, specialization and diversification. Prigogine [15] considered the economy as an indicative case of *dissipative structures*, of which the complexity emerges after an increase in energy availability. His approach is followed by Tainter [19] who introduced the concept of the *Energy-Complexity Spiral* and studied the collapse of many civilizations in energetic terms. The current availability of international trade data, has allowed the development of *economic complexity* indices [9] and studies of energy use to social complexity [2].

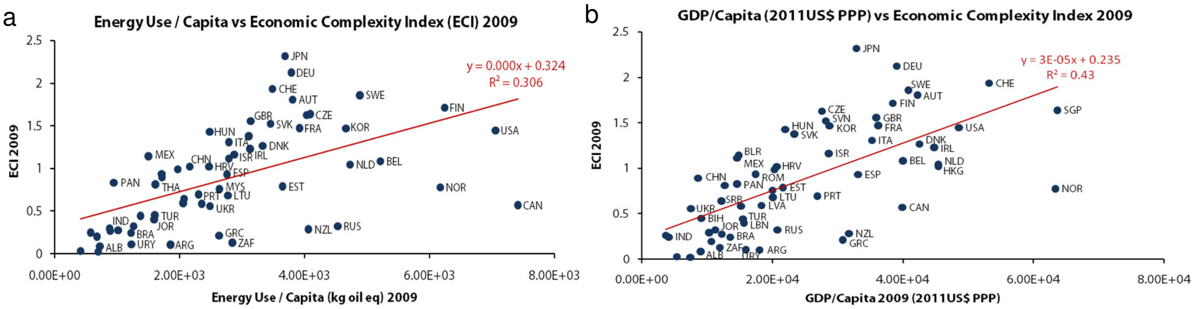

Fig. 2. (a) Correlation between *Primary Energy Use per Capita* and the *Economic Complexity Index* (ECI) for 2009. The ECI was developed by Hausmann et al. [9]; (b) Correlation between *GDP per Capita* and the *ECI* for 2009. The source of energy and GDP data is the World Bank [21].

The ECI embodies diversification (nodes), trade interconnections (links) and difficulty to copy a country's output composition. Primary energy was chosen as a measure closer to exergy [14]. It is notable that according to ECI 2009 country correlations, the economic complexity of most developing countries is more depended on energy/capita.

5.1. Exergy and the Anthropocene

Humanity's shaping of the *Anthropocene* is a subject of debate [8]. In this paper, a proposed general criterion is *humanity's ability to impact thermodynamically the Earth System's fluxes*. A relevant index is the *Kardashev Scale* (KS) [12]; with C. Sagan's formula as benchmark, fitted to the scale of daily planetary exergy flux intensities (TW):

$$K = \left(log_{10} E_T(t) - 6\right) / 10 \tag{5}$$

The KS originally consists of 3 scales, with $K=1$ being a benchmark at which our civilization harnesses *primary energy* from all possible planetary sources. Global primary energy use data (of 2010) in Eq. (5), suggest a $K \sim 0{,}72$.

$$E_T(t) = \sum_{i=1}^{n} E_i(t) \tag{6}$$

Eq. (6) denotes global exergy resource variety [10] that can affect humanity's exergy consumption composition in time. Moreover, the KS may relate to heat wastes' production that can destabilize interlocked ecosystem fluxes.

$$B = A / \left(e^{E_A / R \cdot T}\right) \tag{7}$$

The argument for the above equation is that environmental capacities to absorb pollutants rely on the stability of biogeochemical cycling sequences, which –in turn- rely on the sensitive balance between *Activation* and *Gibbs Free* energies. Heat wastes from the exergy consumption of fossil fuels, increase temperatures and provide the necessary activation energy to reactions that distort interlocked biogeochemical sequences; accumulating undesirable products.

5.2. Exergy and the energy paradigm transition process

A crucial dimension of the Anthropocene, concerns the process of *energy paradigm transitions*, which is directly connected to *sustainability*. A *general* process of exergy consumption of a fuel *i*, is based on the *Gamma Function*:

$$E_i(t) = C_i \cdot t^a \cdot e^{-b \cdot t} \tag{8.1}$$

Modern economies base their complex operations on non-diminishing exergy fluxes; however under the pressure of their depleting sources. Hence, *energy paradigm* transitions are inevitable, in which various fuel types coexist.

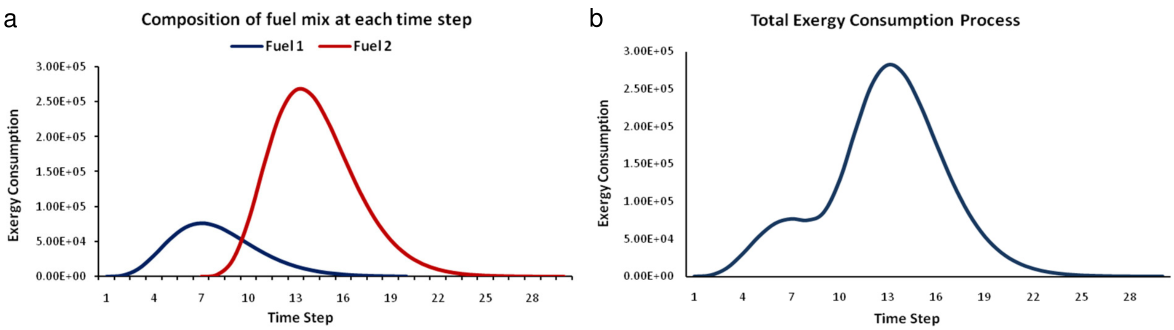

Fig. 3. (a) Exergy consumption processes of two (2) fuels. Use paths and fuel mix compositions depend on parameter values; $C_1=C_2=100$; $a_1=7$; $a_2=8$; $b_1=-1$; $b_2=-1{,}1$; (b) Cumulative exergy consumption path. For a constant non-diminishing total exergy consumption level, every reduction in the use of Fuel 1 must *at least* be compensated by a respective increase in the use of Fuel 2. In the example, this condition is met until $t=13$.

The model of Eq. (8.1) is considered more flexible than typical logistic growth models, as it does not assume *by default* asymptotic convergence to a capacity but considers it a specific (desirable) case between the substitution and the depletion rates of the fuel deposits, for avoiding fuel crises. The general formulation of a deposit's depletion is:

$$N_i(t) = N_i(0) - \int_0^t E_i(t)dt \tag{8.2}$$

In Eq. (8.2) there is no prior assumption on the coincidence between deposit depletion and the transition process completion. The transition dynamics depend primarily on the ratio between the parameters of Eq. (8.1). However, it is generally expected that societies possess the mechanisms (eg. R&D) for discovering new exergy sources in order to maintain a non-diminishing exergy consumption level and avoid the downward parts of the curves in Fig. 3 (a,b). This succession of energy paradigms usually results to a monotonically increasing multiple logistic growth pattern.

6. Concluding Remarks

The paper examines thoroughly the microscopic (statistical mechanical) foundations of exergy consumption and entropy production in order to substantiate their macroscopic manifestation as physical work unavailability, which is the physical foundation of economic scarcity. In turn, it discusses why complex economic systems prefer large heat gradients; extending the analysis to the impact of the fossil-fueled civilization transition on social organization, via the unprecedented substitution of human labor and release of social complexity potentials. Within the Anthropocene context, the inevitable thermodynamic integration of social and ecological systems is also discussed. In conclusion, the importance of energy paradigm transition processes is examined as an issue of the new epoch's sustainability.

References

[1] Ayres Robert U, Warr Benjamin. The Economic Growth Engine. Cheltenham: Edward Elgar Publishing Ltd; 2009.

[2] Bond Stephen Richard. Relating Energy Use to Economic Complexity (MSc Thesis). Texas: The University of Texas at Austin; 2015.

[3] Boulding Kenneth E. Ecodynamics: A New Theory of Societal Evolution. Beverly Hills: Sage Publications; 1978.

[4] Chen Jing. The Physical Foundations of Economics. Singapore: World Scientific Publishing Co Pte Ltd; 2005.

[5] Chen GQ. Exergy consumption of the Earth. Ecological Modelling 2005; 184: 363-80.

[6] Cordain Loren et al. Plant-animal subsistence ratios and macronutrient energy estimations in worldwide hunter-gatherer diets. Am J Clin Nutr 2000; 71: 682-92.

[7] Dincer Ibrahim, Cengel Yunus A. Energy, Entropy and Exergy Concepts and Their Roles in Thermal Engineering. Entropy 2001; 3: 116-49.

[8] Fischer-Kowalski Marina, Krausmann Fridolin, Pallua Irene. A sociometabolic reading of the Anthropocene: Modes of subsistence, population size and human impact on Earth. The Anthropocene Review 2014; 1: 8–33; 2014.

[9] Hausmann Ricardo et al. The Atlas of Economic Complexity. Cambridge MA: Puritan Press; 2011.

[10] Hermann Weston A. Quantifying global exergy resources. Energy 2006; 31: 1685-1702.

[11] Karakatsanis Georgios. Modelling the energy use dynamics of human civilizations within the theory of cultural evolutionism. Barcelona: Proceedings of the 7th Biennial International Workshop "Advances in Energy Studies"; 2010.

[12] Kardashev Nikolai. Cosmology and Civilizations. Astrophysics and Space Science 1997; 252: 25-40.

[13] Kümmel Reiner. The Second Law of Economics. New York: Springer-Verlag; 2011.

[14] Lindenberger Dietmar, Kümmel Reiner. Energy and the state of nations. Energy 2011; 36: 6010-18.

[15] Prigogine Ilya. Time, Structure and Fluctuations, Science 1978; 201(4358): 777-85.

[16] Roegen Nicolas Georgescu. The Entropy Law and the Economic Process. Cambridge MA: Harvard University Press; 1971.

[17] Pennisi Elizabeth. Did Cooked Tubers Spur the Evolution of Big Brains? Science 1999; 283(5410): 2004-5.

[18] Shannon Claude E. A Mathematical Theory of Communication. The Bell System Technical Journal 1948; 27: 379-423; 623-56.

[19] Tainter Joseph. Problem Solving: Complexity, History, Sustainability. Population and Environment 2000, 22: 3-41.

[20] Wall Goran. Exergy Capital and Sustainable Development. Kos: Proceedings of the 2nd International Exergy, Energy and Environment Symposium; Paper No. XII-I49; 2005.

[21] World Bank. World Development Indicators (WDI) 2015. Electronically available at: http://databank.worldbank.org/data/views/variableselection/selectvariables.aspx?source=world-development-indicators