Exergy and the economic process

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Summary

The *Second Law of Thermodynamics* (2nd Law) dictates that the introduction of *physical work* in a system requires the existence of a *heat gradient*, according to the universal notion of *Carnot Heat Engine*. This is the corner stone for the notion of *exergy* as well, as exergy is actually the potential of *physical work generation* across the process of equilibration of a number of unified systems with different thermodynamic states. However, although *energy* concerns the *abstract* ability of work generation, *exergy* concerns the *specific* ability of work generation, due to the requirement for specifying an *environment of reference*, in relation to which the thermodynamic equilibration takes place; also determining *heat engine efficiencies*. Consequently, while energy is always conserved, exergy –deriving from heat gradient equilibration- is always consumed. According to this perspective, the availability of heat gradients is what fundamentally drives the evolution of *econosystems*, via enhancing –or even substituting- human labor (Boulding 1978; Chen J. 2005; Ayres and Warr 2009). In addition, exergy consumption is *irreversible*, via the gradual transformation of useful physical work to *entropy*; hence reducing its future economic availability. By extending Roegen's relative approach (1971), it could be postulated that this irreversible exhaustion of exergy comprises the fundamental cause of *economic scarcity*, which is the corner stone for the development of economic science. Conclusively, scarcity consists in: **(a)** the difficulty of allocating -in the Earth System- very high heat gradients that would make humanity's heat engines very efficient and **(b)** the irreversible depletion of existent heat gradients due to entropy production. In addition, the concept of exergy could be used to study *natural resource degradation* and *pollution* at the biogeochemical level and understand why heat gradient scarcity in the Earth System was eventually inevitable. All of these issues are analyzed both theoretically and quantitatively.

Keywords: 2nd Law, heat gradient, Carnot Heat Engine, reference environment, entropy, scarcity, resource degradation

Contribution of the Project

Energy is **conserved** but its ability to generate physical work is **consumed** across heat gradient depletion. Exergy consumption (or destruction) can be also founded in *statistical mechanics*. *Exergy* is an *integrated concept* as it incorporates *a priori* the constraints of **heat gradient availability** and **heat waste capacity** that have been a determinant for econosystems' productive capability, internal sophistication (complexity) and growth.

1. Heat Engines: A universal concept

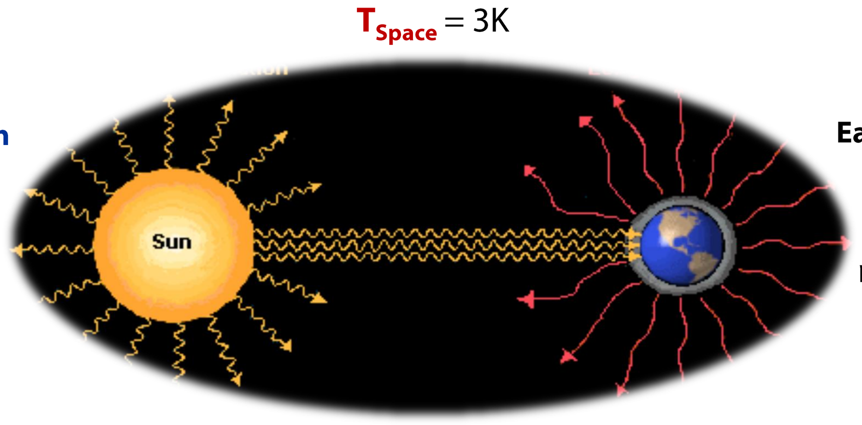
Sadi Carnot (1796-1832) postulated (1824) parsimoniously the mechanism of *physical work generation*; incorporated to the concept that later became known as the *Carnot Heat Engine*. The concept dictates that physical work derives for the process of *heat gradient equalization* of connected heat reservoirs. The size of the heat gradients determines the efficiency of the Carnot Heat Engine.

$$\eta = 1 - (T_C / T_H)$$

η = Heat Engine efficiency, $\eta \in (0,1)$
T_C = Temperature of **cold tank** (in K)
T_H = Temperature of **hot tank** (in K)

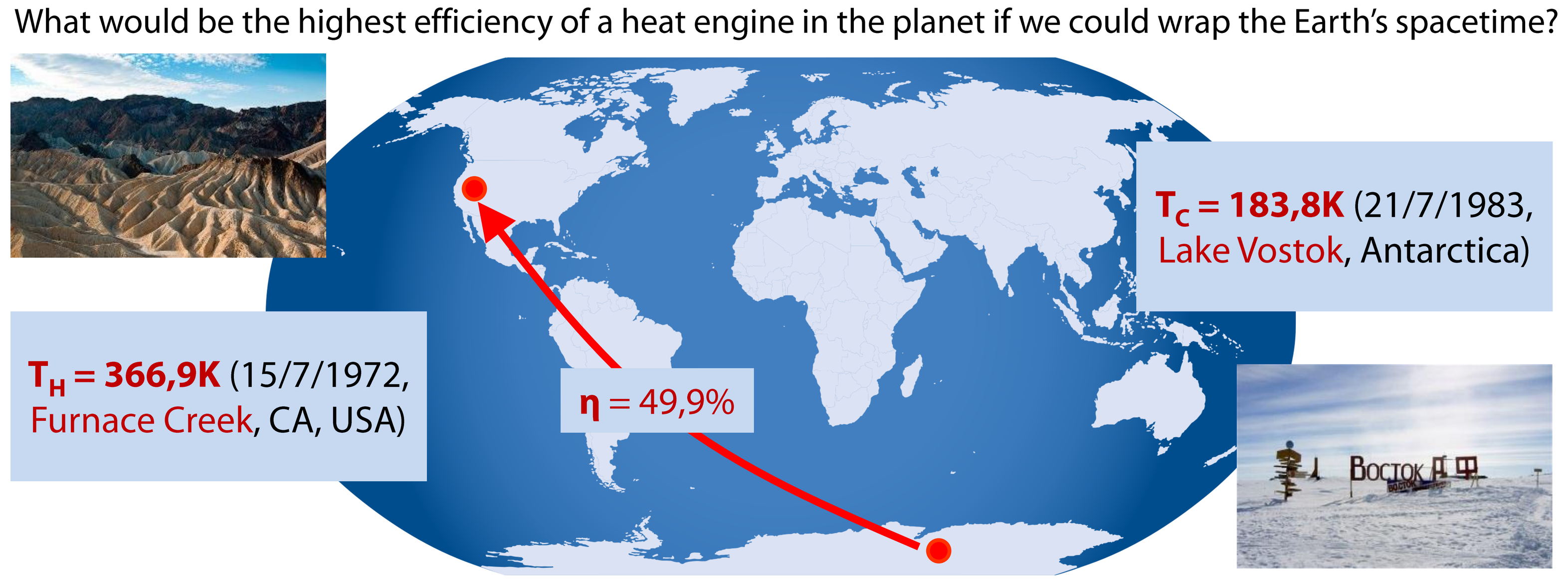
The Sun's and the Earth's radiation as Carnot Heat Engine

Direct black-body radiation to space has very high efficiency due to the extreme temperature gradients

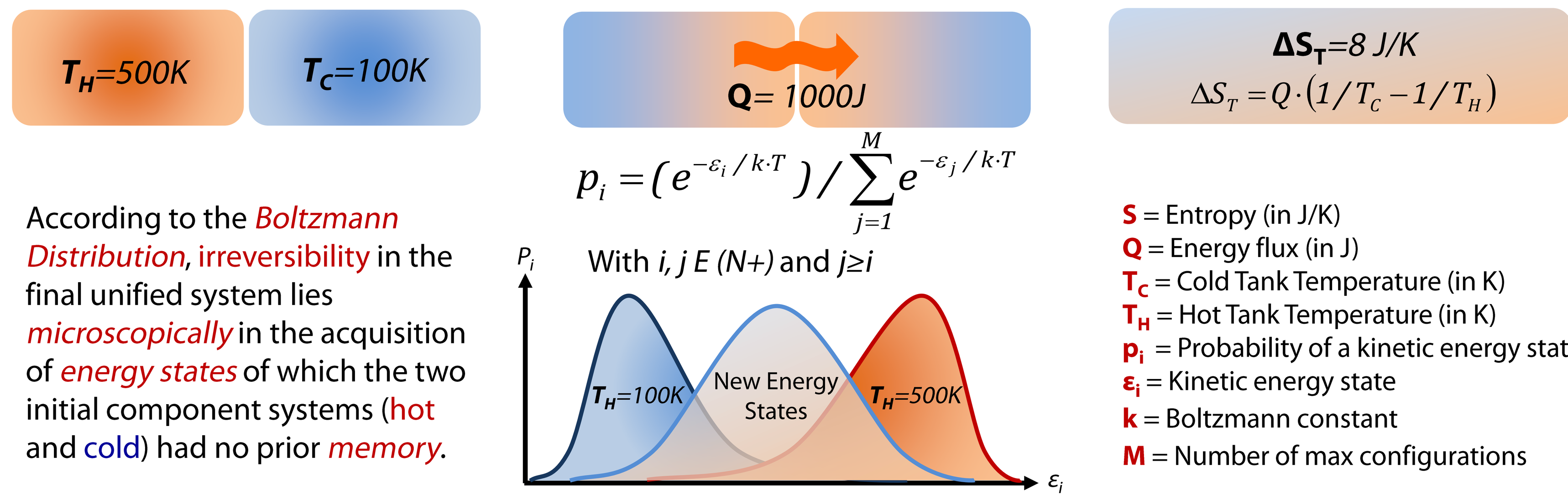


The most efficient Heat Engine on Earth (with no constraints on space and time…)

What would be the highest efficiency of a heat engine in the planet if we could wrap the Earth's spacetime?

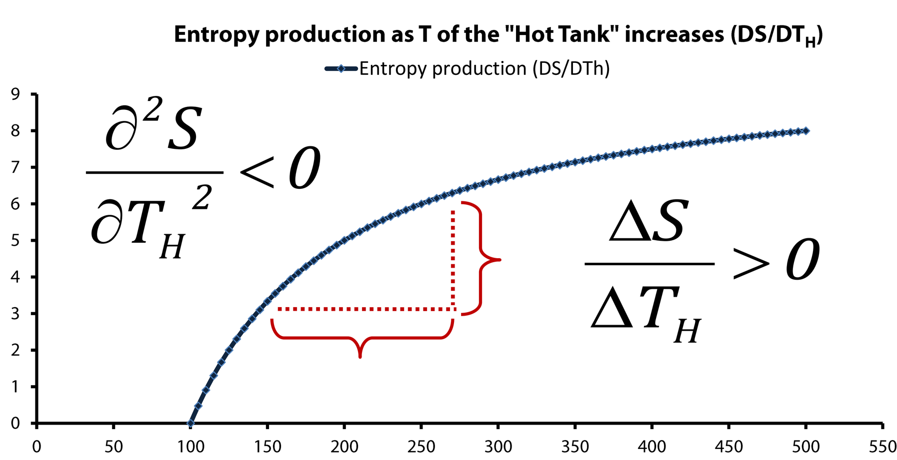


2. Exergy destruction and statistical mechanics



According to the *Boltzmann Distribution*, *irreversibility* in the final unified system lies *microscopically* in the acquisition of *energy states* of which the two initial component systems (hot and cold) had no prior *memory*.

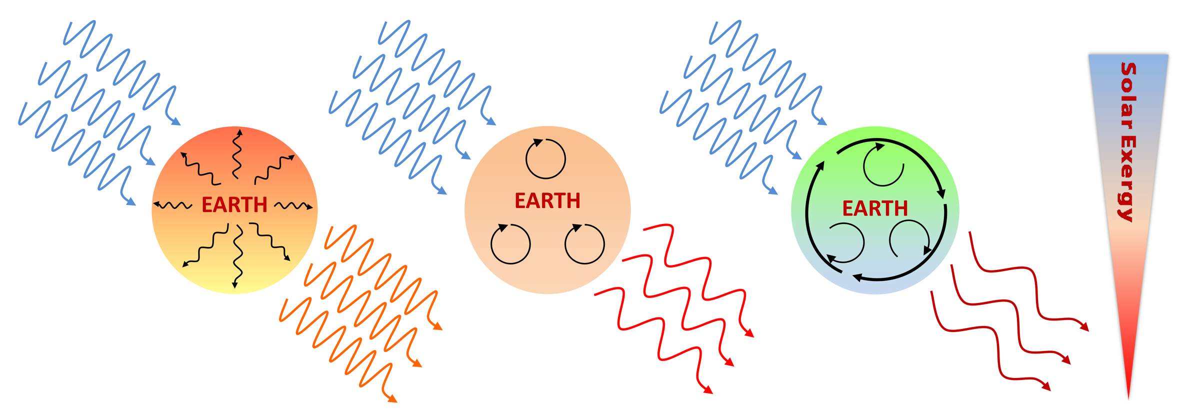
S = Entropy (in J/K)
Q = Energy flux (in J)
T_C = Cold Tank Temperature (in K)
T_H = Hot Tank Temperature (in K)
p_i = Probability of a kinetic energy state
ε_i = Kinetic energy state
k = Boltzmann constant
M = Number of max configurations



Entropy and economic scarcity

Economics is called *the science of scarce resources*. For any given amount of thermal energy flux (*Q*), the *entropy production rate decreases with the increase of the heat gradients*. Hence, economic scarcity lies: (a) in the *scarcity* of high heat gradients (high physical work potential) in the Earth and (b) the *scarcity* of recoverable physical work.

3. Exergy consumption and the Earth System's evolution



Hadean: 4,6-4 Ga Surface Radiation Emission at T~513K (Near Infrared)

Chemosynthesis: 4-3,5 Ga Surface Radiation Emission at T~423K (Near Infrared)

Photosynthesis: 3,5 Ga-today Surface Radiation Emission at T~298K (Infrared)

Exergy and the biosphere

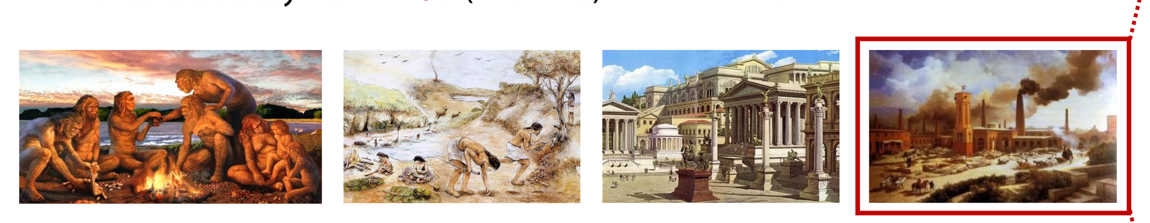
The biosphere functions at a daily level of exergy consumption (*Chen G. 2005*). The *Hadean earth* lacked any kind of life form; the evolution of *chemosynthetic life* created partial and generally fragmented biogeochemical control. With the transition to *photosynthetic life*, global biomass increased quite rapidly, consuming large amounts of solar exergy and *controlling energy and nutrient fluxes* in both regional and global level.

4. Exergy, power and human productivity

Daily energy budgets per capita (based on *Kümmel 2011*):

- ✓ Gatherers' (fruits, vegetables) Society = **2 kWh/d**
- ✓ Hunters' Society ~**3-4 kWh/d** (without fire)
- ✓ Hunters' Society ~**6 kWh/d** (with fire)

} **Primitive Societies** (Muscle heat engines)

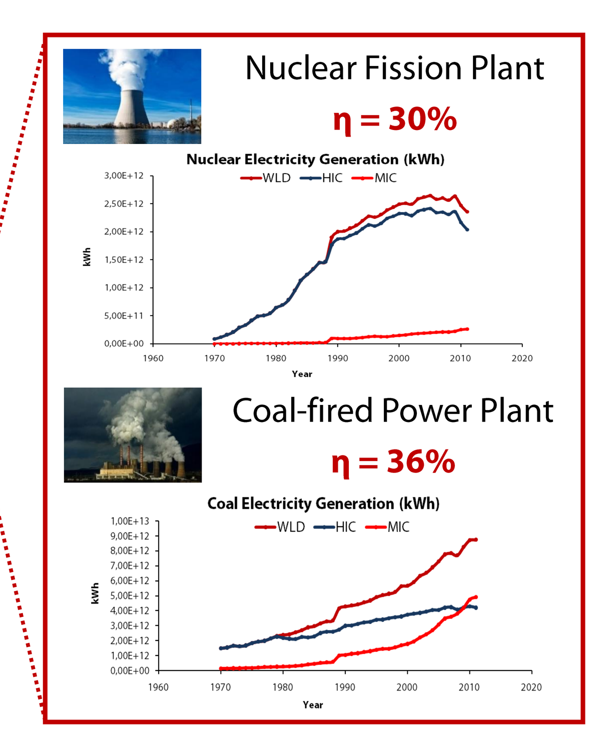


- ✓ Classical and Roman Ancestry = **20kWh/d**
- ✓ Middle Ages (1400 AC) = **30 kWh/d**

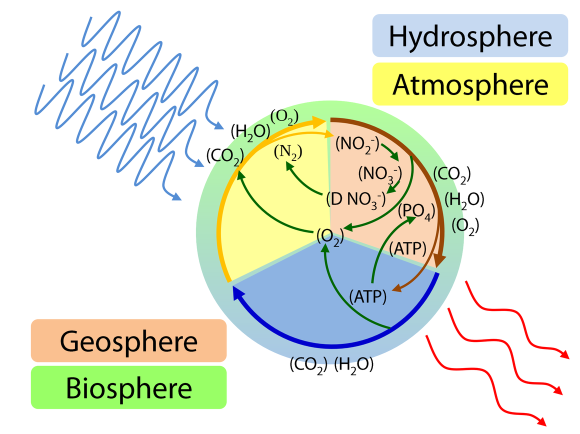
} **Agricultural Civilization** (Biochemical solar input stocks)

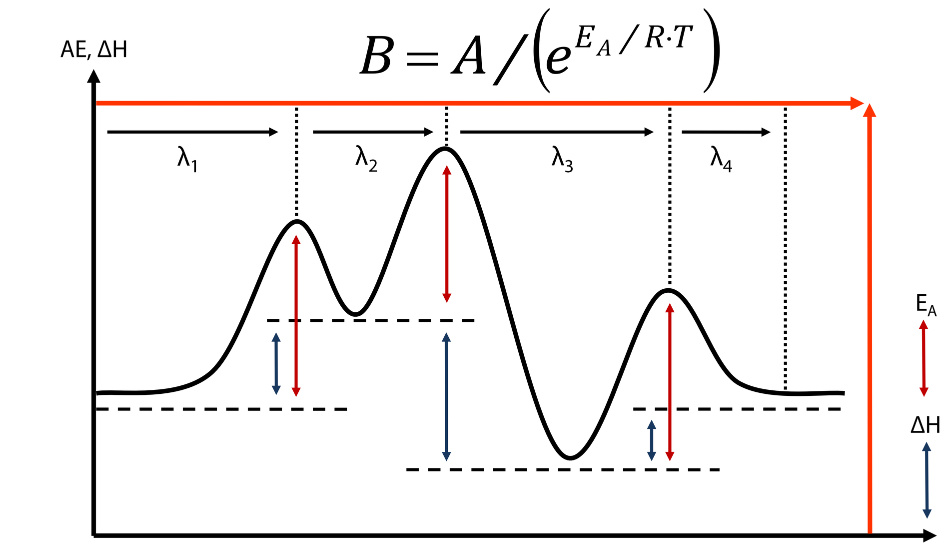
- ✓ Industrial Revolution (1850 AC) = **76 kWh/d**
- ✓ Modern Electrification Era = **112 kWh/d**

} **Fossil-fueled Civilization** (Fossil solar input stocks)

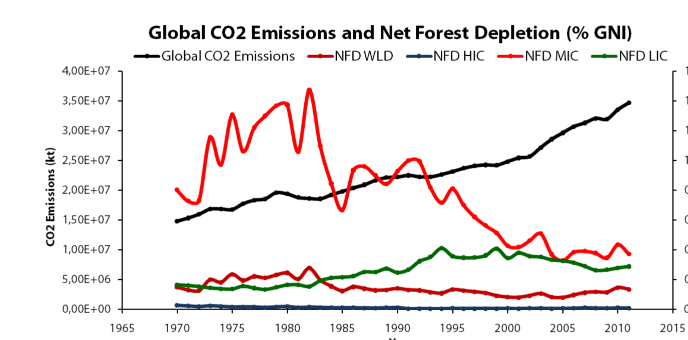


5. Exergy, pollution and biogeochemical cycles





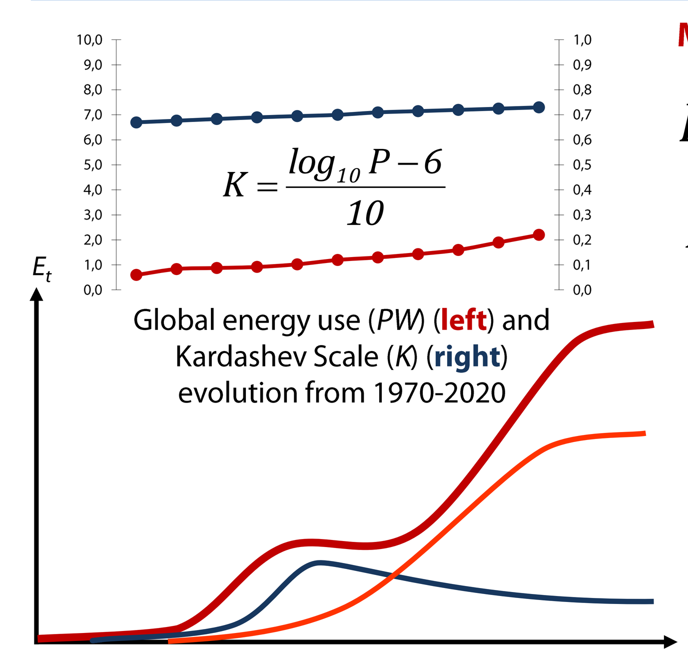
B = Chemical Reaction Rate
A = Kinetic Frequency Factor
E_A = Activation Energy
R = Universal Gas Constant
T = Temperature
ΔH = Gibbs Free Energy
λ = Frequency of Individual Reaction



The environment as exergy wastes' tank

Environmental capacity to absorb pollutants relies on the stability of the *biogeochemical cycling sequence*, which in turn relies on a sensitive balance of *Activation* and *Gibbs Free Energies*. Heat wastes from exergy consumption (like CO_2) in combination to *global forest depletion*, increase temperatures, providing the necessary Activation Energy to reactions that otherwise would not be produced. That *distorts normalities* (periodicities) in biogeochemical sequences; creating accumulation of *undesirable chemical products* (pollutants).

6. Exergy and the limits to growth



Global energy use (*PW*) (**left**) and Kardashev Scale (*K*) (**right**) evolution from 1970-2020

Modelling exergy macrodynamics of human civilizations

$$E_i(t) = A_i \cdot t^a \cdot e^{-b \cdot t}; R_{it} = R_{i0} - \int_0^t E_i(t)dt$$

$$E_{Tt} = \sum_{i=1}^{n} E_{it}$$

$A, a \geq 1; b \geq 0$

E_i = Exergy use / fuel type
A = Scale factor of exergy use
a = Intrinsic growth of E
b = Reduction rate of fuel *i* use
R_{i0} = Initial exergy stock / fuel type

Exergy and the energy paradigm transition process

Civilization exergy use follows multiple logistic growth dynamics, based on the co-existence and succession cycles of exergy stocks' (blue and orange curves) utilization, so that total exergy use (red curve) increases. For renewables, ***b*** is constant and =0, while for exhaustibles is >0, so that E_{it} diminishes monotonically.

7. Conclusions

- ✓ Exergy derives from the universal concept of Carnot Heat Engine.
- ✓ Exergy is an integrated concept, informing on the actual ability of energy to do physical work.
- ✓ Exergy is equivalent to energy quality; thus is destroyed, while energy is always conserved.
- ✓ Exergy destruction is founded in statistical mechanics as proportional size to information production, via the occupation of new energy states across thermodynamic equilibration.
- ✓ Exergy informs not only on the available work but where it comes from as well; hence for economics it is a more useful concept on natural resource availability than energy.
- ✓ Economic scarcity is founded in: (a) the difficulty to find very large heat gradients on the planet and (b) the irreversibility of the available heat gradients' consumption.
- ✓ The evolution of the Earth's biosphere consists in the increase solar exergy consumption.
- ✓ Pollution can be interpreted as the distortion of the energetic sequence of biogeochemical processes; either of their power or frequency due to heat wastes after exergy is consumed.
- ✓ The evolution of civilization lies in the increase of exergy resource consumption, via a sequence of discovering stocks of higher abundance, heat gradient potential and power.

Sign Nomenclature

Progress Report

Conceptualization: Indicates a conceptual scheme or a theoretical visualization of an important energetic process

Complex System: Indicates the presence of a complex system across the performance of an energetic process

About the Author

Georgios Karakatsanis is an economist; graduate of ***Athens University of Economics and Business (AUEB)***, from which he received training in the field of *International Economics*. He continued his studies in ***National Technical University of Athens (NTUA)***, from which he gained a MSc. in the field of *Environment and Development*. Currently he is a joint PhD Candidate in ***NTUA*** and ***Technische Universität München (TUM)***. His core research interests are: energy, water resources, economic development and growth, innovation finance, economic complexity, economic geography, econometrics and agriculture. His area of interest is Africa, with Ethiopia as his focus country, which experiences its first historical phase of development and industrialization via rapid increase of energy use.

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