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Exergy and the economic process

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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*.

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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

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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, $N_i(t) \geq 0$