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Misuse of thermodynamic entropy in economics

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ABSTRACT

The direct relationship between thermodynamic entropy and economic scarcity is only valid for a thermodynamically isolated economy. References to the second law of thermodynamics in economics within the context of scarcity ignore the fact that the earth is not an isolated system. The earth interacts with external sources and sinks of entropy and the resulting total entropy fluctuates around a constant. Even if the mankind finally proves unable to recycle industrial waste and close the technological cycle, the economic disruption caused by the depletion of natural resources may happen while the total thermodynamic entropy of the ecosystem remains essentially at the present level, because the transfer of chemically refined products may not increase significantly the total entropy, but it may decrease their recyclability.

The inutility of industrial waste is not connected with its entropy, which may be exemplified with the case of alumina production. The case also demonstrates that industrially generated entropy is discharged into surroundings without being accumulated in ‘thermodynamically unavailable matter’.

Material entropy, as a measure of complexity and economic dispersal of resources, can be a recyclability metric, but it is not a thermodynamic parameter, and its growth is not equivalent to the growth of thermodynamic entropy.

1. Introduction

As the intensity of human activity grows, the finiteness of available resources related to the concept of scarcity in economics becomes an important problem. Georgescu-Roegen [1] put forth the SLT (Second Law of Thermodynamics) as the basis of economic scarcity, implicitly assuming material entropy as an equivalent of thermodynamic entropy. Indeed, entropy is ‘produced’ in non-equilibrium processes, and it is associated with the quality of energy: low-entropy energy is more useful. Thus, entropy production implies depreciation of energy resources. This makes entropy a seemingly good measure of economic scarcity and depletion of resources, which explains the role of entropy in ecological economics. This paper is intended to demonstrate that thermodynamic entropy cannot be a measure of economic scarcity and references to the SLT within this context are erroneous. In the absence of the relation to the thermodynamic entropy, Georgescu-Roegen's material entropy can be understood as a recyclability measure similar to the Shannon entropy.

Despite a long debate about the thermodynamic nature of economic scarcity (the Section 2 includes a brief description of this debate and the Section 3 explains its flaws), there have been no attempts to estimate quantitatively ‘real-life’ entropy generation within an economic process and analyze its sinks in connection with the thermodynamic view on material entropy. The case of alumina production described here in the Section 4 clarifies the connection between entropy production, entropy accumulation and economic availability of industrial waste. The Section 5 describes the relationship between the anthropogenic entropy production in the Bayer process and natural entropy sinks to show the relevance of the diathermal character of the earth for the discussion of scarcity. Informational aspects of material entropy are discussed in the Section 6, which demonstrates that, despite references to thermodynamics, material entropy used as a synonym of dispersal is not a thermodynamic but rather informational parameter, a measure of recyclability of economic products.

The paper does not consider the entire relationship between thermodynamics and economics which is generally beneficial (thermoeconomic optimization is an example [2]). However, physical reasoning outside the context of quantitative physical models poses a problem. Hammond argued that references to thermodynamics in economics often “simply reflect a weak analogy

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or metaphor, rather than represent< … > thermodynamic limits in a physical sense" [3]. This work exemplifies his statement.

2. Entropy as an estimate of scarcity

Georgescu-Roegen was the first to assume the close connection between entropy and economic scarcity ("the Entropy Law is the taproot of economic scarcity" [4]) in his series of works starting with [1]. In Ref. [5] Georgescu-Roegen described 'unavailable' high-entropy matter-energy and stated that it cannot be used again in economy. In this analysis he used the term 'material entropy'[1] as a measure of homogeneity or uniformity of matter in the earth ecosystem. Finally, he formulated the so-called 4th law of thermodynamics ("In a closed system, the material entropy must ultimately reach a maximum" [5:269]).

While the SLT postulates the existence of entropy based on experimental evidence so that its elementary change equals $\delta Q/T$, the existence of 'material entropy' as a property is unfounded. The classical SLT reads that entropy reaches a maximum in an isolated system, not a closed one. The problem with multiple references to entropy in ecological economics is that the newly suggested 4th law is implicitly merged with the perfectly established SLT: the adjective 'material' is omitted and the entropy becomes seemingly thermodynamic. Then, the neglect of the boundary conditions makes it possible to mistake a closed system for an isolated one. As a result, a new 'anthropogenic entropy' emerges and tends towards a maximum in a closed but not isolated system.

Despite an almost unanimous critical reaction to his 4th law, Georgescu-Roegen's analysis attracted followers such as H.E. Daly [8,9] (see a more detailed review in Ref. [10]) emphasizing the fundamental importance of low entropy [9]. Lozada reassured the importance of the SLT for economics [11]. Krysiak analyzed the consequences of the SLT for economic activity and concluded that "limits to growth of production and consumption are likely to exist" [12]. Tietenberg and Lewis [13] referred to the 'entropy law'. So did Nafziger having concluded that "Georgescu-Roegen's perspective is one not of decades but of millennia, as his preoccupation is with our survival as a species" [14: 452].

Valero and Valero elaborated on Georgescu-Roegen's reasoning in ecological economics and suggested to switch from entropy accounting to exergy [15], which causes additional complication. Exergy is a relative property depending on the reference environment. Defining the reference environment is problematic because it is the degradation of the environment itself that is under consideration. Thus, what separate entity could be used as a reference? The authors formulated the concept of "a completely degraded crepuscular planet with the absence of fossil fuels and mineral deposits" [15:229], but this state is perfectly abstract and hypothetic. Using it as an exergy reference environment is speculative because the definition of exergy includes the dead-state equilibrium with the reference environment, not a comparison with an abstract hypothetic state.

The use of the SLT as the basic principle underlying the economic scarcity has already been criticized by Ayres who demonstrated that recycling in a diathermal system ('spaceship economy' with 'sufficient energy flux') decouples economic activity from limitations imposed by SLT [16]. Gillett indicated that the idea of entropy 'accumulating' in the earth's biosphere is unwarranted because the earth interacts with two thermal reservoirs [17]. Finally, Young criticized Georgescu-Roegen's entropic scarcity principle as inapplicable to the diathermal earth as well as his use of material entropy [18]. Surprisingly, this criticism did not include specific estimates of entropy production and entropy sinks which are described below in the Section 4 And 5.

3. Entropy balance

Since entropy is a property of a system, entropy as a parameter makes no sense without a definition of the system which 'has' the entropy. The definitions of a thermodynamic system, its boundary and the form of boundary conditions depend on the problem under consideration, but these definitions should be described appropriately. In non-equilibrium thermodynamics, fluid dynamics and heat transfer physics, the classical thermodynamic equilibrium becomes a local phenomenon due to the introduction of the elementary volume. This allows to transform thermodynamic properties into differentiable scalar fields such as $T = T(x,y,z,t)$, but it does not revoke the necessity to describe boundary conditions. Moreover, in addition to boundary conditions, one has to define initial conditions to compute the evolution of the system. Works on 'entropic scarcity' use entropy without definitions of thermodynamic system. For example, Daly and Farley claimed that the "linear throughput <of matter-energy> is the flow of raw materials and energy from the global ecosystem's sources of low entropy (mines, wells, fisheries, croplands), through the economy, and back to the global ecosystem's sinks for high entropy wastes (atmosphere, oceans, dumps)" [9:29]. This formulation may suffice in supply chain management, but it does not define a thermodynamic system.

Given the definition of the thermodynamic system, initial and boundary conditions, the rate of entropy change can be written as a balance equation:

$$\frac{dS}{dt} = \oint \frac{\dot{Q}}{T} d\upsilon + \oint \dot{m} s d\upsilon + \int \Omega dv, \tag{1}$$

The right side of the equation includes entropy transfer caused by heat exchange across the boundary (zeroed for adiabatic systems), entropy brought with mass flows into the system (for an open system) and the entropy production term Ω (υ denotes the boundary of the system and v is its volume). In this equation, mass flows and heat fluxes represent the boundary conditions. The mass flow term in Eq. (1) is effectively zeroed for the global entropy balance.

The system confined between the outer troposphere and the deepest points affected by the human activity (the Kola superdeep well SG-3 [19] or its newer analogs) includes all relevant anthropogenic effects. A precise entropy balance for this system is not feasible[2] because it requires detailed information about compositions, temperatures (and temperature gradients causing heat flows) throughout the system. But several simple estimates may help clarify the connection between entropy and scarcity. Weiss estimated entropy production rates [7] and showed that the civilization accounts for less than 0.03% of total entropy production: he decomposed total entropy production rate into the radiative and material production and demonstrated that, while the latter is 3.4% of the total, the civilization generates less than 1% of the material production. In other words, the anthropogenic entropy production is of marginal importance in the Eq. (1), because economies

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[1] Criticized by Silver ("the term material entropy < … > has not the slightest connection with entropy" [6: 321]). Here, the term 'material entropy' should not be confused with material entropy production as opposed to the radiative entropy production used by Weiss [7].

[2] Wu and Liu exemplified some uncertainties in entropy balance [20], a more detailed analysis of entropy production may be found in Refs. [21,22].