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Article

Economies Evolve by Energy Dispersal

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Abstract: Economic activity can be regarded as an evolutionary process governed by the 2nd law of thermodynamics. The universal law, when formulated locally as an equation of motion, reveals that a growing economy develops functional machinery and organizes hierarchically in such a way as to tend to equalize energy density differences within the economy and in respect to the surroundings it is open to. Diverse economic activities result in flows of energy that will preferentially channel along the most steeply descending paths, leveling a non-Euclidean free energy landscape. This principle of ‗maximal energy dispersal', equivalent to the maximal rate of entropy production, gives rise to economic laws and regularities. The law of diminishing returns follows from the diminishing free energy while the relation between supply and demand displays a quest for a balance among interdependent energy densities. Economic evolution is dissipative motion where the driving forces and energy flows are inseparable from each other. When there are multiple degrees of freedom, economic growth and decline are inherently impossible to forecast in detail. Namely, trajectories of an evolving economy are non-integrable, *i.e.* unpredictable in detail because a decision by a player will affect also future decisions of other players. We propose that decision making is ultimately about choosing from various actions those that would reduce most effectively subjectively perceived energy gradients.

Keywords: energy transduction; entropy; hierarchy; evolution; natural process; natural selection; statistical physics; thermodynamics

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1. Introduction

Parallels between economic and biological systems have not gone unnoticed. Common roots stem from the formulation of evolutionary theory based on natural selection [1]. Darwin was inspired by the idea that favorable variation is preserved under a struggle for existence when reading Malthus [2]. The tenet of self-directed and self-regulatory processes was first posited by classical liberalism as being manipulated by an ‗invisible hand' [3], and was later reworded as laissez-faire policy [4] and is today given, albeit in more refined terms, as free-market principles [5].

It is time to re-inspect the fundamental resemblance between economic and biological systems using the 2^nd^ law of thermodynamics, which was recently formulated as an equation of motion for natural processes [6–8]. In this form, evolution by natural selection can be recognized as being guided by the 2nd law. This relationship is in agreement with earlier reasoning about the governing role of the 2nd law, known also as the principle of increasing entropy, in directing numerous natural processes, animate as well as inanimate [9–18].

Certainly in the past too, the principle of increasing entropy has invigorated cross-disciplinary thinking [19,20] and given rise to evolutionary economics, thermoeconomics and econophysics [21–28]. However, the inspiration has not been exhausted, because *the entropy law*, in the words of Georgescu-Roegen *is still surrounded by many conceptual difficulties and equally numerous controversies* [19].

Common considerations about entropy contrast with the principal findings of this study. It is reasoned here that economic activities are not confined by the 2nd law but are actually manifestations of it. The entropy of an entire economic system does not decrease due to its diverse activities at the expense of entropy increase in its surroundings. Rather, it follows from the conservation of energy that both the economy and its surroundings are increasing in entropy (decreasing in available energy) when mutual differences in energy densities are leveling off as a result of economic activity. The key here is that according to the statistical physics of open systems increasing entropy means dispersal of energy, rather than as increasing disorder. Finally, we understand the *ultimate* motivation of economic activities, not as the maximizing of profit or productivity, but rather to disperse energy.

These conclusions stem from the same statistical theory [6–8] that has been recently applied to understand diverse evolutionary processes [29–37]. The 2nd law is found to yield functional structures, hierarchical organizations, skewed distributions and sigmoid cumulative curves that also characterize economies. Here, we use the thermodynamic formalism to address some fundamental questions of economics. What drives economic growth and diversification? Where do the law of diminishing returns, the Pareto principle, the balance of supply and demand, and the principle of comparative advantage come from? Why is it so difficult to predict economic growth and decline?

These questions are approached here from a strictly material and operational standpoint. It is understood that this standpoint of thermodynamics which relates everything directly or indirectly in terms of energy may immediately strike some as deficient. For example, is not information, as an essential guide of economic activities, immaterial? However, it has been argued that no information can be stored or processed without being represented in a physical form that, in turn, is subject to the laws of thermodynamics [38–40]. Moreover we fully acknowledge that physics in its traditional deterministic and reductionist form applicable for closed systems is rightfully rejected in attempting to account for behavior of open systems, *e.g.*, for human endeavors. However the 2nd law, when formulated properly using the statistical physics of open systems, reveals that nature is an intrinsically interdependent system and its evolution is inherently a non-deterministic process. Thus, our holistic account aims to remove doubts and concerns commonly leveled against physicalism. Yet, our objective is not to turn economics into physics, but to clarify economic activity in the context of the 2nd law, which accounts for all irreversible motions in nature.

We will proceed to describe an economy as an energy transduction system, first in qualitative and then in mathematical terms. Thereafter the intractable nature of economic progression and regression is clarified, and, as well, accompanied structural, functional and organizational changes are exemplified. Some familiar economic relationships and regularities are derived from the ubiquitous natural law. Finally, the subjective nature of decision making is discussed.

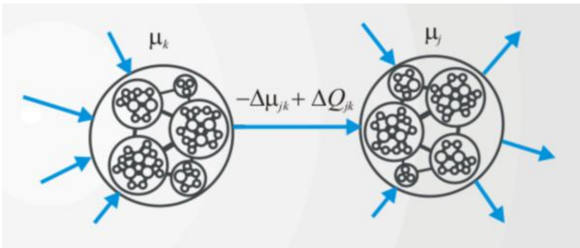
2. Economy as an Energy Transduction System

According to our naturalistic approach, an economy is an energy transduction system. To describe its characteristics and evolution in a self-similar manner using the statistical physics of open systems, all entities of the system are regarded as systems themselves (Figure 1). Each entity is associated with an energy density that results from its physical production processes. When all entities are valued by their energy density, it is possible to deduce from the corresponding density differences where an economic system is on its way. Its motion, as flows of energy, will direct, along available channels wherever constraints allow, from high densities to low densities. Entropy, the additive logarithmic probability measure, quantifies the system‘s evolutionary course toward increasingly more probable states.

We begin by defining elementary concepts so as to leave less room for misunderstandings. Products in numbers N_j that result from production activities are indexed by j. They are made from various raw materials or semi-finished products available in numbers N_k. Agricultural, industrial, logistical, informational, *etc.*, processes that transform N_k to N_j also couple quanta of energy, ΔQ_{jk} per each unit product. The energy supply may be in various forms including labor which, in terms of physics, is work. Each material entity j, is associated with an energy content denoted by G_j relative to the average energy k_BT of the system per entity. For historical reasons the everyday meaning of ambient temperature T relates via k_B to the average energy density of the geophysical system as sensed by thermometers In the same way body temperature is measure for the average energy density of the biological system. In the same sense the common k_BT is a meaningful concept for a sufficiently statistical economic system where entities interact with each other frequently [41]. In previous studies economic systems have been compared on the basis of the average energy density [42]. A pool of indistinguishable (identical) entities

N_j, that are the result of natural processes such as chemical reactions, is a repository of energy denoted by the density $\phi_j = N_j \exp(G_j/k_B T)$ [43].

Figure 1. Self-similar description of an economy as an energy transduction system. Each entity is regarded as a system (circle) of its own in interactions (lines and arrows) with its surrounding systems (larger circles). The energy difference $\Delta\mu_{jk}$ between the j and k system and the external energy flux ΔQ_{jk} (grey background) that couples to the transformations are the driving forces of economic activities. The energy differences are the forces that generate flows of energy (blue arrows) and propel the economic system toward a thermodynamic stationary state where energy density differences within the system and in respect to its surroundings have leveled, hence there is neither growth or decline. The steady state is maintained by the incessant to-and-fro flows of energy between the system and its surroundings.



It is worth emphasizing that we discern a distinct entity as different from another entity in energetic terms, not by its configurations (*e.g.*, having isergonic topological or geometric properties). In other words, the mutual order of energetically identical entities in the system is immaterial. In terms of economic energetics, any of these identical commodities is of equal value. This way Gibbs' formalism [43–45] allows us to relate any entity k to any other j in an economy by comparing the corresponding potentials $\mu_k = k_B T \ln\phi_k$ and $\mu_j = k_B T \ln\phi_j$. When $\mu_k + \Delta Q_{jk} > \mu_j$, more products N_j can be made from the available raw-materials N_k and any input energy ΔQ_{jk}. On the other hand when $\mu_k + \Delta Q_{jk} < \mu_j$, there is a surplus of products that the economic system would then be searching for ways to reduce. Thus, the free energy, known also as the affinity $A_{jk} = \mu_k + \Delta Q_{jk} - \mu_j$, is the driving force of economic activities that generate diverse flows of energy in both material forms and radiation, which are in terms of physics scalar and vector potentials.

We emphasize that each entity, including information via its physical representation, is assigned an energy density resulting from its production process. For example, a speech does not exist without being physically produced and represented as transient fluctuations about the ambient average air pressure. Admittedly the associated energy content in this example is minuscule but not negligible. The speech must exist to be heard. Subsequently it may be interpreted (processed) to unleash flows from gigantic reservoirs of energy. Thus, according to the natural tenet, even the most ―immaterial" goods and services do not exist without physical forms. The energetic ―costs" of representations can be very small but essential to understanding the thermodynamic imperatives, most notably conservation of energy in the flows of energy that all economic activities are also subject to.

The view of economic activities as energy flows that direct down along energy gradients, is plain. Yet it may appear unfamiliar because production processes are not usually perceived as spontaneous but actively driven as if the motion was ―uphill". We emphasize that the driving force is precisely the free energy (known also as exergy), including any external influx ΔQ_{jk}, *e.g.*, work. The total force, when positive ($A_{jk} > 0$), makes the production of N_j a probable process ($dN_j/dt > 0$), *i.e.*, the energy flow is statistically speaking always ―downhill". According to our natural approach, all processes, regardless of being either conscious or unconscious, must follow the law of energy dispersal.

An economy, just as an ecosystem, is powered by an energy influx from its high-energy surroundings, *e.g.* by consuming fossil fuels and capturing solar radiation. Conversely, all products that have emerged from endergonic production processes are subsequently subject to exergonic degradation when exposed to low-energy surroundings and cut off from the sources that powered their production or carried out repairs and restorations. Thus, goods are limited by life spans just as are living entities. Therefore economic, like chemical potentials μ_j, are constantly regenerated using surrounding supplies. This leads to incessant circulation of matter in both economic systems and ecosystems. Under these conditions random variation in syntheses or deliberate design of production may yield more effective mechanisms of energy transduction which will be naturally selected by the flows themselves to level the density differences even more effectively.

3. Economic Evolution as an Energy Dispersal Process

The physical portrayal of an economy as an energy transduction system associates all interacting entities with energy densities. The density differences within the system and in respect to its surroundings are the forces that direct flows of energy to diminish the differences. This notion is a generalization of Carnot's observation that *wherever there exists a difference of temperature, motive force can be produced* [46].

The concept of probability, *P,* is a concise measure to capture the energetic state of the entire economic system in its myriad of motions due to numerous flows being directed by diverse forces. According to the self-similar formalism $P = \Pi P_j$, is a product of probabilities so that each P_j is associated with a subsystem composed of entities *j* in numbers N_j (for the derivation see references [6,8]):

$$P_j = \left(\left(\prod_k N_k e^{-\Delta E_{jk}/k_B T} \right)^{g_{jk}} \Big/ g_{jk}! \right)^{N_j} \Big/ N_j! \tag{3.1}$$

The scale-independent notation shows, in a recursive manner, that N_j are themselves also made of various entities *k* each distinct ingredient available in numbers N_k (Figure 1). The form ΠN_k in the numerator ensures that if any of the *k*-ingredients is missing, no *j*-product can be made ($P_j = 0$). The degeneracy g_{jk} denotes the number of *k*-components that remain indistinguishable (symmetric) even after being assembled in the *j*-product. The energy difference $\Delta E_{jk} = \Delta G_{jk} - \Delta Q_{jk}$ in the production process is bridged by the intrinsic difference $\Delta G_{jk} = G_j - G_k$ between the raw materials and products and by the external influx ΔQ_{jk}. The division by the factorial $N_j!$ means that the combinatorial configurations of identical N_j in the system are indistinguishable. The nominator is raised to the power of N_j because the production process may combine the raw materials into any of the indistinguishable products.

The total logarithmic, hence additive, probability measure of the economic state is entropy $S = k_B \ln P$. It takes into account all densities of energy and paths of transformations:

$$S = k_B \ln P = k_B \sum_j \ln P_j \approx k_B \sum_j N_j \left(1 - \sum_k A_{jk} / k_B T \right) \tag{3.2}$$

where the energy difference, *i.e.*, free energy $A_{jk} = \Delta\mu_{jk} - \Delta Q_{jk}$ is the motive force that directs the transformations from N_k to N_j. The potential difference $\Delta\mu_{jk} = \mu_j - \Sigma\mu_k$ contains co-products and by-products of N_j in Σ_k with the opposite sign. The Stirling's approximation implies that the system is well-defined by being sufficiently statistical, *i.e.*, $A_{jk}/k_BT << 1$ to absorb or emit quanta without a marked change in its average energy density k_BT. Otherwise, if S is not a sufficient statistic for k_BT [41], the embedded entities, *e.g.* semi-finished products N_k themselves would be transforming rapidly. Obviously then the assembly of N_j would be jeopardized. For example, it would be difficult to build a house from bricks that themselves were still soft and deforming. In such a case, the production process must be analyzed at a lower level of hierarchy [47,48] where the submerged evolutionary processes involving the k-entities, *e.g.*, the fabrication of bricks, would be described using the same self-similar formalism.

The economy evolves from one state to another by diminishing free energy. The equation of probable motion resulting from the dispersal of energy down along the diverse gradients by various activities is obtained from Equations 3.1 and 3.2 by differentiating and using the chain rule $(dP_j/dN_j)(dN_j/dt)$:

$$\frac{dP}{dt} = LP \geq 0 \tag{3.3}$$

where the process generator:

$$L = -\sum_{j,k} v_j \frac{A_{jk}}{k_B T} \tag{3.4}$$

drives a series of state changes by way of numerous flows $v_j = dN_j/dt$ that consume the motive forces A_{jk}. The population change dN_j and the time step dt have been denoted as continuous only for convenience whereas actual processes advance in quantized steps ΔN_j during Δt.

The 2nd law of thermodynamics in the form of an equation of motion for the overall probability (Equation 3.3) is a powerful description of an evolving economy. Yet, it is not P itself but numerous activities and material flows that are amenable for monitoring the economic state. In a sufficiently statistical system each flow:

$$v_j = -\sum_k \sigma_{jk} \frac{A_{jk}}{k_B T} \tag{3.5}$$

is proportional to the corresponding motive force by a conductance (production capacity) $\sigma_{jk} > 0$ to satisfy the continuity $v_j = -\Sigma v_k$ between the density ϕ_j and diverse densities ϕ_k [6,49].

The linear relationship in Equation 3.5 is familiar from Onsager‘s reciprocal relations which are considered to be valid close to the stationary state [50,51]. Here the condition $A_{jk}/k_BT << 1$ of being a sufficiently statistical system is assumed but it is not unusual that the assumption does not hold. This critical phenomenon is also familiar from fluid mechanics when a flow changes from laminar to turbulent. When the transformation mechanism σ_{jk} itself is evolving or when the free energy A_{jk} is comparable to the average energy density k_BT, the linear relationship between the flow and force (Equation 3.5) fails, but this is no obstacle for the self-similar description. When the condition of being sufficiently statistical is not satisfied at a particular level of hierarchy, the process would need to be described in a finer detail at a level further down in the hierarchy. For example, a series of improvements on a production line will increase the throughput by increasing σ_{jk}. The time-dependence of the evolving conduction system is fully contained in the recursive, scale-independent system description according to Equations 3.1–3.5.

The statistically sufficient assumption $A_{jk}/k_BT << 1$ will fail also when energy is not distributed effectively enough within the system to maintain its integrity, *i.e.* to maintain common k_BT. The economy is subject to disintegration when an economic sector is receiving high influx (or another is draining high efflux). The rapidly growing subsystem acquires greater independence when it is not connected effectively enough to distribute acquired assets to others. Eventually when the high influx ceases, redistribution processes catch up and the excursion for independence ends. The disintegration and reintegration processes are fully contained in the self-similar formalism.

We emphasized that the energy density differences A_{jk} (Equation 3.5) drive the flows, not the differences in number densities N_j, which are commonly used in economic [52] as well as in ecological models, *e.g.*, written as sets of coupled differential equations [53]. These models based on the law of mass action [54] erroneously picture that transformation rates would be changing during kinetic courses even when the system is sufficiently statistical. Consequently it may appear as if kinetics was inconsistent with thermodynamics.

The equation of motion for an evolving economy (Equation 3.3) can be rewritten using the definition of entropy $S = k_B\ln P$ as the law of increasing entropy [6,8]:

$$\frac{dS}{dt} = k_B \frac{d(\ln P)}{dt} = \frac{k_B}{P}\frac{dP}{dt} = k_B L = -\sum_{j,k} v_j \frac{A_{jk}}{T} \geq 0\,. \tag{3.6}$$

The equation of motion says that entropy S is increasing when energy density differences, contained in A_{jk}, are decreasing by way of various flows v_j. The non-negativity of dS/dt is apparent from the quadratic form obtained by inserting Eqaution 3.5 in 3.6. The formula obtained from statistical physics of open systems is consistent with the basic maxim of chemical thermodynamics [45], *i.e.*, the entropy maximum corresponds to the free energy minimum as well as with the classical form of dS given by Carnot [46], the Gouy-Stodola theorem [55,56] and the mathematical foundations of thermodynamics [50,57,58].

The form of Equation 3.6 makes it explicit that it is the energy density difference between the system and its surroundings that drives the probable motions. The economy will prosper when the difference from its surroundings is positive and conversely the economy will decline when the difference is negative. The significance of surroundings is apparent, for example, when an economy is curtailed by an embargo. It is emphasized that both during economic progression and regression, the entropy of the economy, just as the entropy of its surroundings, are increasing. There is no room for a provisional proposition that the entropy of a system could possibly decrease at the expense of entropy increase at its exterior (or *vice versa*). Such generosity would violate the conservation of energy because the system and its surroundings share the same flows at their mutual interfaces [8].

Eventually, when no further and faster means to consume free energy and no additional sources are found, the economy reaches a steady-state, just as an ecosystem attains a climax, the mature state with maximal gross transduction [59,60]. The maximum entropy state is characterized by a distribution of entities without mutual density differences [6]

$$dS = 0 \Leftrightarrow \mu_j = \sum_k \mu_k + \Delta Q_{jk} \Leftrightarrow N_j = \prod_k N_k \exp\frac{-\Delta E_{jk}}{k_B T}. \quad (3.7)$$

The steady-state populations N_j and N_k of energy transduction mechanisms are governed by the mutual energy differences $\Delta E_{jk} = \Delta G_{jk} - \Delta Q_{jk}$ relative to the average energy $k_B T$ per entity in the particular system. The everyday notion of temperature T, when given in units of Kelvin and multiplied with k_B, refers to the average energy of ambient atmospheric gas per molecules that the thermometer is sensitive to. In the same physical sense the average energy density of an economy can be quantified. However, it would extremely tedious to tabulate changes in energy in every transaction. Instead, various economic barometers are used to sense the status of the economic system. The maximum entropy state $S_{max} = k_B \Sigma N_j^{ss}$, where all energy density differences have vanished, is a dynamic stationary state so that variations ΔN_j about the steady-state populations N_j^{ss} are rapidly averaged out by economic activities that correspond to conserved flows ($\Sigma \Delta N_j \Delta \mu_{jk} = 0$). In modern times, apart from some transient periods, economies have not been in stationary states. Instead the average energy influx from the surroundings has been and is still growing due to more and more effective agricultural, industrial, logistical and informational processes [61].

4. Origin of Non-Deterministic Economic Evolution

The 2nd law in the form of an equation of motion clarifies the fundamentals that underlie difficulties in providing accurate economic forecasts. The equation of evolution (Equation 3.3), despite being simple, cannot be solved analytically, *e.g.*, integrated in a closed form, because when there are multiple degrees of freedom the variables L and P cannot be separated from each other as they both depend on N_j and A_j. The non-integrable characteristics of the evolving system mean that economic trajectories are non-deterministic. The uncertainty stems from the following factors.

First, an economy, just as in any other thermodynamic system, is composed of interacting entities. In other words, a potential μ_k is in a functional relation to other potentials μ_j via available transformation mechanisms (Figure 1). In a market μ_k can be transformed to μ_j by various transactions, here expressed using numerous flow equations (Equation 3.5), so that the products and other economic entities, just as any other forms of energy, are interdependent. Owing to the continuity $v_j = -\Sigma v_k$ in the transformations it is impossible to change one entity without affecting others. The energy flows v_j and driving forces A_{jk} are inseparable in L from each other when there are three or more degrees of freedom (agents). Flows affect driving forces that, in turn, affect the flows. A decision taken by a player will change sets of states accessible by other players that, in turn, by their own decisions, affect the sets of accessible states of others. When the currents are not conserved, the *ceteris paribus* assumption does not hold and the equation of motion cannot be solved by a transformation to yield an analytical formula to determine the system's time course. Hence evolutionary courses, including economic growth and decline, are non-integrable, *i.e.* trajectories of an evolving economy cannot be predicted in detail. The problem is exactly the same as was encountered first in the context of the three body problem [62] and later recognized to seed also chaotic behavior [63,64]. The non-deterministic course toward a defined solution–here, the free energy minimum–identifies the problem of predicting economic growth among many other natural processes in computational terms, as non-polynomial time complete [34,65].

Second, to understand the origins of intractability of evolving economies, it is crucial to recognize that changes of state are dissipative. It is impossible to transform an entity into another distinct one without acquiring at least a quantum of energy from the surroundings or expelling a quantum to the surroundings [6–8]. When assembling from semi-finished products, it is easy to see that some of the external energy becomes incorporated in the product. It is the essential ingredient that distinguishes the product from raw-materials. Owing to the energy influx (or efflux) an open, evolving system is capable of transformations that cause net changes in identities, whereas a closed and stationary system is limited to isergonic exchange of identities. The equation of motion (Equation 3.3) and the flow equation (Equation 3.5) differ from the conventional physical formalism that has been devised for closed, conserved systems which display only isergonic and deterministic dynamics. Such an invariant description by normalized probabilities is not sufficient to account for an open, non-conserved economy. The open system will grow or shrink in its energy content due to energy influx or efflux until it has arrived at a stationary state, *i.e.* attained an energy balance in its surroundings. As long as the system's energy content is changing, there is no norm, which would be necessary to find a unitary transformation to solve the characteristic equation. Thus, economic growth, just as ecological succession [35], is a process without invariants of motion. Since, the Noether's theorem [66] does not hold and Liouville's theorem is not satisfied for this non-Hamiltonian system, much of the powerful machinery of physics devised for closed, deterministic systems is disabled when analyzing economic systems. This means that it is impossible to predict (determine) future states because these do not pre-exist, instead a particular state at each moment results from the irreversible evolutionary processes.

It is concluded that the difficulties in forecasting economic growth or decline are not exclusively due to incomplete knowledge of the system's properties but rather follow from the inherent characteristics of natural processes. Of course it has been recognized already for a long time that the conventional closed system formalism does not describe open systems appropriately. However, the evolutionary equations are not usually derived directly from the fundamental principle using statistical physics. Instead, stochastic processes such as Markovian chains or deterministic analytical formulae are used [67] to model inherently non-deterministic evolutionary courses. Certainly these are practical approximations but are not explicit in communicating why it is difficult to forecast economic growth and decline.

The flow Equation 3.5 can be used to build an economic model and the state Equation 3.6 to monitor the economic status. The model system will respond to influxes and effluxes by non-deterministic evolution. The obtained scenarios are representative to the degree that the input is realistic and that the model accommodates relevant interaction mechanisms within the system and with its surroundings. The scale-independent formalism allows one to model both micro- and macroeconomics. Also, when using a self-similar model, computational capacity can be dynamically allocated to refine the description into significant details, or instead, coarse-graining it from insignificant factors. In any case, to gain certainty and scope in prognoses by deterministic finite automaton is a tedious process because an evolving state space is huge and searches through it are intractable [68].

The intrinsically non-integrable behavior of an evolving economy does not, of course, mean that information of its diverse potentials μ_k, flows v_j and available jk-transformation paths would not help to estimate the current state and to project toward future states. But the prognoses, even when based on the same premises, will diverge when extended over longer and longer periods of time. Furthermore, it is emphasized that mere information gathering and its exposition are thermodynamic processes themselves that will inevitably affect the course of economy. This has, of course, been understood in practice and regulated by legislation, but has here been associated with the fundamental properties of non-conserved systems with degrees of freedom where forces and flows are inseparable from each other. For example, the use of insider information is prohibited because it would endanger the overall progression by limiting conceivable actions.

5. Natural Selection Criterion

The principle of increasing entropy is not only about increasing but increasing as fast as possible. This has been recognized in the form of the maximum entropy production principle [17]. This principle has in it that a system that is capable of assuming many conformations will tend to assume one, or frequently return to one, that maximizes the rate of dissipation of the powering energy gradients. This dissipation promotes entropy production even when some of the energy is captured as exergy because of the statutorially poor energy efficiency of any work. The natural law manifests itself here in iterative improvement of the energy transduction machinery. An economy develops to hold increasingly more effective mechanisms just an ecosystem evolves to house increasingly more effective species. Natural selection for the most effective mechanisms of energy dispersal is often pictured to be driven only by mutual competition, sometimes referred to as an arms race, whereas less attention has been given to the gains that are obtained by evolution to hierarchical organizations, sometimes viewed as co-evolution, co-operation or even altruism.

The energy gradients are the motive forces of physical process just as they are of economic activities but we note that these forces are not sensed by the system when there is no mechanism to funnel the flows of energy. For example, a voltage difference has no effect without a conducting path just as supplies of raw materials and customers‘ purchasing power constitute an energy density difference but which has no effect on the economic state as long as there is no flow to equalize the gradient. This stationary state will change first when a production line, as a mechanism of energy transduction, begins to pump out a particular flow of products according to Equation 3.5. A prototype mechanism is superior to nothing, and serves only to trigger the development of more refined machinery.

The key to understanding natural selection as a bias for more and more effective machinery is to recognize that entities are limited by life spans and hence must be regenerated. Consequently, the competition for common resources is incessant. This competition tends to increase work rates, which in turn increases the rate of entropy production. When several mechanisms of transduction, characterized by the transduction coefficients $\sigma_{jk} > 0$, consume a common pool of free energy, the magnitudes of flows from the same source via distinct mechanisms distribute according to σ_{jk}. When a particular mechanism is unable to acquire enough flow from the common resources even for its own regeneration, it will, in biological terms, face extinction as a result of competition. Technological developments alter energy flows and redirect economic growth just as advantageous genetic mutations change the food chain and affect biological evolution. Eventually the most effective paths of economic productivity funnel all flows and leave nothing for the least effective means of energy dispersal, that then ‗run out of business'. This thermodynamic principle for maximal entropy production, equivalent to the maximal energy dispersal, is universal.

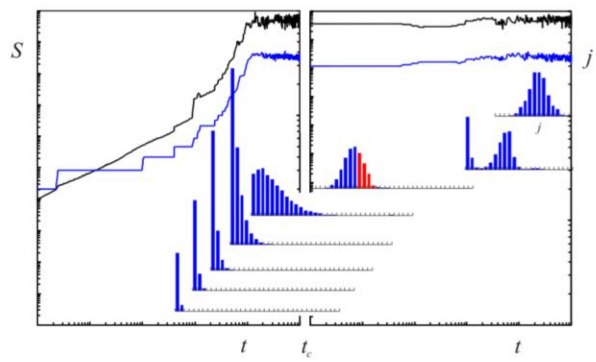
When a comparative advantage appears among mechanisms, the energy flows will redirect accordingly. A rerouting may happen rapidly, especially when the consumed free energy can be used to boost the particular superior mechanistic capacity. In economic terms, profit is invested in increasing the production capacity. In biological terms, food is invested in raising the population. In terms of our statistical physics formulation of evolutionary theory those mechanisms that channel most of the energy are naturally selected through the flows [1,6,7,69]. According to the self-similar hierarchical theory, natural selection is systemic notion since a mechanism, just as an individual or a group, is a system. Given sufficient undiminishing energy sources, evolution is not merely manifesting itself in ‗selfish' rivalries but also in integration by specialization, co-operation and even ‗altruistic' conduct that aim at increasing the total rate of energy dispersal to arrive at win-win circumstances.

We note that the natural bias for the maximal energy dispersal down along the steepest gradients was anticipated in the economical context as being directed by ‗an invisible hand'. However, we emphasize that, according to the 2nd law, the primary motive of economic activities is the most effective dispersal of energy, whereas it is of secondary importance whether the processes are defined as conscious or unconscious. Therefore, legislation and its enforcement that also consume free energy in redirecting flows and in altering mechanisms, are regarded as natural forces. Also in biological systems natural selection is at work both when particular traits are intentionally sought by breeding and when they appear in response to unintentional forces [1]. The selection between mechanisms by the rate of entropy increase is a particularly stringent criterion when free energy is becoming depleted. This condition is usually referred to as ‗operating on a small margin'. As well, unit costs are reduced by way of voluminous transformations (‗economies of scale').

Since the kinetic mechanisms (*e.g.* production lines) themselves are assembled by synthesizing flows, mere random variations may, once in a while, give rise to an improved mechanism, although we usually think of rationalized production as a result of engineering design and coordinated actions. It is important that regardless of an action being accidental or intentional, a revised mechanism, when it increases the consumption of free energy, will tend to be adopted. Economic growth via technological improvements, just as biological evolution via genetic mutations, is mostly ‗tinkering' [70].

The interplay between the energy gradients, flows and mechanisms is particularly intriguing every time a new, highly effective mechanism appears in the system (Figure 2). Then a stationary state would be punctuated by a rapid evolution when the highly effective mechanism is consuming the free energy accessible to it and cumulating new densities that may quickly become out of balance with other densities. Soon the system will redirect its course to correct for the overshoot. Owing to its autocatalytic nature, *i.e.* positive feedback mechanisms, the trajectory toward a steady state may proceed in an oscillatory manner. Even large modern economies may first experience periods of fast growth that later terminate to severe declines when highly effective mechanisms emerged and succeeded in drawing large assets but remained poorly integrated in the system, *e.g.* due to lack of effective control and redistribution mechanisms. Eventually evolution settles to a stasis when excess resources have been consumed. The intermittent course of punctuations and stases [71], also referred to as self-organized criticality [72,73], is inherent in evolution. This is in conflict with the desire for a steady economic growth where the system would retain its integrity by evolving so that $dS/dt > 0$ while all $A_{jk}/k_BT << 1$.

Figure 2. Simulated evolution of an economy based on the 2nd law of thermodynamics. Flows, including sporadic variation (up to 10% in the flows), direct down along the steepest gradients of free energy according to Equation 3.5. Entropy (*S* black line) is increasing as long as the system emerges with novel, increasingly more effective mechanisms of various kinds (*j* blue line) that are able to acquire more and more energy from the surroundings. When a new mechanism appears, the growth rate increases whereas the stationary state is approached with diminishing returns. During the evolutionary course the distribution that was sampled at various times *t* (blue bar charts), shifts from simple mechanisms at low-*j* fractions to sophisticated machinery at high-*j* fractions. Each fraction is proportional to a population's effectiveness in energy transduction relative to the others. A catastrophe is introduced at t_c. It demolishes a fraction of the stationary state production capacity (red bars). Consequently, entropy will momentarily plummet as it takes time for the system to recover by restoring the skewed distribution. Scales of axes are in arbitrary units because the simulation is based on scale-independent formalism. See appendix for technical details.



6. Evolving Energy Landscape

The thermodynamic description of an economy via Equations 3.1–3.7, despite their concise notation, is very precise. Numerous terms denote all potentials μ_j, their mutual differences, all transforming flows v_j and all jk-transforming mechanisms. However, to model an economy to the precision of an atom and a quantum is neither practical nor instructive, but coarse-grained simulations of natural processes are easy to set up and execute according to Equation 3.5 [29–37].

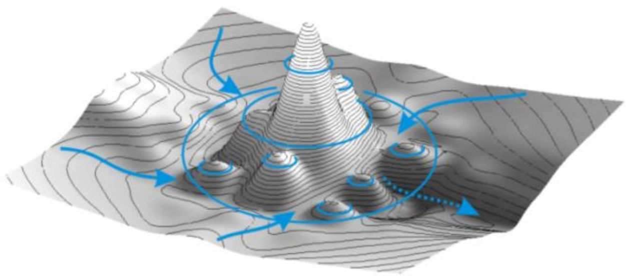
Simulations serve to exemplify the principal characteristics and non-deterministic features of evolution but much can be understood directly from the equation of motion (Equation 3.6) when it is pictured as an energy landscape in evolution [7]. To that end the rate of entropy change dS/dt is rewritten as an energy balance for the flows

$$T\frac{d}{dt}S = -\sum_{j,k}\frac{dx_j}{dt}\frac{\partial U_k}{\partial x_j} + i\frac{\partial Q_{jk}}{\partial t} \tag{6.1}$$

by multiplying $d\ln P$ with the average energy k_BT. Time-dependent tangential vectors as directional derivates $D_j = (dx_j/dt)(\partial/\partial x_j)$ span an energy landscape, properly referred to as an affine manifold, in the continuum limit [7,8,49,74] (Figure 3). Heights of the manifold are high potentials $\mu_k/k_BT = \ln[N_k\exp(G_k/k_BT)]$ at the site x_k and valleys are low potentials $\mu_j/k_BT = \ln[N_j\exp(G_j/k_BT)]$ at x_j. Their difference in the continuum limit is denoted by the gradient $-\partial U_k/\partial x_j$ and the external energy by the field $\partial Q_{jk}/c\partial t$ in the orthogonal direction denoted (redundantly) by i. The various economic activities generate continuous flows $v_j = dx_j/dt$ from the heights to the valleys. During evolution the landscape is leveling due to numerous flows.

The energy landscape given by Equation 6.1 is curved, *i.e.* non-Euclidean [75]. This means that a distance between two points is directional and the sum of triangle‘s angles between three points is not equal to 180°. These are not exotic properties of a curved space-time, but well-established, *e.g.* in information theory [41]. These characteristics are also familiar from economic systems. The directionality means that putting together a product from raw-materials by coupling the influx of energy to the assembly is not the same as breaking apart the product into raw-materials where the efflux of energy is released. The two opposite processes differ by the net direction of energy flux. The assembly is typically endergonic whereas the disassembly is an exergonic process. The triangle inequality means that the overall cost of a product depends on the particular semi-finished products that are used in its assembly. The less energy is required in the assembly, the more Euclidean (even) the landscape is. Production processes are optimized to transform along the paths of least action (the variational principle), *i.e.* along the least curved paths. That would be the most economical trajectory. This motion along the optimal paths corresponds to minimal squandering. Another way to state the same principle is described in ―constructal theory" [76].

Figure 3. Economy is pictured in a self-similar manner as systems within systems (encircled cyclic paths) that are embedded in the surrounding energy landscape. The diverse high-energy densities in the hierarchical organization are associated with transduction mechanisms that direct flows of energy (blue arrows) among themselves and from the surroundings down to the economy. Eventually the landscape may develop to open up for new flows (dashed arrow to right), so that a previously confined steady-state systems will face evolution, *e.g.*, perceived as economic restructuring due to integration.



The non-stationary energy landscape composed of finite material densities is curved by the amount of net dissipation $\partial Q_{jk}/\partial t$ in the *jk*-transformations. The external energy (*i.e.* work) drives the production process in addition to the potential difference between the raw-materials and products. However at a local region, as Gauss noted, the curved landscape can be viewed as nearly Euclidean [8,77]. In other words, to a good approximation the high-density source μ_k does not deplete during the outflow, and the low-density sink μ_j does not fill during the inflow. In economic terms, the Euclidean approximation means that prices of raw-materials and products do not alter during an on-going transaction. In practice, it is of course noticed that, in particular, huge bargains do change the prices of subsequent deals. Contracts aim at predictability but only time-limited offers are given, ultimately because nature is, when depicted as an energy density landscape, inherently non-Euclidean.

To picture an economy as a landscape that evolves by flows of energy is admittedly abstract but allows one to use notions that have been established in other contexts. Mathematically speaking the evolving landscape is an affine manifold undergoing a geometric flow [75]. In terms of physics, the evolving landscape is a thermalizing system of interacting densities. In biological terms, the evolving landscape is a maturing food-web of interacting species. In economic terms, the evolving landscape is a growing market economy of players.

7. Motives of Integration and Disintegration

Economies, just as ecosystems do, organize themselves in nested hierarchical systems to improve on energy dispersal. At each level of hierarchy a larger system provides the surroundings for its integral subsystems. Throughout the hierarchy the incentive of activities is nevertheless the same, the dispersal of energy. The holistic description of an economy as a nested hierarchy of energy transduction systems is self-similar with regard to energy transductions so that the landscape contains basins within basins (Equations 3.3. and 6.1). In other words, the global economy is comprised of national economies, each housing economic zones that in turn accommodate districts, firms, households and so on.

Likewise, the biosphere is comprised of ecosystems, each housing populations of individuals that in turn encompass organs, cells, organelles and so on [78]. Biological systems were integrated already eons ago into the biosphere, which also houses systems within systems. For example, a eukaryotic cell houses cellular organelles, chloroplasts and mitochondria that are thought to have once been independent organisms [79]. Also at higher levels of hierarchical organization various forms of symbiosis and co-operation are found.

Restructuring of activities will contribute to economic growth. Two similar units, *e.g.* firms that generate similar potentials (*e.g.* products) by drawing from the same resources μ_k will be in competition with each other [12]. Such a system is not stable according to the Lyapunov criterion [44,64]. This situation, referred to in the biological context as competitive exclusion, may resolve if the units differentiate in respect to each other [80] or one of them disappears, or becomes assimilated to the other in a merger.

On-going economic integration emerges with numerous technological standards to ensure and boost the consumption of free energy. The value of standardization increases with an increasingly larger system. Likewise, biological standards such as universal metabolites, amino acid chirality consensus and common genetic code have allowed intimate integration of the biosphere by differentiation based on the same base constituents [29].

Product differentiation or specialization in integrated activities leads to an increase in entropy production, denoted by an increasing number of terms in the sums of Equation 3.4. New mechanisms access new potentials or more effectively utilize those that were not fully exploited. It is well observed that economic growth generates further economic growth, just as biological diversity builds on diversity. As well, many policies promote economic diversification. Despite efforts to diversify activities some particular potentials may remain limiting or specific mechanisms may appear as bottlenecks of economic growth. Likewise, shortage of water curtails growth and diversification of terrestrial ecosystems. Ultimately the Second Law itself imposes, by depleting the surrounding energy density, a limit of growth for all systems [61].

In a highly integrated and versatile economy numerous flows rapidly redirect along alternative paths in response to changing potentials and mechanistic innovations or failures. An economy with effective infrastructure will quickly redirect its flows along newly emergent gradients and adapt to forces imposed by its surroundings. Furthermore, a wealthy society has a large capacity, *i.e.* a high-energy content to influence its surroundings and to resist changes. In contrast, a disjointed and one-sided economy is slow in adjusting its course in response to altered surroundings. Furthermore, a poor community has hardly any influence on its surroundings and its feeble potentials are soon exhausted in attempts to oppose changes.

Integration, however, is not an end in itself. When the integrated machinery is not superior in its energy transduction to its internalized subsystems working as independent systems, we suggest that the organization is bound to disassemble. The integration at each level of hierarchy is supported or opposed by a subsystem depending on its local subjective view of its surroundings. According to the 2nd law (Equation 3.6) subjectivity will be shaped only by perceived proximate gradients. A subsystem supports integration when it gains in dS/dt. Conversely, we propose that a subsystem will tend to break loose when the integration seems to afford a smaller rate of dS/dt than the system could produce independently. How this driving force for integration (or disintegration) actually transpires as flows in any particular system will depend upon available mechanisms. Consistently, it has been proposed that new levels may appear in a dynamical hierarchy only if that results in a more rapid overall energy gradient depletion [81].

To attribute economic integration to the universal law of energy dispersal may at first appear counterintuitive since the dispersal means spreading while economic activities are accumulating aggregates [82]. However, an aggregate, such as an intense technological infrastructure, is a mechanism that allows the economy to extract resources from its surroundings. For example, crude oil sources are the high-energy surroundings that are intensively drawn from by the global economic system. Conversely, when an economy disintegrates, energy flows out of the system as the interactions break apart. Then, aggregate units, such as railway, power and telephone networks, have become higher in energy density than the relatively impoverished surroundings, and these high-energy infrastructures will be subject to plunder. Likewise, in biological terms, a big carcass is a generous supply for other organisms. At each level of hierarchy the surroundings, must be higher in the total energy content for the system to profit from them. In the converse case, the surroundings will profit from the system. The law is the same, only the viewpoint is different.

Today we witness economic globalization that is motivated by attempts to access and consume increasingly larger surrounding pools of free energy so as to keep the economy growing. The integration aims at boosting energy transduction by enhancing interactions and adjusting subsystemic mechanisms to funnel flows ever more rapidly. This manifests, *e.g.*, as division of labor and specialization, and yields comparative advantages and disadvantages. These internal changes, referred to as restructuring, are basic to economic integration where interactions assemble subsystems to systems. Trust between partners is a sign of mutual understanding of interdependence and adherence to the common system. The co-operative functions of an integrated system are enforced, *e.g.*, by practices, rules, tabus, legislation and traditions. In accord with earlier ideas [83] cultures have emerged and devised hierarchical organizations to facilitate effective dispersal of energy.

8. Roots of Economic Relations and Regularities

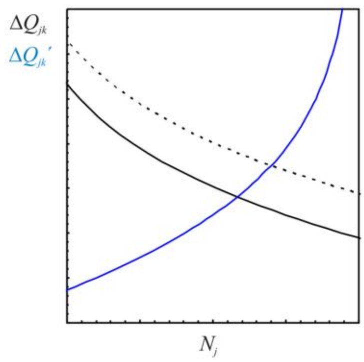
The natural process of energy dispersal, despite being non-deterministic, imposes certain relations and regularities on economic systems by requiring that, while energy is conserved globally, flows of energy direct down along the steepest gradients.

A typical economic growth curve is an overall sigmoid on linear scales and dominated by a power-law region on a log-log plot [84,85]. Initially the free energy is high and growth is soon nearly exponential. As a result of the transforming activities, free energy diminishes. The diminishing difference $\Sigma\mu_k(t) + \Delta Q_{jk} - \mu_j(t) \geq 0$ per unit time represents profit from the viewpoint of a producer of μ_j. The producer may invest acquired free energy in increasing its production capacity, as well as in obtaining more raw materials and energy, in hopes of maintaining rapid growth to improve its entropy production status. However, eventually, when no new innovations and no supplies are found, the free energy declines. This particular business branch is maturing and its growth is slowing down. Finally, when the free energy vanishes altogether, no more profit can be made, but to make a living is still possible when the market is saturated with products, just as animate populations tend to be in balance in a mature ecosystem.

It follows from the diminishing difference $\Sigma\mu_k(t) + \Delta Q_{jk} - \mu_j(t) \geq 0$ that an additional input ΔN_k will give an additional output ΔN_j with diminishing marginal returns. Often this classical law by Ricardo is supplemented with a caveat that only ―after a certain point”, the diminishing returns would first set in. This empirical observation of initially increasing marginal products results from the aforementioned initial growth that may be prolonged by restructuring of activities, increasing capacity, efficacy and specializing. As a result of autocatalysis, the initial growth curve is concave and only later becomes convex yielding an overall sigmoid, nearly logistic form [86].

At the market equilibrium, $\Sigma\mu_k + \Delta Q_{jk} = \mu_j$, the demand and supply are equal, *i.e.*, in balance. For a given supply the increase in consumer demand, denoted by an increase in ΔQ_{jk}, gives rise to a difference, $\Sigma\mu_k + \Delta Q_{jk} > \mu_j + \Delta Q_{jk}'$ that is balanced by raising the price denoted by $\Delta Q_{jk}'$. For a given demand the increase in producer‘s supply gives rise to a difference that is balanced by lowering the price, assuming as usual that no other alternatives would open up (Figure 4). The money associated with potential contributes to the transaction motive, just as does the external energy ΔQ_{jk}. Also a value-added tax, customs, *etc.*, are associated with potentials that influence rates of transformations (Equation 3.5) and affect the market equilibrium (Equation 3.7), and also indirectly when the collected assets are returned to the system. In general a change in a particular commodity price will also affect the demand and supply of other products, and then elasticity behaves non-deterministically. These intractable responses can be simulated using the flow equations Equation 3.5.

Figure 4. Demand (black) and supply (blue curve) relate by purchasing power ΔQ_{jk} and pricing $\Delta Q_{jk}'$ to the quest for the balance (Equation 3.7) between energy densities ϕ_j and ϕ_k associated with the products (N_j) and raw-materials (N_k).



From the physical perspective the free market economy, by its statistically independent actions of trade and transactions, is free to seek the steepest gradient and thus is likely to move, according to Equations 3.6 and 6.1, by most voluminous flows along steepest gradients toward a local balance. Considering that natural processes are non-deterministic it would be difficult to command an economy along the steepest gradients. This idea of freedom was once voiced as laissez-faire. However, it should be noted that although integration in hierarchical organizations structures energy dispersal processes, it also fosters statistical independence in transformations, *e.g.*, by legislation that prohibits monopolies, cartels and use of insider information.

Our examination of economic relationships from this physical principle is not intended to be exhaustive but exemplary. There are also relationships whose validity is questioned [87], *e.g.* the Phillips curve [88] that seems to fail in relating inflation and unemployment rates under stagflation. Although the physical counterpart of money is energy in its nearly immaterial form, *fiat* currency is an agreement. Since deterministic agreements hold strictly only under steady-state conditions, the trust in money is not fully firm during non-Euclidean growth and decline conditions. The mistrust in money is particularly apparent in a time of war when in disrupted regions the economy disintegrates. When taking these aspects of trust into account, the dependence given by the Phillips curve can be understood so that the size of a quantum, *i.e.* the unit of money as the transaction motive, is decreasing *relative* to the average energy density (k_BT) of an economy that is growing. Obviously, unemployment is reduced during the growth period as the growth is consuming the labor force, literally A_{jk}. Conversely, a reducing economy faces deflation risk and increasing unemployment.

9. Economic Stability, Fluctuations and Oscillations

Economic systems are rarely subject to steady surroundings or free from internal perturbations but the stationary-state properties are worth a study to understand the nature of stability and the causes of disturbances.

The natural distributions are nearly log-normal and their cumulative curves are sigmoid [31,89]. The size of a particular population N_j in Equation 3.7 depends on its ability to acquire energy from its surroundings relative to all other mechanisms in the same system. For example in a developed economy, characterized by high k_BT, the most abundant fractions associate with median-income households. These dominant fractions of the distribution on a log-log plot follow the power-law, which in the context of incomes, is referred to as the Pareto principle. The low-income fractions associated with the poorest are smaller, as are the high-income fractions of the long tail [90] associated with the richest [91]. The corresponding distribution of a developing economy, characterized by low k_BT, peaks at the lower fractions [92,93]. Usually the income distributions are taken as inequality indicators [94] whereas here insight to the evolving distribution of wealth is drawn from the law of energy dispersal. Earlier these skewed distributions and their cumulative curves viewed as power-laws have been obtained using statistical physics concepts [95], in particular self-similarity in scaling [28], or using Tsallis' entropy [96], but not explicitly from the 2nd law, although maximum principles have been understood as being in control [87].

When an economy is growing, the distribution shifts higher in energy because during development new more productive mechanisms are adopted and infrastructure is built, while less productive processes and outdated traditions are abandoned (Figure 2). The rate of production and fast circulation of matter using external energy is of the prime importance to reach increasingly higher total economic status as represented by *S*. For example, automation will free up resources for other purposes and so speed up the regeneration of potentials that in turn serve as raw materials for other product potentials. These fervent actions follow directly from the fact that economic potentials are metastable, *i.e.* they are subject to degradation. Increasingly higher turnover requires more energy or more effective use of energy. Therefore economic growth is inevitably coupled with increasing consumption of energy.

The same scaling laws and relationships between overall energy intake and diversity in economic systems hold also for biological systems, where distributions of individuals within a species are skewed, nearly log-normal distributions that peak at the fractions that contribute most to the energy transduction [31,59]. The energy influx and the size of an ecosystem, usually given per area, scale the average energy dispersion and the most abundant fraction of the distribution [32].

The stationary state economy is a conserved system maintained by a steady through-flux without net flows of energy ($dQ_{jk}/dt = 0$). Its isergonic motions, *i.e.*, dynamics on the Euclidean energy landscape, are along statistically predictable trajectories determined solely by the potential and kinetic energy equilibrium condition $2K + U = 0$ as the net flux $\langle Q \rangle = 0$. The steady-state kinetic energy to-and-fro flows correspond to commodity exchange without net profit or loss. The stationary state structure-functional diversity, *i.e.*, the maximum entropy partition of energy transduction mechanisms, can be referred to as the Pareto-efficient economy in the context of game theory or as the Nash equilibrium that is maintained by mixed strategy [97]. However, the stationary state is often only evanescent since the surroundings seldom stay invariant for long, and a system will subsequently tend to senesce and become recycled [12].

The steady-state economy is stable against fluctuations in N_j according to the Lyapunov criterion $\delta S < 0$ and $d\delta S/dt > 0$ [44,64]. Any excess or shortage $\pm\delta N_j$ will be soon be abolished by an opposing gradient that drives the reverse flow dN_j/dt and returns the system back to a maximum entropy partition. The same phenomenon is familiar from population fluctuations in ecosystems that are maintained by a steady influx of energy accompanied by a steady thermal outflow. We emphasize that any particular steady state of a dissipative system is stable only against variations in the existing densities and mechanisms, but must adapt to changes in surroundings as well as those imposed by new mechanisms. Variations in production may yield new superior mechanisms to provide access to new resources. Then the system is once again on an evolutionary track. Thus, for any economy, just as for an ecosystem, there is no absolute guaranty of stability. Furthermore, owing to the limited life span of any dissipative system, there are always systems within systems at various developmental phases on their way toward maturity.

When the surrounding energy density varies periodically, such as by an annual rhythm, it imposes a corresponding variation on ecosystems and also on economic systems. Sporadic changes in surroundings are perceived as fluctuations and perturbations. For example, gross national product declines temporarily when a natural disaster demolishes some energy transduction machinery. Likewise, in biological systems photosynthesis plunges when fire burns a forest. Also, in chemical systems concentrations fluctuate, and temperature varies in physical systems. Since evolution aims at the S_{max} state, stability is naturally sought by all mechanisms. Accordingly, contemporary human endeavors at the global scale aspire after a greater control of increasingly larger surroundings, *e.g.* by meteorite surveillance and accompanied precautionary measures. These conscious actions aim at contributing to the global homeostasis that has been maintained approximately for eons by biotic means. This proposition was articulated by the Gaia theory [98] and recently shown to follow from the 2nd Law [33].

Endogenous fluctuations, oscillations and economic trends are of particular interest in hopes of understanding how they originate and propagate, as well as how to interfere with them and to lessen their adverse consequences. These autocatalytic and progressive phenomena are not exclusive to economic systems but manifest alike as ecosystems' correlated population fluctuations and chemical systems' oscillations, as well as induced emission in physical systems. In all cases, when a powerful transduction mechanism appears for the first time in the system, voluminous flows will be generated and they will be, in turn, invested in increasing the transduction capacity. There are many ecological examples where introduction of exogenous species has caused major changes in endogenous populations.

When a new mechanism emerges, novel potentials build up fast, but one-sidedly, to result in an unbalanced ecological or economic structure. In particular, an autocatalytic process will readily drive a system into imbalance, *i.e.*, away from the distribution given by Equation 3.7. When inserting an autocatalytic dependence, $dN_j/dt \propto N_j$, into Equation 3.6 we realize that then $\delta S < 0$ and also $d\delta S/dt < 0$, which means that the Lyapunov stability criterion is violated. Therefore the autocatalytic processes will easily disrupt the balance. When a powerful mechanism appears in an economy, densities associated with raw-materials, semi-finished products, savings *etc.*, will easily become over-depleted by the over-populating products or assets. These self-reinforcing kinetic mechanisms are reasons for intrinsic economic perturbations. For example, energy densities associated with fuels, food supplies, stocks, *etc.*, but represented in modern electronic forms, can be transformed swiftly from one form to another. A rapid accumulation of huge deposits and large deficits signals an imbalance and entails an inevitable restructuring to regain the steady-state partition.

When the flows redirect to restore the balance, their consequences, despite the natural objective of attaining a steady state, may themselves be devastating. Since economic systems, just as with ecosystems, depend on energy influx, the restructuring processes will affect a system's mechanistic abilities to draw from its surroundings. When the corrective actions undershoot the balance, it takes time to restore the vital mechanisms to regain the high-entropy status that preceded the crisis (Figure 2). Indeed government interference is often directed to slow down activities to prevent overheating or a ‗bubble' and conversely to speed up and maintain activities to prevent recession. However it is not easy to predict consequences of these decisions because the ensuing motion is by its nature non-deterministic. For example, legislative measures targeted on specific potentials and mechanisms will often give rise to unexpected side-effects. On the other hand, general measures tend to be slow. For example, raising the interest rate and reducing the amount of money affect the whole economy. An interest rate, like a tax, will, as an additional transaction cost, shift the balance given by Equation 3.7 and slow down the rates given by Equation 3.5. The reduction in the amount of money will cut the overall liquid potential for transactions. Similarly, shortage of sunlight or of a vital ingredient such as water will curtail the growth of an ecosystem. Despite progress in economic monitoring and ecosystem surveillance, it is difficult to keep track of all potentials and flows, and to recognize various autocatalytic mechanisms in order to respond appropriately and in a timely fashion. Thus, our herein presented statistical formalism for open systems does not provide simple solutions about how to act in a particular case but gives understanding of the inherent difficulties in predicting and directing non-deterministic processes.

10. On Decision Making

The principle of increasing entropy is simple, yet it is not always obvious how to decide among alternative actions and to choose the one that generates flows along the steepest gradients. However, when goods j and $\hat{j}$ are perfect substitutes there is no difficulty to choose the one with the lowest unit price. According to an entropy related utility function, the consumer favors the product j over $\hat{j}$ when $(dS/dN_j)(dN_j/dt) > (dS/dN_{\hat{j}})(dN_{\hat{j}}/dt)$. The consumer, as a thermodynamic system, makes decisions among alternatives on a subjective basis about the factors affecting its capability to further entropy production. Also the producer makes decisions based on a subjective view of energy gradients. Each player in the market will prefer a particular series of transformations, usually referred to as a strategy, to move from one state to another higher in entropy production. For this natural reason the views of consumer and producer are not identical but they do not have to be opposite either, rather, more like parallel in a highly integrated economy.

Since the players are interdependent via direct or indirect flows of energy, every action is accompanied by reactions, usually referred to as its complement [99]. Consequently, flows keep redirecting as the entire economic system evolves to level the energy density differences among players and in respect to the surroundings. The entropy of the entire economic system is an additive measure for the overall global process that sums up from the numerous local processes all directing down along the gradients. Thus, there is no need for each and every player to be aware of the global course which results from their numerous individual actions and mutual interactions. Synergistic actions, collaborations or even altruistic behavior indicate that free energy is drawn by mutual interactions whereas individual efforts, competitions or even selfish deeds imply activities at a lower level in the hierarchical organization.

We emphasize that the decision making is subjective without a universal standard of ‗rational choice' because the gradients are subjectively experienced. To optimize the non-deterministic dispersal process, each player aims at taking into account in its decision making the effects caused by decisions made by others. It is natural that the decision making seems at times inconsistent. A choice that appears most prosperous and consistent with previous decisions is not necessarily chosen when it is coupled with a significant risk of ending up with lowered dS/dt. Consequently, behavior is varied, *i.e.* mixed strategies are used to ensure that on the average dS/dt will remain high. Put otherwise–to ensure maximal energy flows through the system. It is also conceivable that players shun strictly consistent conducts because, in general, deterministic demeanor is not the optimal response to non-deterministic natural courses.

A large economy provides for its subsystems (players) numerous opportunities, *i.e.* various energy gradients. A decision to exploit a particular one may, despite careful considerations, after all reduce the rate dS/dt. The risk has been realized because a particular subsystem may not have been informed of other crucial currents so as to anticipate its future status more realistically. The evolving economic landscape may also change rapidly so that once prosperous conditions have turned into poor circumstances. Due to its inherently non-deterministic and chaotic characteristics, economic development (growth or decline) may direct itself along unexpected trajectories. The integrated dissipation sums up the loss in terms of lost energy and matter from the economy. All in all, the physical portrayal of decision making does not expose its intricacies, but provides fundamental insights into the non-deterministic process.

11. Discussion

In this study the cross-disciplinary examination of economics is not an end in itself but a consequence of applying the universal natural law of energy dispersal. Economic systems are not described as mimicking biological systems but both are seen to be manifestations of the ubiquitous natural law that is equally valid also for chemical and physical systems. Admittedly, the principle of increasing entropy seems technically trivial in its mathematical form but its conceptual consistency draws from the principles of hierarchy theory. Self-similarity in energy transduction and dissipative transformations are the key elements that overshadow disciplinary divisions of historical origin.

Traditionally, economic activities are viewed as being motivated because they provide means for human welfare, or simply because they make profit possible. Our definition of economic activity as a means to increase entropy production sums up numerous terms just as does the gross national product (GNP), the familiar measure for all produced goods and services. However, we emphasize that not all and every productivity counts for the economic growth measured by entropy production that turns negative, *e.g.* due to temporary over production. In a command economy or in a poorly operating market it may take a while before the adverse behaviors are noticed and corrective actions are taken. Indeed, recent studies have revealed that the stability of an economy against incessant endogenous perturbations is compromised when most of its agents are sparsely linked and only a few central hubs have a large number of connections [100,101]. Economic evolution directs naturally toward highly integrated hierarchical systems where statistically independent actions secure maximal flows of energy that rapidly level all accessible gradients of energy. Ensembles of arbitrary actions will be statistically random.

Information deserves no special status in the thermodynamic description of economic activities. Information in its physical representations is a commodity like any other, although its value, measured by entropy increase resulting from instructed actions is often high [40]. Information asymmetry [102] means that informed agents are simply more appropriately equipped with mechanisms than their uninformed counterparts. Adverse selection, *e.g.*, encountered in the principal-agent problem, follows from the subjective nature of decision making that is an inherent characteristic of changing open systems. It is in the interest of the economic system to use various mechanisms, including those that are referred to as rules, traditions and legislation, to promote growth, on the one hand by protecting owner‘s rights in accumulating aggregates that are needed to assemble powerful mechanisms, and on the other hand by ensuring that its agents are informed and equipped with adequate mechanisms, *e.g.* acquired during education.

Utility, that essential but elusive concept, is herein identified with the rate of entropy production; the ultimate but invisible incentive is to disperse energy. Economies evolve by diminishing free energy, equivalent ultimately to increasing entropy, toward more probable distributions of matter under an influx of energy. This reasoning, based on statistical physics, does not undervalue decision making in directing economic activities but allows us to rationalize or framework human behavior.

It is not surprising that a statistical description yields statistical laws and regularities that are characteristic of diverse economic systems, but it is intriguing that the same theory also provides insight into the decision making by individual agents. The self-similar hierarchical formalism considers an individual as a system of its own whose decision making results from a natural process eventually driven by many, and even conflicting, forces. This naturalized view of economic activity, however, does not deny the concept of *free will* but realizes that it is constrained by bearing free energy configurations.

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Appendix

Evolution of an energy transduction system can be simulated by calculating for each entity j the rates of population changes dN_j/dt using the flow equation Equation 3.5. The starting state of the system is determined by assigning all entities j with initial values N_j, and G_j as well as defining endergonic and exergonic jk-transformations with rates σ_{jk}. The initial state of the surroundings is defined likewise by the amounts of entities N_k with energies G_k and energy ΔQ_{jk} that couples to the reactions in the system. The initial free energy terms A_{jk} are calculated and used to drive the population changes ΔN_j in a step of time Δt. Subsequently all driving forces are updated and used again to drive the next step of population changes. When the step Δt is kept short, the forces will not change abruptly and the system remains sufficiently statistical to be described by a common average energy density k_BT. In this way the simulated evolution advances step by step while entropy (Equation 3.6), as a status measure, is only monitored. The simulation approaches a dynamic stationary state where populations fluctuate about the free energy minimum values. A representative ensemble of non-deterministic process can be obtained by varying the rates σ_{jk} (randomly).

In general, simulations of non-deterministic processes will not complete in polynomial time. The computational time increases rapidly with increasing amount of basic building blocks N_1 (stable entities) and available jk-transformations. When using a PC, a simple brute-force simulation that starts off with 10^5 basic building blocks will arrive at a stationary state partition housing 10^2 j-classes in overnight. Presumably the convergence can be improved by algorithms that map the free energy landscape and direct the course along optimal descents.

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ECONOMICS OF ENGINEERING DECISIONS

Laws of thermodynamics and sustainability of the economy

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The consequences of mass and energy conservation and the laws of thermodynamics for economic activity are analysed. As the objectives, for this content of the relations between thermodynamics and economics is critically investigated. First, the relations between mass and energy conservation and the Laws of Thermodynamics are discussed. Then the analysis of neoclassical economics attitudes to the Laws of Thermodynamics is given. After this the analysis of the concept of weak sustainability and the Laws of Thermodynamics are discussed. Methods of systematic scientific literature analysis, general and logical analysis, comparison and generalization were used as the methods of the research.

The relation between Thermodynamics and Economics is a paramount issue in Ecological Economics. Basically, the Laws of Thermodynamics are relevant to the economy because economic activity is entropic. The integration between economics and thermodynamics at the substantive level is of crucial importance because economic processes obey thermodynamic laws and therefore a sound economic theory must be coherent with thermodynamics.

When applying a systems perspective to resources and environmental issues, it is natural to start with thermodynamics. Many resources and environmental problems have their roots in fundamental aspect of conservation of matter. When we analyzing the environment-economy interaction and taking economy, there in each stage of the production process waste will arise. The amount of waste in any period is equal to the amount of natural resources used. The reason for this equivalence is the First Law of Thermodynamics.

But some waste can be converted back to resources. Materials in goods can be recycled. But why not all waste is recycled? It is here that the Second Law of Thermodynamics become relevant. The materials that are used in economy tend to be used entropically and entropy places a physical obstacle, a 'boundary', in the way of redesigning economy as a closed and sustainable system.

In recent years a new discipline Industrial Ecology, has emerged. This new discipline has been built, to a large extent, based on perceived analogies between economic and ecological systems. But the essential ecological difference between people and other species is that, in addition to our ***biological*** *metabolism, people created enterprises with* ***industrial*** *metabolism. This stands as a crucial opposition to evolution of biosphere, which took many billions of years to evolve.*

Interpretations of strong and weak sustainability can also be justified by studying the possibilities of substituting supplies of nature's and economic capital or complementing each other. Strong sustainability requires both types of capital not to decrease for the benefit of one of significant indicators. The version of weak sustainability contains (making an unrealistic assumption about the perfect substitution of nature's and man-made capital) the sum of the forms of both capital – nature's and economic capital – or any other aggregated unit of measurement, and requires it not to decline all the time.

Keywords: *Economy; Mass and energy conservation; Entropy; Exergy; Laws of Thermodynamics; Sustainability; Neoclassical economics; Ecological economics*

Introduction

The Problem. The relation between Thermodynamics and Economics is a paramount issue in Ecological Economics. The question whether physical laws like the entropy law or the conservation laws of mass and energy are relevant to economic analysis has given rise to disputes. From the other side, the neoclassical economics which dominates resource and environmental analysis and policy is based on atomistic and mechanistic assumptions about individuals, firms, resources, and technologies which are inappropriate to the complex and pervasive physical connectivity of both natural and economic systems.

The Research Object. The main attention in the article is given to analyze the relation between thermodynamics and economics issues.

The Objective. The content of the relations between thermodynamics and economics is critically investigated in the article.

The Tasks. In order to fulfill these objectives, the following research tasks had to be accomplished:

To investigate the relations between mass and

- energy conservation and the Laws of Thermodynamics.
- To discuss neoclassical economics attitudes to the Laws of Thermodynamics.

- To investigate the concept of weak sustainability in the context of the Laws of Thermodynamics.

The Methods of the research. Logic abstraction, which encompasses generalisations on theoretical systems analysis of the environmental and ecological economics, according to the conclusions and reasoning of scientists from other countries was used in the article. The main scientific works related to the problem have been reviewed and thoroughly analysed.

Mass and energy conservation and the Laws of Thermodynamics

The relation between Thermodynamics (that part of physics which deals with conversions of energy and matter) and Economics is a paramount issue in Ecological Economics.

Generally, all systems are (at minimum) thermodynamic systems (in addition to their other characteristics) so that thermodynamic constrains and principles are applicable across both ecological and economic systems (Eriksson, 1991). This fact points out the need for a systems perspective on materials flows and the need to ask fundamental questions about the relationship between society and nature.

Basically, the Laws of Thermodynamics are relevant to the economy because economic activity is *entropic*. (*Entropy* is a measure of the disorder in a system, a highly organized system is said to be low-entropy, while a disordered system is said to be high-entropy. Entropy increases as order deceases. In this paper entropy will mean the tendency of matter and energy to degrade or disperse into less useful forms during economic activity). Economic production is utterly dependent on the availability of low-entropy inputs of natural resources (Daly and Cobb, 1989).

As shown by T. S. Domingos (2006), the integration between economics and thermodynamics at the substantive level is of crucial importance because economic processes obey thermodynamic laws and therefore a sound economic theory must be coherent with thermodynamics. This integration highlights the dependence between the economic system and the biophysical framework contributing to the analysis of the sustainability of economies, which are complex adaptive systems, that is, composed of large and increasing number of both components and of the relationships between them.

When applying a systems perspective to resources and environmental issues, it is natural to start with thermodynamics. Many resources and environmental problems have their roots in fundamental aspect of conservation of matter. As shown by D. W. Pearce and R. K. Turner (1990), when analyzing the environment-economy interaction and taking economy, there in each stage of the production process waste will arise. The processing of resources creates waste W_R, as with overburden tips at coal mines; production creates waste W_P in the form of industrial effluent and air pollution and solid waste; final consumers create waste W_C by generating sewage, litter, and municipal refuse.

The amount of waste in any period is equal to the amount of natural resources used *R*:

$$\mathbf{R = W = W_R + W_P + W_C} \quad (1).$$

The reason for this equivalence is the *First Law of Thermodynamics*. This law essentially states that we cannot create or destroy energy and matter, we can only transform it. In modern physics, matter itself is a form of energy, as is shown by A. Einstein's famous equation:

$$\mathbf{E = mc^2} \quad (2).$$

Whatever we use as resources, they must end up somewhere in the environmental system. It cannot be destroyed (Ayres and Kneese, 1969, Ayres, 1978). It can be converted and dissipated. For example, coal consumption in any year must be equal to the amount of waste gases and solids produced by coal combustion. Some of it will appear as slag, some as carbon dioxide and so on.

But we can take some of the waste, *W*, and convert it back to resources. *Closing the flow* of materials within society implies that the same asset or material is used again and again. We can *reuse* goods: we are all familiar with bottle banks for recycling glass bottles. Materials in goods can be *recycled* as with, for example, metals. Many metals (the metal in aluminum cans or the lead in lead-acid batteries) are recycled. Some waste paper returns to be pulped for making further paper, and so on. But a great deal of waste, indeed the majority of it, is not recycled.

Why not all waste is *recycled*? It is here that the *Second Law of Thermodynamics* becomes relevant. (This law was developed in connection with steam engines in 1824 by French physicist S. Carnot). The materials that are used in economy tend to be used *entropically* – they get dissipated within the economic system. Moreover there is a whole category of resources that cannot be recycled – energy resources. Entropy therefore places a physical obstacle, a 'boundary', in the way of redesigning economy as a closed and *sustainable* system.

So, there is another point of apparent similarity between ecological and economic systems that has attracted special attention in recent years, namely, 'recycling'. It is well-known that the industrial system is very wasteful of materials and recycles very little. Many well-meaning environmentalists seem to imagine that the biosphere is a perfect recycler and suggest that the industrial world should imitate 'nature' in this regard, i.e., to achieve 'zero emissions' in the industrial landscape by recycling all wastes. However, as shown by R. U. Ayres (2004), while most biomass is recycled fairly quickly, it is not true that there are no unrecycled wastes in nature. The idea of 'zero emissions' is based on the (false) idea that every biological waste is 'food' for some other organism. This is true, essentially, only for carbon-based organic materials and, especially, the well-known carbon-oxygen cycle. But the idea that some industry can always be found (or created) to consume another industry's waste, or even just its solid waste, is naive. In fact, 'zero emissions' from industry are only feasible in a few narrow and highly specialized contexts, primarily in the realm of food processing (Enzell et al., 1995). Recycling is another matter entirely, and a lot of industrial waste can be recycled, albeit not perfectly, and only by the application of significant amounts of energy (exergy) from somewhere outside the system.

Speaking about shortages of neoclassical economics, H. E. Daly (1995) argues that standard economics explains circular flows because they are mechanistic in nature (reversible and quality less) and that it does not explain the one-way flow of resources into waste because irreversible and mechanistic models cannot deal with irreversibility.

This irreversibility in processes and components depends on the energy degradation rate and not only on the ratio between the intensities of output and input flows, energy quality can be quantified by entropy analysis. Recently, several works have been published on the relation between exergy and environment (Rosen, 2002). Exergy is strictly connected to environmental impact, because pollution potential is proportional to the extent of energy conversion and utilization processes. Generally, exergy shows the value of energy as work, and permits comparisons between energies which are different from a Second Law point of view: it is defined by the maximum amount of work which can be ideally produced by a system as it comes to equilibrium with a reference ambient (Gong and Wall, 2001). In a real process, exergy consumption is related to entropy production due to irreversibilities, so the exergy takes into account the entropy increase in the environment due to the process: *the exergy loss is proportional to the entropy production*. Entropy is used as indicator of the sustainability of different areas from urban areas to agricultural zones; the entropy variations of a studied area are also used as a measure of the environmental pollution cost by the waste exergy approach to quantitative comparison of environment impacts. The Life Cycle Analysis method was initially based both on mass conservation and First Law of Thermodynamics. More recently the Second Law was considered and also an Exergy-based Life Cycle Costs Analysis (Ayres, 1998, Rosen, 2002).

Generally, as shown by F. C. Krysiak (2006), since the publication of the first economist who perceived the significance of *thermodynamic restrictions*, especially *the entropy law*, to the economic theory N. Georgescu-Roegen "The Entropy Law and the Economic Process" (Georgescu-Roegen, 1971), the question whether physical laws like the entropy law or the conservation laws of mass and energy are relevant to economic analysis has given rise to disputes. Two major positions have been developed.

The mainstream position has been formulated by R. M. Solow as "[…] everything is subject to the entropy law, but this is of no immediate practical importance for modeling what is, after all, a brief instant of time in a small corner of the universe" (Solow, 1997, p. 268). Thus mainstream economists acknowledge the existence of these laws, but they claim that these laws have no substantial consequences for economic analysis and can therefore be safely neglected.

This position has attracted much criticism, especially from ecological economists. H. E. Daly (1997) among others, argues that it is based on a misinterpretation of the entropy law and the conservation laws; in a form suitable for open systems, these laws do not only apply to the universe as a whole but to all systems that process mass or energy, including economic production and consumption activities. Furthermore, these laws have important consequences as they rule out the common model of a closed, nature-independent economy that can grow without limits.

H. E. Daly (1973) was among the first to introduce the issue of *permissible scope of economic activities* which was ignored by neoclassical economic theory (especially on the macro-level) in his works on the economy of *stationary status*. The author transferred the focus of economic research from *the economy of production scope*, reflecting effectiveness in changing scope of company or industry's production, to *the economy of scope*. His essential finding can be concluded as follows: *the economic activity should assume the intelligent (permissible) scope, reflecting ecological capacity of ecological systems* (Čiegis, 2004).

Seeing the environment as a complex ecosystem that is finite, non growing and materially closed (the exchange of matter with space is indeed very small compared to the flows on Earth), while open to a non growing, finite flow of solar energy, which is balanced by an outflow of energy in the form of heat radiation into space, and economy as an open subsystem forces to realize that consumption is not only disarrangement within the subsystem, but involves disarrangements in the rest of the system, the environment. As mentioned by H. E. Daly (1996), taking matter/energy from larger system, adding value to it, using up the added value, and returning waste, clearly alters the environment. The matter/energy we return is not the same as the matter/energy we take in. Common observation tells us, and the entropy law confirms, that waste matter/energy is qualitatively different from raw materials. Low-entropy matter/energy comes in, high-entropy matter/energy goes out, just as in organism's metabolism.

Since the work of R. U. Ayres and A. V. Kneese (1969) and of N. Georgescu-Roegen (1971) many studies have analyzed the consequences of thermodynamic laws for economic analysis. On the microeconomic level, Islam (1985) analyzes the consequences of the second law of thermodynamics, showing that it implies that the isoquants of a production process cannot comply with the often-used assumption of a Cobb–Douglas technology. On a macroeconomic scale, R. U. Ayres and A. V. Kneese (1969) have introduced mass and energy balances into static input–output analysis. Perrings (1986) has extended this analysis to linear dynamic models, showing that these balance equations can lead to instabilities. However, as shown by F. C. Krysiak (2006), mass and energy conservation alone, that is, without considering the second law of thermodynamics, does not challenge the fundamental concepts of economic analysis.

The possible consequences of the second law on a macroeconomic scale are subject to an ongoing dispute.

Some scientists argue that although the second law may have consequences on a microeconomic scale, it is not relevant on a macroeconomic scale because the earth is an open system that imports "low entropy" by solar radiation. Furthermore, the capability of human beings to innovate provides a way to defer possible negative consequences of the second law to an unforeseeable future or even to avoid them completely (Krysiak, 2006). But others argue that they are based on an inaccurate implementation of the second law of thermodynamics. Especially, they argue that all feasible production processes are subject to the laws of thermodynamics, so that innovation will not provide a means to escape the constraints imposed by these laws.

From the other side, as was shown by J. Martinez-Alier (1991), to see economy as entropic does not imply ignorance of the anti-entropic properties of life (or, in general, of open systems). This point must be made explicitly because the growth of "social Prigoginism", i.e., the doctrine that human societies self-organize themselves in such a way as to make worries about depletion of resources and pollution of the environment redundant.

N. Georgescu-Roegen (1971) developed a critique of standard economics from the standpoint of the second law of thermodynamics. But low entropy is necessary, but not a sufficient condition to transform matter into use-value. New science *bioeconomics*, based on the assertion that the economic process increasingly produces higher entropy that limits economic growth, centering its attention on the technological transformation of matter, suggests that entropy growth can be controlled by "social modeling" (Leff, 1996).

Neoclassical economics and the Laws of Thermodynamics

Economies are open complex adaptive systems far from thermodynamic equilibrium, and neoclassical environmental economics, which is based on atomistic and mechanistic assumptions about individuals, firms, resources, and technologies which are inappropriate to the complex and pervasive physical connectivity of both natural and economic systems, seems not to be the best way to describe the behaviour of such systems. In contrast to the materials-based approach of classical economic theory, neoclassical economics lacks any representation of materials, energy sources, physical structures, and time-dependent processes that are basic to an ecological approach. Worse, it is inconsistent with the physical connectivity and positive-feedback dynamics of energy and information systems (Christensen, 1991).

The belief that neoclassical economics is based on a formal analogy to classical mechanics and on isomorphism between the equations of mechanics and the equations of economic equilibrium of neoclassical economics after 1870 is common among ecological economists (Amir, 1995; Martinez-Alier, 1997; Costanza et al., 1997). Based on supposed analogy to classical mechanics, the main formal criticisms of neoclassical economics are: utility does not obey a conservation law as energy does; an equilibrium theory cannot be used to study irreversible processes. But T. S. Domingos (2006) argues that neoclassical economics is not formally identical to classical mechanics and that the correct identification of the formalism that underlies the construction of neoclassical economics is vital in the evaluation of its internal coherence. He shows that economics is formally identical to thermodynamics because they are both problems of static constrained optimization. However, it is of fundamental importance that the fact that neoclassical economics is formally identical to thermodynamics does not mean that it is compatible with thermodynamic laws.

It is generally claimed that neoclassical economics is based on classical mechanics because throughout the history of economics many economists used analogies from classical mechanics. As shown by T. S. Domingos (2006), this approach of establishing analogies between mechanics and economics was taken to its extreme by Irving Fisher who in 1892 established the most extensive relation between mechanics and economics. Given the history of economic analogies to mechanics, there is a widespread claim that neoclassical economics is fundamentally flawed because the assumptions on which classical mechanics is based do not apply to consumer theory. The most important aspects usually referred in the literature are: 1) utility does not obey a conservation law as energy does; 2) an equilibrium theory cannot be used to study irreversible processes. Some of the examples of this are described by T. S. Domingos (2006). He agreed that if neoclassical economics were indeed formally identical to classical mechanics it would be internally incoherent. However, he argued that neoclassical economics is based on a wrong formulation of classical mechanics, being in fact formally identical to thermodynamics. Both neoclassical economics and thermodynamics are equilibrium theories and can be developed as formalisms of constrained optimization.

However, it is of fundamental importance that the fact that neoclassical economics is formally identical to thermodynamics does not mean that it is compatible with thermodynamic laws. As shown by T. S. Domingos (2006), examples of flaws in the integration between economic theory and thermodynamic laws already identified are: economic theory considers a circular flow between households and firms without considering the one-way flow that begins with resources and ends with waste (Georgescu-Roegen, 1971); energy and capital are generally not substitutes, as assumed by production functions, but complements (Daly, 1997); and production theory does not fully possess thermodynamic irreversibility (Baumgärtner, 2005).

We would like to emphasize that the substantive integration between thermodynamics and economic systems should not be based on the thermodynamic theory of isolated systems. Economic systems are open thermodynamic systems far from equilibrium and therefore a thermodynamic analysis of economic systems should be based on the thermodynamics of non-equilibrium open systems (Kondepudi and Prigogine, 1998).

But *the neoclassical* model, assuming that nature is not involved in the production process and, consequently, production growth is not influenced by natural forces, *has separated the economic system from natural and other social systems.* It has concentrated exceptionally upon *value measures, such as*: *abstract labour* and *abstract capital invested*, totally ignoring their physical interfaces with the ecological sphere and functional qualities of utilised ecological systems. Therefore, the traditional *circulating economic model* was built upon the assumption that *economy* was the *whole* (but isolated) *system,* and *nature*- its *subsystem*. It described a closed, renewable system where natural resources and ecological systems were viewed as inexhaustible and renewable and primal factors, limiting economic development, were solely considered to be labour and capital.

This is also the economy which is self-sustaining. In neoclassical production theory, each input is assumed to be incrementally productive. Materials, energy, resources, physical connectivity, and the structures and organization of real world production are ignored (Christensen, 1991). Besides, another assumption is made in the traditional aggregated, homogeneous neo-classical *Cobb-Douglas's function of production*:

$$\mathbf{Y = A \times L^a \times K^b} \quad (3),$$

where: *Y* – national incomes, *K* – capital, *L* – labour, *a* and *b* are constants.

This *Cobb-Douglas's function* states that all production factors, limited and independent in nature, but *complementing* each other, can be *interchangeable or substituted* (Čiegis, 2004). Therefore, in such rare cases when the cost of natural resources (*R*) was reckoned in the *Cobb-Douglas's function* alongside with capital (*K*) and labour (*L*)- (for example, as suggested by *J. Stiglitz* in his aggregated production function), it was performed mathematically replacing *K* with *R*, where *R* equals zero, without any effect on the proportion of national income (*Y*).

Consequently, it was assumed that the capital created by man as the outcome of the technological changes could successfully replace the nature's capital on a regular basis, without any thermodynamic restrictions. These growth models never considered the fact that economies exist and are directly related to the biological world, which place restrictions to physical world. Eventually, it turned out that the economic models, which continue to ignore biological restrictions, are doomed, as they are hopelessly imperfect.

It is more obvious that we are dealing with complex natural-social systems, which no longer can be monitored within the classical paradigmatic framework of mechanics and engineering science. As was shown, biological and economic processes obey physical principles: the first and second laws of thermodynamics (conservation of energy and materials and the entropy law) and the principles governing individual material and energetic transformations (Ayres, 1978). These principles underlie the physical connectivity which characterizes biological and economic systems.

Thus, we need to replace the linear thinking about economic life with a more complex non-linear thinking, as well as we should apply a more holistic and evolutionary approach to economic activity, accepting ethic consequences of moral decisions, which we should make during the economic process. In fact, we need an analytical system, which could comprise ecological and social-economic systems. And the inputs of an ecological economics are not land, labour, and capital, but flows of materials, energy and information and the engines, machines, and workers organized to process materials, energy, and information.

Processes, occurring in the techno-sphere, are difficult to be explained according to the traditional economic paradigm, the direction of development which was determined only by interests of labour and capital economy as well as by the pursuit of maximum productivity. As mentioned by R. U. Ayres (1989, 2004), in recent years, new discipline, Industrial Ecology, (or Industrial Metabolism,) has emerged. This new discipline has been built, to a large extent, based on perceived analogies between economic and ecological systems. There is an attractive analogy between nature and industry, based on the similarity of natural functions and certain industrial activities. But the economic system is not closely analogous to an ecosystem. The one element that both biologists and economists might be able to agree on is that both biological and economic evolutions are equilibrium seeking processes. But, as shown by R. U. Ayres (2004), to be sure, the relevant definitions of equilibrium are quite different in two cases. In biology, as in physics, the notion of equilibrium is based on thermodynamics. Another approach would emphasize the accumulation of information or 'orderliness' in a sense that might be possible to define and quantify. However, equilibrium in economics is quite different. It is a hypothetical steady state in which supply and demand are balanced for every commodity (Arrow and Debreu, 1954). Economists, having proved many theorems about the existence of such a state and its properties, have felt constrained to postulate that economic growth occurs in equilibrium, although it does not and cannot.

As shown by R. U. Ayres (2004), the main (and crucial) difference between biological and economic perspectives on evolution can be summarized succinctly. Biological evolution is a very slow unconscious process driven by physical phenomena (e.g., mutation) and implemented by competitive reproductive strategies adapted to specific environmental 'niches'. Economic evolution is, of course, much faster than biological evolution. Moreover, it is entirely driven by conscious human decisions bearing little resemblance to mutation and adjustment via population dynamics.

A crucial condition of an industrial economy operating through time is its ability to obtain flows of low entropy energy and materials. As Alfred Lotka noted, any organism that discovers how to take advantage of unused energy running over a dam gains a selective advantage over other organisms (Christensen, 1991). The essential ecological difference between people and other species is that, in addition to our ***biological*** *metabolism*, people created enterprises with ***industrial*** *metabolism*. This stands as a crucial opposition to *evolution* of biosphere, which took many billions of years to evolve. Thus, the society, trying to achieve "*economic evolution*", should "take lessons" from the biosphere (Čiegis, 2004).

The concept of weak sustainability and the Laws of Thermodynamics

Literature analysis has shown that in a static setting, physical conservation laws and the second law of thermodynamics imply that economic activity is likely to depend critically on natural resources and on the ability of the environment to absorb generated emissions. Without either of these, no production or consumption is possible, except for goods that are produced and consumed by completely reversible processes. In a dynamic setting, the physical constraints imply that, even with the possibility to accumulate human or physical capital, more production of a good with non-vanishing marginal entropy production always necessitates more resource use.

Interpretations of *strong* and *weak sustainability* can also be justified by studying the thermodynamic possibilities of substituting supplies of *nature's* and *economic* capital or complementing each other (Čiegis et al., 2005). *Strong* sustainability requires *both* types of capital not to decrease for the benefit of one of significant indicators. In other words, according to *the law of strong sustainability, the aggregate physical quantity of nature's capital or general nature's capital (despite its type) and its value should not decrease and should be preserved for future generations*. (In a more stringent version of *very strong sustainability* stationary limitations should be already defined in the macro-economic level). In addition, according to criteria of strong sustainability, a supposition is made that nature's and economic capital are *complementary* in the production process rather than *substituting* (Costanza, Daly, 1992). Actually, it is recognised that some natural resources and services cannot be totally substituted as these forms of nature's capital supply vital services for all life-supporting environmental systems. The version of *weak* sustainability is more acceptable for dominating economic theories, oriented towards securing the status where "wealth does not decrease in the time lag" (Pearce, 1993). (In case we apply a more narrow approach of *very weak sustainability*, then productivity potential of common economy would resume untouched to ensure constant consumption per person in a given time). The version of *weak sustainability* contains (making an unrealistic assumption about the perfect substitution of nature's and man-made capital) the sum of the forms of both capital – nature's and economic capital- or any other aggregated unit of measurement (for example, the "green" GNP). *So there is orientation to the stock of the capital, which we are living for the future generations, expecting that this capital stocks must be not lesser as have our generation* (Pearce, Atkinson, 1993).

So, as described F. C. Krysiak (2006), weak sustainability holds that each generation has the moral obligation to keep the total capital stock at least constant, where the total capital stock is comprised of the stocks of natural and produced capital. We can formalize this by defining a total capital stock *C* that is an aggregate of resource stocks x_i (comprised of the stocks of exhaustible and renewable resources) and the stocks of capital goods Z_i. Furthermore, such an aggregate is commonly taken to be a linear aggregate, that is, we have:

$$\mathbf{C} = \sum_{i=1}^{q+v} \beta_i x_i + \sum_{j=1}^{n} \gamma_j Z_j \quad (4),$$

Where: β_i and γ_j are constant weights attached to the different stocks.

This form of aggregation implies an infinite elasticity of substitution between the different stocks, that is, it is always possible to exchange one unit of resource stock *i* for β_i / γ_j units of capital stock Z_j leaving the aggregate *C* unchanged.

But the important questions are under which conditions this property does not devaluate the aggregate *C* as a measure for sustainability and whether these conditions are consistent with physical constraints.

In fact, the foundation of weak *sustainability* was made by *J. Hartwick* (1977; 1978) and his proposed idea of *compensation*, elaborating on nature's capital and its loss which should be compensated by the additional man-made capital or by the combination of man-made capital and nature's capital. If we mark the letters K_t, H_t and R_t as resources of physical, human and nature's capital respectively in time period t, the net value of changes in general capital resources will acquire the following expression (5):

$$I_t^N = \frac{dK_t}{dt} + \frac{dH_t}{dt} + \frac{dR_t}{dt}$$

If $I_t^N = 0$, then the country reserves its general capital resources and it is capable of securing its consumption level. This result was named after Hartwick as *"the Hartwick rule"*. It postulates that economic growth can be considered "sustainable", if the level of investment is higher than the value of extracted resources, constituting the *scarcity rent*, i.e. if $I_t^N > 0$. It means, that where the capital stock includes exhaustible or depletable natural resources, a necessary condition for the value of capital to be non-declining is that the rents deriving from resource depletion should be reinvested in reproducible capital to compensate for the user costs of depletion.

But much of the industrial countries' wealth came from the exploitation (sometimes liquidation) of natural capital, not only within their own territories, but also within former colonies, taking its territories carrying capacity. And, as mentioned by W. E. Rees and M. Wackernagel (1994), this persistent relationship is an inevitable consequence of thermodynamic law. The techno-economic growth and high material standards of developed countries require continuous net transfers of negentropy (exergy and available energy/matter) to the industrial center. Conversely, less-developed regions and countries must experience a net increase in entropy as natural resources and traditional social structures are dismembered.

Conclusions

1. The marginal analysis applied in neoclassical economic theory caused the correlation among economic production, consumption and equity as a whole and natural resources and ecological systems not to be properly assessed and evaluated.
2. The irreversibility of the real processes implies exergy destruction and waste flow to the environment.
3. From the point of the mainstream economist, a rigorous proof that the entropy law and the conservation laws of mass and energy matter for economic analysis is still missing.
4. Literature analysis has shown that the formal criticisms of neoclassical economic theory are wrong because they are either based on mixing up the substantive and formal levels or they are based on the wrong assumption that the microeconomic formalism is analogous to the classical mechanics formalism.
5. It is of fundamental importance that the fact that neoclassical economics is formally identical to thermodynamics does not mean that it is compatible with thermodynamic laws.

6. In the neoclassical Cobb-Douglas function of production the assumption is made that all production factors can be replaceable and substituted. Therefore, growth models here do not suggest that economy's functioning depends on the biological world, which eventually places restrictions on physical growth.

7. One of the most significant ecological and social challenges of today brought up to the new paradigm of economic development is the importance of evaluating industrial metabolism, envisaging the analogy between economy and environment on the material level.

8. A biophysical organizational approach to ecological economics starts from a recognition of the environmental, technological, individual and social sources and support systems of productivity.

9. The version of weak sustainability contains (making an unrealistic assumption about the perfect substitution of nature's and man-made capital) the sum of the forms of both capital – nature's and economic capital – or any other aggregated unit of measurement (for example, the "green" GNP), and requires it not to decline all the time.

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Termodinamikos dėsniai ir ekonomikos darnumas

Santrauka

Šiame darbe nagrinėjamas masės ir energijos tvermės bei termodinamikos dėsnių poveikis ekonomikai. Šiuo tikslu išsamiai išanalizuotas sąryšis tarp termodinamikos teorijos ir ekonomikos teorijos. Pirmiausia aptartas ryšys tarp masės ir energijos tvermės bei

termodinamikos dėsnių. Tada pateiktas neoklasikinės ekonomikos teorijos požiūris į termodinamiką. Po šios analizės aptartas silpno darnumo ir termodinamikos dėsnių sąryšis.

Darbe naudojama sisteminė mokslinės literatūros analizė, taip pat bendroji ir loginė analizė, lyginimo ir apibendrinimo metodai.

Sąryšis tarp termodinamikos ir ekonomikos teorijos yra ypač svarbus, kai nagrinėjame ekologinės ekonomikos teorijos klausimus. Iš esmės termodinamikos dėsniai yra tiesiogiai susiję su ekonomika, nes ekonominė veikla didina *entropiją*. Ekonomikos teorijos ir termodinamikos sujungimas realiame lygyje yra ypač svarbus, tai reiškia, kad ekonominiai procesai tenkina fundamentinius termodinamikos dėsnius, ir bet kokia gyvybinga ekonomikos teorija privalo būti suderinta su termodinamikos postulatais.

Kai taikome sisteminį požiūrį išteklių ir aplinkosaugos problemoms, analizę natūralu pradėti nuo termodinamikos klausimų. Daugelio išteklių ir aplinkos problemų esmė siejasi su fundamentiniu masės tvermės dėsniu. Kai analizuojame aplinkos ir ekonomikos sąveiką ir nagrinėjame ekonomiką, tai matome, kad kiekviename gamybos žingsnyje atsiranda atliekų. Kiekvieno laiko periodo atžvilgiu atsiradusių atliekų kiekis yra lygus panaudotų gamtinių išteklių kiekiui. Tai paaiškina *pirmasis termodinamikos dėsnis*.

Aišku, dalį atliekų galime perdirbti į naudingas žaliavas. Taigi medžiagos, iš kurių gaminami produktai, gali būti *pakartotinai perdirbtos*. Bet kodėl negalima taip sutvarkyti visų atliekų? Kaip tik čia ir svarbus tampa *antrasis termodinamikos dėsnis*. Gamyboje naudojame medžiagas *entropiškai*, todėl visos sistemos entropijos didėjimas yra fundamentalusis gamtos barjeras, neleidžiantis sukurti ekonomikos kaip uždaros ir *darnios* sistemos.

Nagrinėdami neoklasikinės ekonomikos teorijos trūkumus, straipsnio autoriai tvirtina, kad standartinė teorija paaiškina tik ciklinius srautus, kadangi šie yra mechaninės prigimties (grįžtami ir mažėjančios kokybės), ir negali paaiškinti negrįžtamo išteklių perdirbimo į atliekas tėkmės, nes jos negrįžtami ir mechanistiniai modeliai tinka tik grįžtamiems procesams modeliuoti. Šis procesų ir atskirų komponentų negrįžtamumas priklauso ne tik nuo santykio tarp įtekančių ir ištekančių.

Pasirodžius N. Georgescu-Roegen veikalui „Entropijos dėsnis ir ekonomikos procesai“, pradėta plačiai diskutuoti, ar tokie fizikos dėsniai, kaip masės ir tvermės ar entropijos, yra svarbūs ir ekonominėje analizėje. Susiformavo du svarbiausi požiūriai. Dauguma ekonomistų, besilaikančių vyraujančios ekonomikos teorijos požiūrio, pripažįsta šių dėsnių egzistavimą, bet teigia, kad jie neturi nors kiek didesnės reikšmės ekonominei analizei ir todėl gali būti ignoruojami. Šis požiūris sulaukė daug kritikos, ypač energingai tai darė ekologinės ekonomikos atstovai. Jie tvirtino, kad jis remiasi neteisinga entropijos ir tvermės dėsnių interpretacija.

Ekonomikos yra atviros, sudėtingos, prisitaikančios sistemos, esančios toli nuo termodinaminės pusiausvyros ir neoklasikinės aplinkos ekonomikos teorijos, kuri remiasi atomistinėmis ir mechaninėmis prielaidomis apie individus, firmas, išteklius. Skirtingai negu klasikinė ekonomikos teorija, grindžiama medžiaginiu požiūriu, neoklasikinėje teorijoje nėra jokių medžiagų, energijos šaltinių, fizinių struktūrų bei nuo laiko priklausančių procesų aiškinimo ir naudojimo, o kaip tik tai ir sudaro ekologinio požiūrio pagrindą.

Tarp ekologinės ekonomikos šalininkų populiarus požiūris, kad neoklasikinė ekonomikos teorija remiasi formalia analogija su klasikine mechanika bei vienareikšmišku sąryšiu tarp mechanikos ir ekonomikos pusiausvyros lygčių. Tačiau šiame straipsnyje parodoma, kad neoklasikinė ekonomikos teorija nėra net ir formaliai tapatinga klasikinei mechanikai ir kad teisingas apibrėžimas formalizmo, sudarančio neoklasikinės ekonomikos karkasą, yra gyvybiškai svarbus, kai vertiname šios teorijos vidinę darną. Tačiau tai, kad neoklasikinė ekonomikos teorija yra formaliai panaši į termodinamikos teoriją, nereiškia, jog ji yra suderinama su termodinamikos dėsniais.

Buvo parodyta, kad biologiniai ir ekonominiai procesai paklūsta fizikos principams: pirmajam ir antrajam termodinamikos dėsniams (masės ir energijos tvermės bei entropijos dėsniams) ir principams, valdantiems atskirų medžiagų ir energijos rūšių transformacijas. Šie principai ir sudaro fizikinio susiejamumo, apibūdinančio biologines ir ekonomines sistemas, pagrindą.

Pastaraisiais metais atsirado nauja disciplina – pramonės ekologija. Ši nauja disciplina sukurta labiausiai remiantis analogija tarp ekonominių ir ekologinių sistemų. Tačiau esminis ekologinis skirtumas tarp žmonių ir kitų rūšių yra tai, kad žmonės, šalia mūsų ***biologinio*** *metabolizmo*, sukūrė ir įmones su ***pramoniniu*** *metabolizmu*. Čia matome milžinišką skirtumą nuo biosferos *evoliucijos*, kurios formavimasis truko milijardus metų.

Stipraus ir *silpno darnumo* interpretacijos taip pat gali būti grindžiamos *gamtinio* bei *ekonominio* kapitalo atsargų pakeičiamumo ir vienas kito papildymo galimybėmis.

Stiprus darnumas reikalauja, kad *abu* nemažėtų kurio nors svarbaus indikatoriaus požiūriu. Tai yra, laikantis *stipraus darnumo taisyklės*, reikalaujama, kad *visuminis gamtinio kapitalo fizinis kiekis, arba bendro gamtinio kapitalo, neatsižvelgiant į jo tipą, vertė nemažėtų ir būtų išsaugota ateinančioms kartoms*. Drauge, vadovaujantis stipraus darnumo kriterijais, skirtingai negu silpno darnumo koncepcija, daroma prielaida, kad gamtinis ir ekonominis kapitalas gamybos procese labiausiai yra vienas kitą *papildantys*, o ne *pakeičiantys*.

Vyraujančias ekonomines teorijas atstovaujantiems ekonomistams yra priimtinesnė *silpna* darnumo versija, orientuota į būklės, kuriai esant „gerovė nemažėja laikui bėgant“ užtikrinimą. *Silpno darnumo* versija apima (darant nerealią prielaidą apie gamtinio ir žmogaus padaryto kapitalo tobulą *pakeičiamumą*) abiejų kapitalo formų – gamtinio ir ekonominio kapitalo – sumą ir reikalauja, kad šis nemažėtų laikui bėgant.

Faktiškai *silpno darnumo* versijos pagrindas yra *J. Hartwick* pasiūlyta *kompensavimo* idėja, teigianti, kad gamtinio kapitalo praradimas turi būti kompensuotas papildomu žmonių padarytu kapitalu ar žmonių padaryto ir gamtinio kapitalo kombinacija.

Raktažodžiai: *ekonomika, masės ir energijos tvermė, entropija, eksergija, termodinamikos dėsniai, darnumas, neoklasikinė ekonomikos teorija, ekologinė ekonomikos teorija*

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To observe or not to observe:
Complementary pluralism in physics and economics

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Introduction

This quotation from **Einstein** expresses the essence of what this paper hopes to say.

> Whether you can observe a thing or not depends on the theory which you use. It is theory which decides what can be observed.
>
> [Said to Werner Heisenberg during his 1926 Berlin lecture, quoted in Salam, 1990]

Rarely, and probably never, has a major discipline experienced systemic failure on the scale that economics has in recent years. Its fall from grace has been two-dimensional. One, economists oversaw, directly and through the prevalence of their ideas, the structuring of the global financial economy that collapsed. Two, except for a few outcasts, economists failed to observe, even before the general public observed, the approach of the biggest financial meltdown of all time. Never has a profession betrayed the trust of society so acutely, never has one been in such desperate need of a fundamental remake.

As an epistemological event, the 2008 meltdown of the global financial system ranks with the observation of the 1919 solar eclipse. If professional practice in economics resembled that in the natural sciences, then in the wake of the recent global disaster economists would be falling over each other to proclaim the falsity of their theories, the inadequacy of their methods and the urgent need for new ones so that they could observe economic reality.

It is now evident to nearly everyone except economists, and increasingly even to many of us, that our collective failure to see the coming of the calamity before it occurred and the fact that the system that collapsed had been tailored to fit mainstream teachings means that our profession harbours fundamental misconceptions about the way economies, most especially their markets, function.

But there exists in economics a malaise more fundamental than its theories themselves. The malaise concerns how economics regards and uses its theories, and it is this and its relation to the teaching of economics that this paper addresses, because it is really this that must be corrected if economics is to be made less a facilitator of human disaster in the future.

I need to be clear about what I mean by the word “pluralism” in an epistemological context. So here is the definition which this paper presumes.

“Pluralism” refers to

- some degree of acceptance

[1] I am indebted to my University of the West of England colleagues for their helpful comments.

- of two or more mutually inconsistent theoretical frameworks
- which pertain to the same or overlapping domains of reality.

So, given multiple theoretical frameworks within a field of study, there are three variables in that definition of pluralism:

1. degree of acceptance
2. degree of mutual inconsistency, and
3. degree or extent of overlapping domains.

With regard to the first of the three variables, the degree to which mutually inconsistent theoretical frameworks are tolerated or accepted or valued by practitioners of a scientific or scholarly discipline, this paper makes a distinction between what I call **competing pluralism** and **complementary pluralism**.

I am going to begin by considering complementary pluralism, because it is the kind with which we as economists are least, or even not at all, familiar. Its paragon exemplification is 20th century physics. And, having begun with Einstein, I am going to continue to draw examples directly from physics.

Physics

Every scientific pursuit launches itself from a conceptual framework, a set of presuppositions about the nature of reality that, by providing a radical simplification of reality, makes investigation possible. These include such things as

- a classification of entities,
- which properties of those entities are taken into account,
- the types of connections recognized,
- whether all events are determinate or not,
- the nature and direction of causal relations,
- and whether or not there exist structural relations as well as aggregate ones.

In this way a conceptual framework defines a particular point of view toward its object of enquiry, and consequently, different conceptual frameworks offer different points of view. Or in Einstein's words, they determine "whether you can observe a thing or not."

For example, what one observes when one looks at Michelangelo's statue of David depends on the standpoint from which it is observed. Therefore, a full appreciation of David requires observing it from more than one perspective. Likewise, knowledge accumulation often depends upon investigating empirical domains through more than one conceptual lens. The acceptance of this view has been embraced by modern physics, because the profession realizes that the advancement of knowledge of the physical world ultimately depends on it.

The celebrated physicist David **Bohm** describes the pluralist nature of knowledge accumulation as follows.

> What is called for is not an *integration* of thought, or a kind of imposed unity, for any such imposed point of view would itself be merely another fragment. Rather, all our different ways of thinking are to be considered as different ways of looking at the one reality, each with some domain in which it is clear and adequate. One may indeed

> compare a theory to a particular view of some object. Each view gives an appearance of the object in some aspect. The whole object is not perceived in any one view but, rather, it is grasped only *implicitly* as that single reality which is shown in all these views. When we deeply understand that our theories also work in this way, then we will not fall into the habit of seeing reality and acting toward it as if it were constituted of separately existent fragments corresponding to how it appears in our thought and in our imagination . . . [Bohm, 1983, pp. 7-8]

It is this ethos regarding the advancement of knowledge within a discipline that I call “complementary pluralism”. My term “competitive pluralism” refers to a very different state of affairs, one where different theories are routinely treated as competitors, and where implicitly the theories are seen not as means contributing to understanding but rather as ends in themselves.

In the economics profession there appears to be a common and ingrained misconception regarding the role and nature of pluralism in the natural sciences. If asked whether the statement “Physics has a long tradition of encouraging pluralism” is true or false, many economists would, I suspect, answer “false”. So I feel obliged to present some more primary examples directly from the literature of physics to show that this view is fundamentally mistaken. I am concerned with the period roughly from the 1880s to the present. For evidence I will, in addition to Einstein and Bohm, look at what four other preeminent physicists, who together roughly span this period, have said regarding pluralism in physics.

I begin with Heinrich **Hertz** (1857-1894). Hertz was first to detect the electromagnetic waves predicted by Maxwell’s unification of electricity and magnetism. Subsequently Hertz wrote a textbook, *The Principles of Mechanics Presented in a New Form.* In it he offered a new theoretical framework congenial to the new developments. In the book’s introduction, intended for advanced physics students, he sets out what he understands to be the prevailing epistemological ethos in his profession in the late 19th century. He writes:

> In endeavouring thus to draw inferences as to the future from the past, we always adopt the following process. We form for ourselves images or symbols of external objects. . . . The images of which we here speak are *our conceptions of things*. [Heisenberg, 1962, p. 154]
>
> . . . various images of the same objects are possible, and these images may differ in various respects . . . [Heisenberg, 1962, p. 155]
>
> . . . we cannot decide without ambiguity whether an image is appropriate or not; . . . One image may be more suitable for one purpose, another for another . . . [Heisenberg, 1962, p. 156]

It is important to understand that Hertz was not making a case for pluralism here, but instead merely describing to the physics student the basis of the ethos of complementary pluralism that he saw as characterizing his profession, and thereby as being the context into which his book was introducing a “new system of mechanical principles”, a new “mode of conception”, a new “mode of treatment”, a new “mode of thought”. All those are Hertz’s phrases.

A second account of the operation of pluralism in physics is provided by Louis **de Broglie** (1892-1987), one of the principal founders of particle physics. He writes as follows:

> . . . the quantum of action compels us today to employ “complementary” descriptions to account for the phenomena on the atomic scale. By this term we are to understand descriptions which are certainly complementary but at the same time, taken strictly, incompatible . .. ; each of these complementary descriptions is an “idealiztion” *permitting us to present certain aspects of the phenomena under consideration, but not all the aspects*. [emphasis added]
>
> The best known instance of such complementary descriptions is supplied by the two descriptions of Matter and Light by means of waves on the one hand and of corpuscles on the other. The employment of each idea . . . *has proved essential for the interpretation of some phenomenon or other*; but the two ideas still remain, despite every effort, incapable of being reduced to terms of the other, and the only connection that can be established between them is of a statistical nature. [emphasis added] [Broglie, p. 277]

This is an even more robust pluralism than the one Hertz describes, as it identifies the necessity of deploying within the same domain theories that are incompatible.

Werner **Heisenberg**’s [1901-1976] understanding of the need for an ongoing pluralism is perhaps even more radical. He writes:

> . . . it was found that already in the theory of electricity an analysis using these concepts was no longer possible, and therefore in the investigation of this new domain of experience there emerged new systems of concepts leading to a final mathematical formulation of the laws of electricity.

And then speaking generally of systems of concepts and laws, Heisenberg writes:

> . . . we cannot expect [its] concepts and laws to be suitable for the subsequent description of new realms of experience. It is only in this limited sense that quantum-theoretical concepts and laws can be considered as final, and only in this limited sense can it ever happen that scientific knowledge is finally formulated in mathematical or, for that matter, in any other language. [Heisenberg, 1962, p. 27]

And there is a quote from near the end of Heisenberg’s life that is very close to the Einstein quote with which I began.

> What we observe is not nature itself, but nature exposed to our method of questioning. [Wikiquote]

The leaders of the next generation of physicists continued to emphasize the importance of pluralist practice as a basic requirement for the advancement of their science. For example, Richard **Feynman** [1918-1988], celebrated for expanding the theory of quantum electrodynamics and particle theory, spoke to his students as follows in one of his published lectures.

> As long as physics is incomplete, and we are trying to understand the other laws, then the different possible formulations may give clues about what might happen in other circumstances.

and

> We must always keep all the alternative ways of looking at a thing in our heads, so physicists . . . pay but little attention to the precise reasoning from fixed axioms.
>
> One of the amazing characteristics of nature is the variety of interpretational schemes which is possible. [Feynman, 1965, pp. 53-54]

The direct contradiction between the basic concepts of relativity and quantum theory, the pinnacles of physics, has almost inevitably led physicists both to emphasize pluralism's necessity for advancement of scientific knowledge and to articulate the epistemological logic underlying the criterion of "appropriateness" asserted by Hertz.

The complementary pluralism of physicists takes it for granted that without utilizing different conceptual systems that often contradict each other, our understanding of physical matter would be a small fraction of what it is. For example, compare the two best known and most important post-Newtonian theories with regards to how they conceive the basic entities, properties and connections of the physical realm.

> General relativity conceives of space and time as continuous; quantum theory conceives of them as discontinuous.
>
> General relativity conceives of matter as particulate; quantum theory conceives of it as a wave-particle duality.
>
> General relativity conceives of physical objects as having actual properties; quantum theory describes them as having only potential properties within the given physical situation.
>
> General relativity conceives all physical reality as determinate and all events as in principle having a causal explanation; quantum theory admits indeterminacy and events incapable of causal explanation.

Conceptual differences greater than these are virtually unimaginable. And yet physicists perceive relativity and quantum mechanics not as competing theories, but rather as different and complementing conceptual approaches to the fundamentals of physical reality. This radical complementary pluralism, which physicists as a group embrace, is physics' response to the complexity of the domain, physical matter, which they wish to understand. They know and appreciate deeply that, as Einstein said, "Whether you can observe a thing or not depends on the theory which you use."

And they want to observe as much as possible. So they use more than one theory, more than one conceptual system. Economics could be conducted in similar fashion if various cultural, institutional and sociological barriers were broken down.

Ideology

These examples from physics show why conceptual pluralism of the complementary sort has proven essential for the broad advancement of knowledge. But in the social sciences, complementary conceptual pluralism is required for another and for some of us a no less important reason: the preservation of democracy. The fact, as explained by Einstein, Hertz, de Broglie, Heisenberg, Feynman and Bohm, that a conceptual system defines, at the exclusion of others, a point of view toward its object of enquiry has in the social sciences, in addition to its epistemological consequence, an ideological one.

There are two reasons why this is so.

First, the conceptual systems of social sciences can alter the objects of their enquiries by becoming part of the conceptual and belief systems through which humans conceive of themselves and of others and by which they make choices. In the daily functioning of societies this recursive dimension of the social sciences, economics especially, becomes increasingly significant as mass higher education becomes the norm, even more so when as in the United States there is a social science input into most undergraduate degrees.

Second, the social sciences, economics especially, provide means by which governments preserve or reconstruct, sometimes fundamentally, the basic realities of societies. Different conceptual systems, such as institutional and neoclassical economics, present different sets of choices, real or imagined, to be chosen and acted upon by human populations at large.

It can never be the case that each of these sets of choices will equally favour every group in society, so that when a social science falls victim to anti-pluralism it becomes inescapably and profoundly ideological. *If only one conceptual framework is permitted, with the consequence that it alone is inculcated into the citizenry and its leaders, then the choices that in a democracy should be out in the open and belong to the people are hidden from view and the free discussion and informed debate upon which all democracy depends is silently eliminated*.

The neoclassical monopoly in the classroom has meant that it has brainwashed successive generations of students into viewing economic reality exclusively through its concepts.

The key word is “exclusively”. I would be violently opposed to the elimination of neoclassical economics from the economics curriculum because, in its limited way, it offers insights into economic phenomena and should be part of the democratic debate. It is not neoclassical economics itself, but rather the forbidding of all the other approaches to understanding and gaining knowledge of economic phenomena that is so dangerous because it fosters ignorance and undermines democracy.

Nor is the menace limited to economics students. Through journalism, their indoctrination is transferred to the general population, so much so that today many leaders of society, including Presidents and Prime Ministers, no longer know how to think about economic matters outside the neoclassical conceptual system. The solution is simple, economics departments should, like other university departments, be barred from acting in effect as political propaganda centres.

Of course complementary pluralism, the epistemological ethos of modern physics, remains a minority position in economics. It may even remain such among non-neoclassical economists. Here, traditionally pluralism has been indulged only in the competitive sense. But not so long ago even this was daring.

In the context of late 20th century economics, the idea of encouraging pluralism of any kind was regarded as profane. And complementary pluralism was unthinkable. This is manifest in the history of the International Confederation of Associations for Pluralism in Economics

(ICAPE), formerly named the International Confederation of Associations for Reform in Economics (ICARE). The "aims and purposes" spelled out by its brave and ahead-of-their-time founders in 1993 included the following:

> to promote a new spirit of pluralism in economics, involving critical conversation and tolerant communication among different approaches, within and across the barriers between the disciplines ….

The very idea that they were seeking to promote "tolerant communication" reveals a desperate state of affairs. But beyond the virtue of tolerance and perhaps some enhancement of career opportunities it was not altogether clear why they were promoting pluralism.

However, ICAPE's avowed reason for supporting pluralism changed decisively in 2000. That was the year the organization changed its name, "pluralism" superseding "reform". Along with the name change, the board issued a statement that, knowingly or unknowingly, embraced the ethos of modern physics:

> the belief that theoretical pluralism and intellectual progress are complements ….

Coming from a generation of economists who had no comprehension of complementary pluralism, this was a courageous and seriously innovative move. It was also an idea nearing its time. That same year the idea was also put forward in Paris by a small group of French economics students. And those students put forward the idea of complementary pluralism for economics with such vigour and flair and optimism, and articulated it so well that they started a world-wide movement. Their Autisme Economie Manifesto, included the following.

> Out of all the approaches to economic questions that exist, generally only one is presented to us. This approach is supposed to explain everything by means of a purely axiomatic process, as if this were THE economic truth. We do not accept this dogmatism. We want a pluralism of approaches adapted to the complexity of the objects and to the uncertainty surrounding most of the big questions in economics.

The students phrase, "approaches adapted to the complexity of the objects" is an in-your-face radicalization of the demand for a complementary-pluralist economics because it inverts the traditional but implicit philosophical idealism of economics, whereby the approach takes precedent over the object of inquiry, the observation and reality of the latter being admitted only to the extent that it is illuminated by the former.

In the past this disposition has characterised not just neoclassical economists, but the various schools generally. In the context of this tradition, the naked spirit of empiricism in the students' petition, their demand that economics should observe the real world, was, and for many economists continues to be, shocking.

Conclusion

The eminent contemporary physicist Jean-Philippe **Bouchaud** [2008, pp. 9, 291] recently commented as follows:

> the crucial difference between physical sciences and economics . . . is . . . the relative role of concepts, equations and empirical data. Classical economics [meaning today's mainstream] is built on very strong assumptions that quickly become axioms: the

> rationality of economic agents, the invisible hand and market efficiency, etc. An economist once told me, to my bewilderment: "These concepts are so strong that they supersede any empirical observation."

Regarding this refusal to observe, Bouchaud writes:

> there is a crucial need to change the mindset of those working in economics . . .. They need to move away from what Richard Feynman called Cargo Cult Science: a science that follows all the apparent precepts and forms of scientific investigation, while still missing something essential.
>
> [Bouchaud, 2008, p. 292]

Economics missing essential, the will to observe, will not be acquired until the profession embraces full-heartedly the elemental truth emphasized by Einstein:

> Whether you can observe a thing or not depends on the theory which you use.

And elaborated by Hertz:

> We form for ourselves images or symbols of external objects. . . . One image may be more suitable for one purpose, another for another . . .

And by Broglie:

> each of these complementary descriptions is an "idealization" permitting us to present certain aspects of the phenomena under consideration, but not all the aspects.

And by Heisenberg:

> we cannot expect concepts and laws to be suitable for the subsequent description of new realms of experience.

And by Feynman:

> We must always keep all the alternative ways of looking at a thing in our heads, so physicists . . . pay but little attention to the precise reasoning from fixed axioms.

And by Bohm:

> One may indeed compare a theory to a particular view of some object. Each view gives an appearance of the object in some aspect.

This complementary pluralism voiced by the most eminent members of the physics profession over the past 130 years should be the goal of the economics profession. The path for economics from epistemological degeneracy to respectability will be long and arduous. But so also was physics' escape from the axiomatic monism policed by the Vatican.

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Maria Laura Giacobello*

La collana di perle di Georgescu-Roegen. Ovvero il Quarto Principio della Termodinamica

Nicholas Georgescu-Roegen, il matematico ed economista rumeno che tra i primi ha analizzato con profondo spirito critico la concezione economica strettamente improntata alla crescita, ha dimostrato puntualmente la vulnerabilità di questa ideologia sotto il profilo della corretta applicazione delle leggi della fisica, in particolare della termodinamica[1]. La sua attenta disamina rivela inequivocabilmente l'urgenza di promuovere processi economici innovativi e conduce, già negli anni Sessanta, a costruire un ponte tra le discipline ecologiche e quelle economiche. Pertanto, proprio dagli studi pionieristici di *bioeconomia* di

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[1] A tal proposito, sembra utile ricordare che proprio Georgescu-Roegen è considerato l'ideatore e il massimo teorico del concetto di decrescita. Il lavoro di quest'autore costituisce infatti un riferimento imprescindibile per ogni riflessione di impronta ecologica, comprese le recenti teorie sulla decrescita di Serge Latouche: già nel 1971, con *The Entropy Law and the Economic Process*, la sua opera più nota, aveva sottolineato appunto come il modello dell' economia neoclassica non tenesse affatto conto del Secondo Principio della Termodinamica (Cfr. N. Georgescu-Roegen, *The Entropy law and the Economic Process*, Harvard University Press, Cambridge, Massachussetts 1971). Condividendo con Georgescu-Roegen questo presupposto, il pensiero di Latouche si specifica in direzione di una severa critica al concetto di sviluppo, a partire dai miti della razionalità occidentale in cui affonda le radici l'immaginario collettivo economico, fino alle sue concrete manifestazioni storico-sociali. Cfr., tra gli altri, S. Latouche, *L'invenzione dell'economia*, [2005], trad. di F. Grillenzoni, Bollati Boringhieri, Torino 2010; Id., *Come sopravvivere allo sviluppo. Dalla decolonizzazione dell'immaginario economico alla costruzione di una società alternativa* [2004], trad. di F. Grillenzoni, Bollati Boringhieri, Torino 2005; Id., *Decolonizzare l'immaginario*, Libro intervista a cura di Roberto Bosio, EMI, Bologna 2004; Id., *Giustizia senza limiti*, trad. di A. Salsano, Bollati Boringhieri, Torino 2003; Id., *Breve trattato sulla decrescita serena* [2007], trad. di F. Grillenzoni, Bollati Boringhieri, Torino 2008; Id., *Per una società della decrescita*, in M. Bonaiuti (a cura di), *Obiettivo decrescita*, EMI, Bologna 2008; e il recentissimo lavoro di S. Latouche, *Come si esce dalla società dei consumi* [2010], trad. di F. Grillenzoni, Bollati Boringhieri, Torino 2011.

Georgescu-Roegen scaturisce una nuova disciplina: l'economia ecologica[2], frutto della confluenza delle più avanzate analisi in ambito ecologico quanto economico. Egli ha preso in considerazione, evidenziandolo, l'aspetto biofisico dell'economia: in realtà, se il nostro sistema economico è attraversato da un processo di produzione, distribuzione ed eliminazione di un flusso di energia e materia direttamente attinte dall'ambiente naturale - che è il sistema all'interno del quale l'uomo vive e si evolve - ne consegue che il metabolismo industriale della società è inestricabilmente connesso alla evoluzione biologica, geologica e chimica della Terra stessa.

L'elaborazione della teoria *bioeconomica* è, in effetti, il risultato della profonda esigenza di un radicale rinnovamento delle ordinarie categorie economiche, che matura in Georgescu-Roegen attraverso un lungo e attento *excursus* all'interno dell'impalcatura concettuale su cui si basa la scienza economica. L'esito di questo itinerario intellettuale si traduce, nel pensatore rumeno, nella cogente consapevolezza dell'inadeguatezza delle categorie dell'economia tradizionale ad affrontare problematiche più articolate rispetto alla semplice dialettica dicotomica produzione-consumo. Infatti, proprio "l' incapacità dell' economia ortodossa di far fronte alle questioni ambientali ha dato origine all' economia ecologica, che è lo studio della compatibilità tra l'economia umana e gli ecosistemi a lungo termine. Poiché in questa prospettiva possiamo vedere come l' economia di mercato sia avviluppata in un sistema fisico-chimico-biologico, si pone la questione del valore delle risorse naturali e ambientali per l'economia. È possibile tradurre i valori ambientali in valori monetari?

[2] Robert Costanza, presidente dell'International Society for Ecological Economics, così definisce la nuova disciplina: "L'economia ecologica è un tentativo di superare le frontiere delle discipline tradizionali per sviluppare una conoscenza integrata dei legami tra sistemi ecologici ed economici. Un obiettivo chiave di questa ricerca è quello di sviluppare modelli sostenibili di sviluppo economico, distinti dalla crescita economica che non è sostenibile in un pianeta finito. Un aspetto chiave nello sviluppare modelli sostenibili di sviluppo è il ruolo dei vincoli: vincoli termodinamici, limiti biofisici, limiti di risorse naturali, limiti all'assorbimento dell'inquinamento, limiti demografici, vincoli imposti dalla 'carrying capacity' del pianeta, e, soprattutto, limiti della nostra conoscenza rispetto a ciò che questi limiti sono e a come influenzano il sistema"(citato in E. Tiezzi - N. Marchettini, *Che cos'è lo sviluppo sostenibile? Le basi scientifiche della sostenibilità e i guasti del pensiero unico*, Donzelli editore, Roma 1999, p. 37).

Gli economisti ecologici sono molto scettici circa la possibilità di tradurre o trasmutare future e incerte esternalità irreversibili in valori monetari”[3].

All’interno dell’ampia penombra dialettica, in cui l’economico si intreccia con il sociale e il politico, si verificano imprevedibili sovrapposizioni tra fattori biologici ed economici e, in realtà, secondo Georgescu-Roegen, una corretta analisi entropica del processo economico ne dà una conferma immediata[4]. Tuttavia, “il fatto che i fattori biologici ed economici possano sovrapporsi in modi imprevedibili, benché ampiamente dimostrato, è poco conosciuto fra gli economisti”[5]. Ciò consente agli stessi una professione di fede nei confronti del rassicurante teorema dell’inesauribilità delle risorse, basato sull’assunto della loro infinita sostituibilità.

Ne consegue, evidentemente, che, “se si vuole porre su basi scientifiche l’economia dell’ambiente, occorre un nuovo approccio metodologico di natura interdisciplinare, che porti a un profondo ripensamento dei principi che hanno costituito il fondamento della teoria economica standard”[6]. Non è più possibile negare, infatti, la natura dialettica degli eventi che descrivono la realtà biologica e quella economica: proprio tale natura, decretandone l’ineludibile interconnessione, fonda quel diverso approccio gnoseologico che apre la via a una disciplina

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[3] J.Martinez-Alier, *From political economy to political ecology*, in K. Mayumi – J. M. Gowdy, *Bioeconomics and Sustainability. Essay in Honor of Nicholas Georgescu-Roegen*, Edward Elgar, Cheltenham, UK 1999, pp. 25-50, p. 25.

[4] Georgescu-Roegen avverte evidentemente la necessità di delimitare i confini del metodo logico-deduttivo: “I confini di ogni scienza positiva sono penombre in movimento. La fisica si confonde con la chimica, la chimica con la biologia, l’economia con la scienza politica e la sociologia. Esistono una chimica fisica, una biochimica, e anche un’economia politica, nonostante che siamo restii a parlarne. Soltanto il dominio della logica, concepita come *Principia Mathematica,* è limitato da confini rigidi e nettamente stagliati. La ragione di questo è che la vera essenza della logica è costituita dalla distinzione *discreta*, che pertanto deve valere anche per i confini della logica” (N. Georgescu-Roegen, *Prospettive e orientamenti in economia*, in Id., *Analisi economica e processo economico*, trad. di M. Dardi, Sansoni, Firenze 1973, parziale traduzione della raccolta *Analytical Economics: Issues and Problems,* Harvard University Press, Cambridge, Massachussetts 1966, p. 25).

[5] N. Georgescu-Roegen, *Prospettive e orientamenti in economia*, cit., p. 123.

[6] R. Molesti, *La rivoluzione della scienza e la bioeconomia*, in I., (a cura di), *Economia dell’ambiente e bioeconomia*, Franco Angeli, Milano 2003, p. 7.

come l'economia dell'ambiente. Soltanto una prospettiva sistemica[7] libera, invero, un tale ventaglio di nuovi significati da innescare l'esigenza di un diverso tipo di riflessione: interdisciplinare, appunto. In tal senso, allora, "ciò che Georgescu-Roegen chiamava 'bioeconomia', ha finito per essere denominato 'economia ecologica'. Un settore multidisciplinare in espansione"[8].

Peraltro, i tempi sono maturi per un cambiamento radicale del paradigma scientifico di riferimento[9], anche e soprattutto in economia: disciplina nella quale la moderna struttura meccanicistica ha comportato un'interpretazione della realtà indagata all'insegna della presunta circolarità e reversibilità di un sistema chiuso e autosufficiente, offrendo una visione statica proprio di quei fenomeni economici, cui, viceversa, sarebbe indiscutibilmente più utile un approccio analogico diverso, contiguo, per esempio, al modello offerto dalla biologia. L'insufficienza espressa dalla trappola meccanicistica, che con il suo modo di procedere astrattamente logico studia il processo economico come se fosse

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[7] Le intuizioni di Georgescu-Roegen sono coerenti con la temperie culturale che va maturando nel corso del Novecento sull'onda della rivoluzione scientifica contemporanea e con gli orientamenti epistemologici dell'attuale ricerca, che promuovono il superamento di ogni chiusura settoriale e specialistica all'insegna del dialogo interdisciplinare. In particolare, negli anni Trenta del Novecento l'elaborazione di una vera e propria *teoria dei sistemi* a opera di Ludwig von Bertalanffy segna una tappa determinante: nell'ottica del pensiero sistemico le parti sono solo astrazioni e la realtà è data esclusivamente dalle relazioni. Cfr. a tal proposito L. von Bertalannfy, *Teoria generale dei sistemi. Fondamenti, sviluppo, applicazioni* [1967], trad. di E. Bellone, introduzione di G. Minati, Mondadori, Milano 2010; si veda anche V. De Angelis, *La logica della complessità. Introduzione alle teorie dei sistemi*, Bruno Mondadori, Milano 1996. In realtà, proprio grazie alla natura sistemica del suo approccio alla conoscenza delle dinamiche economiche Georgescu-Roegen è in grado di cogliere quella relazione circolare fra economia ed ecosistema che segna il superamento del paradigma meccanicista e che si ripercuote nell'interpretazione di specifici aspetti del processo economico, compresa la teoria della produzione.

[8] J. Martinez-Alier, *Preface*, in K. Mayumi, *The Origins of Ecological Economics. The bioeconomics of Georgescu-Roegen,* Routledge, London 2001.

[9] In effetti, secondo l'autorevole opinione di Edgar Morin, il principale teorico del pensiero della Complessità, "siamo entrati nella vera età di una rivoluzione paradigmatica profonda, diciamo forse più radicale di quella del XVI-XVII secolo. Credo che noi partecipiamo a una trasformazione secolare che è difficilmente visibile perché non disponiamo del futuro che ci consentirebbe lo sguardo sulla metamorfosi compiuta" (E. Morin, *Introduzione al pensiero complesso. Gli strumenti per affrontare la sfida della complessità*, [1990], trad. di M. Corbani, Sperling & Kupfer, Milano 1993, p. 114).

possibile separare elementi materiali ed elementi umani, è evidente: infatti, "isolando l'uomo dal suo ambiente, il soggetto dall'oggetto, il meccanicismo non può quindi rappresentare il riferimento filosofico adatto per lo studio di quelle situazioni in cui, come nell'economia, appunto, l'accoppiamento materia-vita impone l'adozione dei modi di pensiero analitico e dialettico"[10].

Il cambiamento di paradigma implicito nel ripensamento della disciplina economica elaborato da Georgescu-Roegen, viceversa, getta un' *humus* assai fertile proprio per un'adeguata considerazione dell'indissolubile intreccio con l'ambiente in cui si articola l'economia.

Una compiuta assunzione di questo paradigma comporterebbe un mutamento rivoluzionario dei sommi principi economici, a partire dal diagramma di flusso circolare isolato con cui viene tradizionalmente rappresentato il processo economico: dalle imprese alle famiglie e ritorno, senza punti di contatto con l'esterno, né in ingresso né in uscita. Se questa rappresentazione offre indubbi profili di utilità in tema di analisi degli scambi, essa è senz'altro fallimentare nell'interpretazione dei processi di produzione e consumo, che risultano emancipati da ogni elementare dipendenza dall'ambiente circostante rispetto al proprio mantenimento e rifornimento. A tal proposito, infatti, in merito alle conseguenze deprecabili imputabili alla struttura meccanicistica dell'economia, Georgescu-Roegen critica appunto "la concezione del processo economico come un flusso circolare all'interno di un sistema completamente chiuso e autosufficiente", testimoniata dal "diagramma circolare che connette la produzione (un nome) e il consumo (un altro nome) con il quale anche i più apprezzati manuali rappresentano il processo economico"[11]. E, tuttavia, egli specifica, "questa rappresentazione non è appropriata nemmeno per la circolazione della moneta presa isolatamente, perché persino la moneta (in qualunque forma) si logora e dev'essere sostituita da fonti esterne al flusso monetario circolare. Ma è quasi certo che il flusso circolare della moneta ha influenzato – e tuttora influenza – l'orientamento di praticamente tutti gli economisti. È vero che nessun economista ha mai sostenuto che un processo possa essere completamente rovesciato fino al punto di ritrasformare i mobili in alberi. Eppure, non dobbiamo

[10] S. Zamagni, *Georgescu-Roegen. I fondamenti della teoria del consumatore*, Etas, Milano 1979, p. 94.

[11] N. Georgescu-Roegen, *L'economia politica come estensione della biologia*, in Id., *Bioeconomia. Verso un'altra economia ecologicamente e socialmente sostenibile*, a cura di M. Bonaiuti, trad. di G. Ferrara degli Uberti, P. L. Cecioni, L. Maletti, G. Ricoveri, M. Messori, M. Bonaiuti, Bollati-Boringhieri, Torino 2003, p. 68.

dimenticare che, nella definizione stessa di 'teoria dei cicli economici', la parola 'cicli' rivela che gli economisti non respingono l'idea che nel loro complesso le cose possano tornare a quello che erano prima, ripercorrendo in direzione opposta lo stesso sentiero"[12].

In un simile contesto matura appunto la rivoluzionaria consapevolezza dell'immanenza della legge di entropia a ogni aspetto della realtà, che impone l'esigenza di formulare un nuovo, e più adeguato, paradigma economico. E proprio in tale impresa si cimenta Georgescu-Roegen: con l'elaborazione della *bioeconomia* egli intende rispondere alla necessità di introdurre le leggi del mondo vivente nell'economia, per dare atto della reale complessità espressa dal processo economico e riconoscerne finalmente l'assoluta irreversibilità. E, pertanto, scrive: "Ho ritenuto in passato (e ancora ritengo) che la legge dell'entropia sia la radice profonda della scarsità economica: in un mondo in cui non vigesse tale legge, sarebbe possibile utilizzare tutta l'energia, compresa quella del ghiaccio delle calotte polari, trasformandola in lavoro meccanico, e gli oggetti materiali non si consumerebbero; ma certamente non esisterebbe neppure la vita. Nel nostro mondo, tutto ciò che per noi ha una certa utilità (desiderabilità) è costituito da bassa entropia, ed è per questo che il processo economico è entropico in tutte le sue fibre naturali"[13] .

La *bioeconomia* è, in effetti, il frutto maturo del pensiero di Georgescu-Roegen[14]. Non si tratta di un'intuizione acritica, ma piuttosto del risultato consapevole verso cui convergono tutti gli sforzi intellettuali che lo studioso ha profuso in ogni direzione del pensiero: essa esprime la forza di un'attenta riflessione che si è arricchita rincorrendo se stessa attraverso un percorso non solo critico ma anche propositivo. La competenza fuori dal comune con cui Georgescu-Roegen, grazie alla sua ricca formazione, demolisce con rigore miti e pregiudizi che si implementano reciprocamente, e si spinge fino a proporre categorie autenticamente innovative nel campo economico, lo rende un

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[12] *Ibidem*.

[13] N. Georgescu-Roegen, *Analisi energetica e valutazione economica*, in Id., *Bioeconomia,* cit., p. 153 (già pubblicato in N. Georgescu-Roegen, *Energia e miti economici*, trad. di P.L. Cecioni, Boringhieri, Torino 1982. Tranne *Analisi energetica e valutazione economica*, edizione ampliata di un articolo apparso nel 1979 in "The Southern Economic Journal", i saggi raccolti in questo volume sono tratti da N. Georgescu-Roegen, *Energy and Economic Myths*, Pergamon Press, New York 1976).

[14] Su ciò cfr. M. Bonaiuti, *La teoria bioeconomica. La "nuova economia" di Nicholas Georgescu-Roegen,* Carocci, Roma 2001, pp. 38-40.

interlocutore assai temibile per chiunque trovi confortevole il sistema di valori e conoscenze consolidato.

Considerato, allora, che "la scienza economica ha eliminato la dimensione ecologica dal suo orizzonte", e così "è diventata una scienza astratta, virtuale, disgiunta dalla realtà della biosfera", è più che mai vero che "reintegrare questa dimensione fa paura. Impone di rimettere in discussione duecento anni di scienza economica, dal neoliberalismo al neomarxismo. Tutto il mondo delle 'scienze economiche' è terrorizzato alla sola evocazione del nome di Nicholas Georgescu-Roegen, padre della bioeconomia e teorico della decrescita, che si è appoggiato alla fisica e alla biologia per riportare l'economia con i piedi per terra. Galileo, che aveva affermato che la Terra gira attorno al Sole, è stato condannato all'ergastolo dalla Chiesa. Georgescu-Roegen, che ha dimostrato che la Terra è finita, è stato condannato all'esilio mediatico da tutti i sostenitori del dogma economico, qualunque fosse la loro tendenza. La realtà paralizza gli economisti neoclassici, che non riescono a immaginare come uscire, senza provocare drammi, dalla falsità in cui essi stessi si sono rinchiusi"[15].

L'importanza fondamentale del rapporto uomo-ambiente è stata sostanzialmente rimossa fino a quando non sono prepotentemente emersi i limiti naturali ai programmi di irresponsabile espansione della base produttiva e dei livelli di consumo della società capitalistica. Com'è noto, secondo il dogma meccanicistico, preso a modello dall'economia ortodossa, il processo economico si gioca tutto all'interno di uno schema circolare in cui si rincorrono produzione e consumo: ignorare il ruolo dell'ambiente in cui esso è immerso equivale a "considerare inesauribili le risorse naturali e le utilità che ne derivano"[16]. Tale inesauribilità si fonda, appunto, sull'ingiustificata fiducia nella loro infinita sostituibilità, che, tuttavia, viene inesorabilmente abbattuta dall'impianto teorico che Georgescu-Roegen sviluppa sul principio di entropia: "Detto in soldoni: quando si esaurisce il legno si sostituisce con gli idrocarburi; quando si esauriscono quelli (carbone e petrolio) si sostituiscono con l'energia nucleare. Eccetera. È questione di tecniche da inventare; e di prezzi da pagare. Roegen denuncia l'assurdità di questo teorema. La tecnologia può sostituire una risorsa con un'altra, non può però *creare* nuove risorse: l'ammontare totale delle risorse (energia e materia) è costante. Nulla si crea

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[15] V. Cheynet, *Decrescita e democrazia,* in M. Bonaiuti (a cura di), *Obiettivo decrescita*, cit. EMI, Bologna p. 142.

[16] G. Ruffolo, *Lo specchio del diavolo*. *La storia dell'economia dal Paradiso terrestre all'inferno della finanza*, Einaudi, Torino 2006, p. 38.

e nulla si distrugge. Questa è la prima legge della termodinamica. Dunque, le risorse sono limitate"[17]. Ma questo non è tutto: occorre tenere conto anche del ruolo giocato dall'entropia, come fa Georgescu-Roegen. Infatti, proseguendo l'analisi intrapresa, l'indagine sulla produzione rivela come essa sia "trasformazione, non creazione, di risorse utili in risorse inutili, di 'beni' in 'rifiuti'. In termini scientifici rigorosi, e quindi più oscuri, si deve dire, di bassa entropia in alta entropia; o, che è lo stesso, di ordine in disordine. È la seconda legge della termodinamica"[18]. Ovvero, la tecnologia non può fare miracoli.

In realtà, la termodinamica - introdotta da un memoria di Carnot del 1824 sull'efficienza delle macchine a vapore, secondo la ricostruzione storica proposta da Georgescu-Roegen - produsse uno sconvolgente effetto[19]: poiché la fisica fu costretta a promuovere a legge scientifica l'elementare circostanza che il calore si muove sempre spontaneamente da un corpo più caldo a uno più freddo, "fu necessario creare un nuovo ramo della fisica che si servisse di leggi non meccaniche", in quanto "le leggi della meccanica non possono rendere conto di un movimento unidirezionale"[20]. Infatti, se a causa della differenza di temperatura fra due corpi si genera un flusso spontaneo di calore dal corpo più caldo a quello più freddo, fino al raggiungimento dell'equilibrio termico, una volta prodotto l'effetto, non è più possibile risalire alla causa,

[17] *Ibidem*.

[18] Ivi, pp. 38-39.

[19] Per la precisione, lo scacco definitivo al mito della razionalità matematica onnicomprensiva, alimentato dalla scienza newtoniana, avviene ad opera di uno studioso francese, Jean-Joseph Fourier, che, tra il 1807 e il 1811, elabora le sue prime riflessioni sul calore fino alla formulazione della seguente legge: *il flusso di calore fra due corpi è proporzionale al gradiente di temperatura fra essi.* Si tratta di una legge universale, che offre la stessa cogenza della legge di gravitazione di Newton, perché, come ogni corpo ha una massa, è nello stesso tempo capace di trasmettere e ricevere calore. Fourier, in sostanza, eleva il calore al rango di scienza, e introduce una legge indipendente e incompatibile con quella di gravità, in quanto introduce una direzione privilegiata dei fenomeni, posto che il flusso di calore si muove sempre da un corpo più caldo a uno più freddo. Sul ruolo giocato da Fourier nello studio della propagazione del calore cfr. G. Gembillo, *Le polilogiche della complessità. Metamorfosi della ragione da Aristotele a Morin,* Le Lettere, Firenze 2008, pp. 94 ss.; Id., *Neostoricismo complesso*, Edizioni Scientifiche Italiane, Napoli 1999, pp. 45 ss., 72 ss., 104 ss. e anche Id., *Fuoco! La chimica"fonte" della complessità*, in "Complessità", 1-2, 2009, pp. 65-79. Per una ricostruzione completa delle origini della termodinamica cfr. I. Prigogine e I. Stengers, *La nuova alleanza. Metamorfosi della scienza* [1979], a cura di P. D. Napolitani, Einaudi, Torino 1999, pp. 109 ss.

[20] N. Georgescu-Roegen, *Prospettive e orientamenti in economia,* cit., p. 81.

come accade nella meccanica classica: quando i due corpi hanno raggiunto la stessa temperatura, si è verificato un evento irreversibile, cioè il processo di diffusione del calore, e quindi il concetto di direzione privilegiata degli eventi, di irreversibilità, è subentrato a quello, classico, di reversibilità.

In *Energia e miti economici,* Georgescu-Roegen specifica dettagliatamente come si articola la rivoluzione introdotta dalla termodinamica, distinguendo fra la prima legge, di conservazione dell'energia, con la quale ci si muove sempre nell'ambito di astrazione della dinamica classica, e la seconda legge, che invece si occupa dei fenomeni reali. E, infatti, scrive: "L'energia, indipendentemente dalla sua qualità, è sottoposta a una rigorosa legge di conservazione, la prima legge della termodinamica, formalmente identica a quella di conservazione dell'energia meccanica che è stata prima menzionata. E poiché il lavoro è una delle molteplici forme di energia, questa legge fa capire il mito del moto perpetuo di primo tipo. Non tiene invece conto della distinzione fra energia disponibile ed energia non disponibile; *la legge non preclude la possibilità che una quantità di lavoro possa essere trasformata in calore e che questo calore venga poi riconvertito nell'iniziale quantità di lavoro.* La prima legge della termodinamica permette quindi che un qualunque processo possa verificarsi sia 'in avanti' sia 'all'indietro', in modo che tutto ritorni com'era all'inizio, senza che rimangano tracce di quanto è avvenuto"[21]. Come è evidente, il Primo Principio della Termodinamica si iscrive bene nel perimetro concettuale disegnato dalla scienza classica, e non interpreta alcun progresso in direzione della comprensione della realtà concreta: "Con questa sola legge siamo sempre nel campo della dinamica, non in quello dei fenomeni reali, in cui certamente rientra il processo economico"[22]. E, tuttavia, con l'irrompere della termodinamica nel panorama della scienza, si deve prendere atto, in qualche modo, che le leggi della natura affermano al tempo stesso l'essere e il divenire.

Fin quando ci si è mossi all'interno della cornice concettuale tradizionale, si è tentato di affrontare il problema dei limiti naturali all'espansionismo capitalistico con la formulazione del concetto di sviluppo sostenibile[23], cioè

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[21] N. Georgescu-Roegen, *Energia e miti economici*, in Id., *Energia e miti economici*, cit., pp. 29-30.

[22] Ivi, p. 30.

[23] L'originaria formulazione dei concetti di "sostenibilità" e "sviluppo sostenibile" risale a un documento del 1987, il Rapporto della Commissione mondiale per l'ambiente e lo sviluppo (Commissione Bruntland), in cui si elabora il concetto di uno sviluppo che *garantisca i bisogni delle generazioni attuali senza compromettere la possibilità che le generazioni future rie-*

un modello di sviluppo che, pur conservando come obiettivo la crescita della ricchezza, si impegnasse a renderla compatibile con la salvaguardia dell'ecosistema e della sopravvivenza delle generazioni future. Si tratta, in breve, di una crescita economica rispettosa dei limiti ambientali, promossa mantenendo, tuttavia, una visione antropocentrica.

E, in realtà, da questa trappola ideologica non si esce, se non si comprende che l'ambiente non è una risorsa qualunque, né il contesto in cui l'uomo vive, ma è, piuttosto, il sistema di cui egli è parte e assieme al quale coevolve. Infatti, occorre prendere atto che l'economia, nel suo aspetto biofisico, rappresenta un processo di produzione, distribuzione di beni ed espulsione di rifiuti e, in quanto tale, fa parte del vasto sistema ecologico, dinamicamente interpretato. D'altra parte, come è stato correttamente osservato, "l'evoluzione delle scienze naturali a partire da Carnot e Darwin, cioè a partire dalla termodinamica e dall'evoluzionismo, non permette più di separare gli esseri viventi dall'ambiente terrestre. Si tratta di una co-evoluzione, essendo l'evoluzione biologica in reciproca interazione con i mutamenti dell'ecosistema terrestre"[24]. Si comprende, quindi, in quale senso l'economia "collega il metabolismo industriale della società umana alla bio-geochimica del nostro pianeta"[25].

Dall'esigenza di maturare compiutamente questa consapevolezza emerge l'importanza dell'approccio sistemico, come strumento concettuale per affrontare una diversa esperienza gnoseologica: il paradigma della scienza meccanicista, ancora una volta, infatti, col suo metodo riduzionista, offre categorie inadeguate per accedere alla conoscenza di una realtà inestricabilmente complessa come l'ecosistema, che, evidentemente, non può essere disarticolato in parti senza comprometterne la verità. In questa prospettiva, è

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scano a soddisfare i propri, e si afferma inoltre che "il concetto di sviluppo sostenibile implica dei limiti, non limiti assoluti, ma quelli imposti dal presente stato dell'organizzazione tecnologica e sociale nell'uso delle risorse ambientali e dalla capacità della biosfera di assorbire gli effetti delle attività umane" (R. Della Seta - D. Guastini, *Dizionario del pensiero ecologico. Da Pitagora ai no-global*, Carocci, Roma 2007, p. 361).

[24] J. Grinevald, *Georgescu-Roegen, bioeconomia e biosfera*, in M. Bonaiuti (a cura di), *Obiettivo decrescita*, cit., p. 57. Sull'idea di coevoluzione tra uomo e natura, sistema e ambiente, il riferimento d'obbligo è al concetto di accoppiamento strutturale in Maturana e Varela e all'ipotesi di Gaia di Lovelock. Cfr., per esempio, H. Maturana – F. Varela, *L'albero della conoscenza*, [1984], presentazione di M. Ceruti, trad. di G. Melone, Garzanti, Milano 1999, e J. Lovelock, *Le nuove età di Gaia*, [1988], trad. di R. Valla, Bollati Boringhieri, Torino 1991.

[25] J. Grinevald, *Georgescu-Roegen, bioeconomia e biosfera*, cit., p. 57.

possibile rinvenire una certa contiguità, ad esempio, tra la *bioeconomia* e l'ipotesi di Gaia: "È chiaro che l'economia mondiale deve necessariamente rispettare certi limiti ecologici globali legati alla capacità di carico dell'ecosistema, alla produttività primaria che dipende dalla fotosintesi della vegetazione, all'integrità della biodiversità, alla stabilità dei cicli biogeochimici, all'equilibrio del sistema climatico del globo, deve insomma rispettare la salute, la stabilità dinamica (omeostasi) del complesso sistema geo-fisiologico della biosfera (in senso vernadskiano) che James Lovelock e Lynn Margulis chiamano Gaia"[26]. Per questo motivo, evidentemente, "la vicinanza di pensiero tra Lovelock e Georgescu-Roegen a proposito della vita e dell'entropia, della coevoluzione fra gli esseri viventi e l'ambiente, che attingono in realtà alle stesse fonti scientifiche, è senza dubbio rilevante"[27].

Mentre, in conseguenza di simili considerazioni, si potrebbe ben dire che "la bioeconomia è la scienza pratica dell'economia planetaria"[28], viceversa, ignorando la naturale vocazione dell'ecosistema, la scienza economica classica si rivela indiscutibilmente *pre-termodinamica*, *pre-evoluzionista* e *pre-ecologica*, pertanto, essa è del tutto anacronistica[29].

Allo stato attuale delle conoscenze, in effetti, non può più essere negato che la teoria economica tradizionale è irrimediabilmente viziata da due gravi lacune, che compromettono la corretta interpretazione del ruolo della irreversibilità e di quello delle risorse naturali nel processo economico. Lo spiega bene lo stesso Georgescu-Roegen, quando osserva che "l'adozione dell'epistemologia meccanicistica da parte della scienza economica dominante comporta varie conseguenze deplorevoli. La più importante tra queste è la completa ignoranza della natura evolutiva del processo economico. Stabilita come una scienza sorella della meccanica, la teoria ortodossa non fa all'irreversibilità più posto di quanto ne faccia la meccanica stessa. L'analisi dominante del mercato è interamente fondata sulla completa reversibilità da uno stato di equilibrio a un altro. A eccezione di Alfred Marshall e di pochi altri, i teorici dell'economia ragionano come se un evento (per esempio una

[26]Ivi, p. 68.

[27]*Ibidem*.

[28]*Ibidem*. Un'economia planetaria come quella proposta da Georgescu è in sintonia con la medicina planetaria invocata da Lovelock. Cfr. J. Lovelock, *Gaia: manuale di medicina planetaria* [1991], trad. di S. Peressini, Zanichelli, Bologna 1992.

[29]Cfr. J. Grinevald, *Georgescu-Roegen, bioeconomia e biosfera*, cit., p. 58.

siccità o un'inflazione) non lasciasse alcuna traccia nel processo economico"[30].

Ma, occorre ancora sottolineare, tra le più perniciose incongruenze di questa interpretazione mistificante del processo economico si colloca, appunto, l'impropria valutazione del ruolo giocato dalle risorse naturali, che crea l'illusione che l'economia sia del tutto autonoma rispetto ai processi naturali, e al contempo innesca quel procedimento logico viziato nel quale la ragione umana resta invischiata perdendosi in una trama auto-implosiva. In tal senso, dunque, "l'assimilazione del processo economico a una giostra che girerebbe tra la produzione e il consumo ha comportato una seconda omissione deplorevole, quella del ruolo delle risorse naturali in tale processo"[31].

L'artificio intellettuale che consente di trascurare il Secondo Principio della Termodinamica, e quindi l'irreversibile degradazione dell'energia e della materia, è tra i miti economici che si radicano nella complessiva parabola della ragione occidentale: infatti, la configurazione assunta dalla scienza economica come disciplina autonoma deriva dall'inseparabilità della sua evoluzione dalla storia della ragione occidentale[32]. Al fine di svelare le contraddizioni del dogma meccanicista Georgescu-Roegen può dunque contrapporre il pendolo meccanico alla clessidra termodinamica. Egli scrive, infatti: "Per trovare la radice di tutte queste anomalie, ci basta osservare che, secondo l'epistemologia meccanicistica, l'universo non è altro che un enorme sistema dinamico. Di conseguenza, esso non si muove in un senso particolare. Come un pendolo, può spostarsi altrettanto nel senso opposto senza violare qualche principio della meccanica. Persino i morti potrebbero rivivere una vita in senso opposto e morire alla nascita"[33]. Viceversa, se immaginiamo una clessidra[34] contenente della sabbia, che rappresenta la materia-

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[30]N. Georgescu-Roegen, *Lo stato stazionario e la salvezza ecologica*, in Id., *Bioeconomia*, cit., p. 101 (già pubblicato anche in N. Georgescu-Roegen, *Energia e miti economici*, introduzione di G. Nebbia, trad. di P.L. Cecioni, G. Ferrara degli Uberti e L. Maletti, Bollati Boringhieri, Torino 1998).

[31]*Ibidem*.

[32]A tal proposito, si vedano anche G. Giordano, *Economia, etica e complessità. Mutamenti della ragione economica*, Le Lettere, Firenze 2008, e A. F. De Toni – L. Comello, *Prede o ragni. Uomini e organizzazioni nella ragnatela della complessità*, UTET, Torino 2005.

[33]N. Georgescu-Roegen, *Lo stato stazionario e la salvezza ecologica*, in Id., *Bioeconomia*, cit., p. 101.

[34]Cfr. ivi, pp. 101-103.

energia, possiamo descrivere la prospettiva offerta dalla termodinamica di un sistema isolato. Come spiega la prima legge della termodinamica, la quantità di sabbia, spostandosi da una metà all'altra della clessidra, resta costante; tuttavia, nel nostro sistema, specifica Georgescu-Roegen, intanto la sabbia cambia qualità mentre scorre, in quanto la materia-energia si trasforma da utilizzabile in inutilizzabile, e, inoltre, la clessidra non si può mai capovolgere: pertanto, in un sistema isolato, il degrado entropico è costante e irreversibile, come spiega il Secondo Principio della Termodinamica. E, tuttavia, occorre ancora precisare, innanzitutto, che, se "la trasmutazione entropica" non avvenisse "nello stesso senso del flusso della nostra coscienza, cioè parallelamente alla nostra vita"[35], non avrebbe alcun significato parlare di aumento della materia-energia inutilizzabile, e, che, in ogni caso, i sistemi isolati non si riscontrano nella nostra realtà se non in laboratorio.

In effetti, proprio per il motivo che la scienza economica era destinata, nella sua ambizione di autonomia, a rappresentare "un'estensione della meccanica razionale, addirittura come un'applicazione sociale della meccanica celeste", essa "divenne una disciplina accademica fiorente e via via più astratta, la cui razionalità - favorendo una logica dell'equilibrio ed una concezione circolare ed isolata del processo economico - è di ispirazione esplicitamente newtoniana"[36]. Ma, nonostante la scienza economica si ostini a ignorare la svolta metodologica in atto, "la sorte fatale dell'epistemologia meccanicistica fu decisa quando più di un secolo fa la termodinamica ci costrinse a prendere in considerazione l'irrevocabile diversità che domina il mondo fisico a livello macroscopico"[37].

Alla luce di simili considerazioni, poiché il carattere sostanzialmente autodistruttivo del processo di crescita illimitata innescato dal dogma meccanicistico è ormai evidente, non ci si può limitare a una semplice riforma (quale potrebbe essere ad esempio *la sostituzione di una contabilità energetica alla attuale contabilità monetaria*[38]), ma occorre piuttosto affrontare una sovver-

[35]Ivi, p. 103.

[36]J. Grinevald, *Georgescu-Roegen, bioeconomia e biosfera*, cit., p. 58. Su ciò si veda in particolare S. Latouche, *L'invenzione dell'Economia,* cit., pp. 74 ss., in cui l'autore offre una dettagliata ricostruzione delle origini storiche ed epistemologiche della scienza economica, della formazione dell'immaginario economico collettivo e della intervenuta necessità, per l'uomo occidentale, di emanciparsi da un mito ormai tramontato.

[37]N. Georgescu-Roegen, *Lo stato stazionario e la salvezza ecologica*, in Id., *Bioeconomia*, cit., p. 101.

[38]Cfr. ivi, p. 62.

sione dell'interpretazione delle categorie economiche, tale da consentire una lettura integrata del metabolismo complessivo della specie umana nel metabolismo vincolato della Terra. Dal punto di vista etico è evidente che una simile rivoluzione agisce in direzione dell'assunzione di una più consapevole responsabilità nel determinare il destino della Terra, in considerazione dello straordinario potere di interferire col metabolismo globale, espresso dalla specie umana proprio a causa dell'incontenibile potenziale tecnologico sviluppato[39].

L'approccio bioeconomico offre un'interpretazione insolita dell'economia, idonea a rivelare l'origine biologica dei fenomeni economici e l'assoluta dipendenza dell'esistenza dell'umanità dalla disponibilità di risorse naturali. Infatti, secondo il punto di vista della scuola bioeconomica, "il pensiero economico deve ritrovare la sua originaria ispirazione, che storicamente trovava, come è noto, il suo posto accanto alle scienze naturali, alla fisiologia e all'agronomia"[40].

Questo specifico orientamento assunto dal pensiero di Georgescu-Roegen gli ha probabilmente precluso il pieno consenso che avrebbe meritato nell'ambiente accademico, per la sua natura evidentemente eversiva rispetto alla concezione più tradizionalmente antropomorfica e rassicurante del processo economico[41]. Esso è tuttavia quello che, in qualche modo, gli ha conquistato la maggiore notorietà, considerato che di fatto getta le basi di ogni successivo pensiero ecologico. È vero, infatti, che "la bioeconomia, nel senso in cui la intende Georgescu-Roegen, considera lo sviluppo tecno-economico della specie umana nell'unità del suo radicamento biofisico così come nella diversità della sua evoluzione culturale e istituzionale, senza mai perdere di vista le costrizioni e i limiti della Terra e della sua biosfera. Questa afferma-

[39]In più occasioni, infatti, Georgescu-Roegen invoca l'urgenza di una nuova etica, coerente con la prospettiva ormai innegabile della coappartenenza uomo-natura, che si radichi sulla presa di coscienza *ecologica* della condizione terrestre dell'uomo in merito alla sua relazione vitale con la natura. A tal proposito, si vedano in particolare N. Georgescu-Roegen, *Bioeconomia ed etica,* Id.*, Quo vadis homo sapiens sapiens?,* Id., *L'economia politica come estensione della biologia*, Id., *Ineguaglianza, limiti e crescita da un punto di vista bioeconomico*, Id., *Lo stato stazionario e la salvezza ecologica*, tutti in Id., *Bioeconomia,* cit.

[40]J. Grinevald, *Georgescu-Roegen, bioeconomia e biosfera*, cit., p. 68.

[41]Come scrive Grinevald "È evidentemente questa reintegrazione dell'umano nella natura che sembra più difficilmente accettabile per l'antropomorfismo moderno nato essenzialmente dalla tradizione religiosa giudaico-cristiana dell'Occidente medievale" (J. Grinevald, *Georgescu-Roegen, bioeconomia e biosfera*, cit., p. 72).

zione dei limiti costituisce senza dubbio l'aspetto maggiormente 'ecologico' del messaggio di Georgescu-Roegen"[42].

Lo stesso Georgescu-Roegen, peraltro, ritiene che la sostanza del processo economico "è essenzialmente biologica"[43], e così descrive l'entità del suo impegno scientifico in merito: "Negli ultimi venti anni ho dedicato tutti i miei sforzi di ricerca a questo tema e alle sue conseguenze ecologiche, per mettere a punto un programma bioeconomico che attenuasse gli effetti delle inevitabili calamità ecologiche, le quali altrimenti renderebbero la sopravvivenza della specie umana su questa terra la più breve tra tutte. Tristemente, la mia lotta non ha avuto alcuna influenza sostanziale sul chiassoso dibattito attorno al problema delle risorse naturali, sin da quando presagii l'embargo petrolifero del 1973-74"[44].

Nel saggio *Quo vadis homo sapiens-sapiens?*, l'autore richiama efficacemente i tre punti, da lui enunciati per la prima volta nel 1970, per descrivere un quadro completo della sua teoria bioeconomica: "1) esiste una forte parentela fenomenologica tra il processo economico e il dominio biologico; 2) il processo economico costituisce un superamento evolutivo della biologia che caratterizza la specie umana; 3) occorre riconoscere che la biologia e l'economia si distinguono dagli altri domini della natura in quanto entrambe sono governate specificamente dalla legge di entropia, senza la quale esse non potrebbero essere compiutamente spiegate"[45]. Egli, cioè, a partire dall'evidente affinità sostanziale rivelata dai fenomeni economici e biologici, comprende che il processo economico rappresenta in realtà l'esito di quel particolare tipo di evoluzione imboccato dalla specie umana attraverso l'affinamento degli organi *esosomatici*[46], ed è quindi un corollario del proces-

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[42]*Ibidem*.

[43]N. Georgescu-Roegen, *Quo vadis homo sapiens sapiens?,* in Id., *Bioeconomia*, cit., p. 211.

[44]Ivi, pp. 211-212.

[45]Ivi, p. 212.

[46]Come spiega dettagliatamente l'autore, nei diversi saggi in cui affronta specificamente l'argomento del singolare percorso evolutivo della specie umana, mentre tutti gli esseri viventi si evolvono grazie al miglioramento del loro corredo biologico, di cui sono dotati fin dalla nascita, alcune specie usano organi esosomatici, cioè che non appartengono ai corpi individuali: l'uomo in particolare, migliora il suo grado di adattamento all'ambiente anche attraverso l'utilizzo di strumenti che non appartengono al suo corpo, dal bastone al coltello fino alla progettazione degli strumenti tecnologici più sofisticati. La specie umana, addirittura, si spinge poi fino allo stadio di "costruire strumenti per costruire strumenti che a loro volta vengono utilizzati per costruire altri strumenti" (N. Georgescu-Roegen, *Bioeconomia ed etica*, cit., p. 187), e arriva al punto da riuscire a volare senza ali, come a nuotare senza pinne o branchie

so biologico, e conclude, con inevitabile consequenzialità, che la legge d'entropia è immanente a entrambi i processi.

E, d'altra parte, l'assoluta dipendenza dell'esistenza dell'umanità dalla disponibilità di risorse naturali costituisce una circostanza dalla quale non è possibile prescindere per accedere a una realistica comprensione dei fenomeni economici, se è vero che "la specie umana dopotutto non costituisce un'eccezione nel regno della biologia. Anche noi, come tutte le altre specie biologiche, lottiamo per la vita in un ambiente finito"[47].

La natura bioeconomica del processo economico, in realtà, emerge lucidamente dalla prospettiva finalmente conquistata attraverso una duplice analisi: quella offerta dall'approccio meccanico e quella offerta dall'approccio termodinamico. Vale la pena affrontare interamente la lettura di questo lungo passaggio scritto in proposito da Georgescu-Roegen: "Come è stato detto tante volte, l'uomo non può creare né distruggere materia o energia. Questa però è solo una metà della storia, la metà raccontata dalla meccanica, modello prediletto dalla maggior parte degli studiosi di scienze sociali. Le risorse naturali, però, non sono costituite da sola materia e sola energia, ma da *materia organizzata in strutture ben precise* e da *energia disponibile*. La semplice materia, come l'oro disperso nel fondo degli oceani, non ha per noi alcun valore: abbiamo bisogno di giacimenti auriferi in luoghi in cui l'oro sia disposto in modo da poterlo estrarre in un tempo utile. Nemmeno l'immensa energia termica contenuta nelle acque degli oceani ha per noi alcun valore: una nave che solca i mari ha bisogno di combustibile, cioè di energia allo stato libero; tutto il carbonio, l'ossigeno, l'idrogeno ecc. del mondo non potrebbero so-

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(Cfr. N. Georgescu-Roegen, *L'economia politica come estensione della biologia*, cit., p. 74). Gli economisti considerano gli strumenti che non fanno parte del corredo biologico dell'uomo come capitale fisso, ma, secondo Georgescu-Roegen, il modo in cui li qualifica il biologo Lotka, *strumenti esosomatici* (Cfr. A. J. Lotka, *Elements of physical biology,* Williams & Wilkins Company, Baltimore 1925), rende meglio l'idea che "il processo economico è, in senso lato, una continuazione di quello biologico" (N. Georgescu-Roegen, *Prospettive e orientamenti in economia,* in Id., *Analisi economica e processo economico*, cit., p. 119).

[47]N. Georgescu-Roegen, *L'economia politica come estensione della biologia*, in Id., *Bioeconomia*, cit., pp. 69-70. Maturana e Varela, a tal proposito, hanno teorizzato l'interessante connessione fra conoscenza e azione, sulla base dell'idea che la conoscenza è un fenomeno biologico radicato nell'essere vivente preso nella sua totalità, per cui vivere è agire efficacemente nel proprio dominio di esistenza, e il processo cognitivo è connesso con la struttura di colui che conosce, in un rapporto di circolarità inestricabile tra azione e conoscenza. Cfr. H. Maturana – F. Varela, *L'albero della conoscenza*, cit., in particolare pp. 45, 154, 204.

stentare la vita dell'uomo se non fossero organizzati in una molecola di zucchero, amido o proteina.

Nella metà della storia raccontata dalla termodinamica, le cui leggi sono inesorabili come quelle della meccanica, la materia-energia che costituisce le risorse naturali è qualitativamente diversa da quella che forma lo scarto: quella delle risorse naturali è organizzata secondo schemi ordinati o, come dicono i fisici, ha *bassa entropia*; negli scarti troviamo solo disordine, cioè *alta entropia*. E non è tutto; la seconda legge della termodinamica ci dice anche che tutto l'universo è soggetto a una degradazione qualitativa continua: l'entropia aumenta, e tale aumento è irreversibile. Di conseguenza, *le risorse naturali possono passare attraverso il processo economico solo una volta: lo scarto rimane irreversibilmente uno scarto*"[48]. Associando il punto di vista entropico a quello meccanico, è pertanto possibile accedere a una prospettiva più soddisfacente, che ci consegna nuove informazioni: infatti, occorre prendere atto che "né la fisica, né la chimica, possono spiegare la scarsità economica"[49]. La disponibilità o meno attribuita alle risorse naturali è, in effetti, un concetto connotato del tutto *antropomorficamente*, come, peraltro, la legge stessa di entropia, "l'unica che non è legata al tempo 'cronologico'"[50]. Infatti, l'aumento dell'entropia di un sistema, in conseguenza dell'applicazione di questa legge, implica un confronto fra un *prima* e un *dopo*: si tratta di un'argomentazione che può trovare riscontro solo nella coscienza umana[51]. In realtà, come sottolinea Georgescu-Roegen, "di essa non esiste alcuna spiegazione nell'ambito della meccanica, considerato l'unico valido dal pensiero contemporaneo, che sia stata accettata da tutti. Il ricorso alla teoria della probabilità non ha fatto altro che complicare le cose, dando luogo a gravi errori di interpretazione"[52]. Pertanto, egli stesso confessa, in merito, la natura fenomenologica del suo orientamento gnoseologico: "Quando cominciai a scorgere il significato della legge di entropia attraverso le mie semplici e concrete esperienze, mi fu naturale continuare lungo il mio cammino seguendo

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[48]N. Georgescu-Roegen, *Processo agricolo e processo industriale: un problema di sviluppo bilanciato*, in Id., *Energia e miti economici* [1982], p. 190.

[49]N. Georgescu-Roegen, *Quo vadis homo sapiens sapiens?,* cit., p. 213.

[50]Ivi, p. 217.

[51]Cfr. *ibidem*.

[52]Ivi, pp. 215-216.

un approccio fenomenologico, un metodo cognitivo che ritengo più sicuro di quello meccanicistico”[53].

Non solo il pensatore rumeno proietta l'attenzione su aspetti del processo economico sostanzialmente rimossi nell'analisi tradizionale, ma, denunciando anche l'inesorabilità delle leggi che li presiedono, ne impone l'integrazione all'interno di ogni seria indagine epistemologica diretta alla conoscenza dell'economia. A proposito dell'entropia, egli, infatti, dichiara: “L'uomo non può sconfiggere questa legge, più di quanto non possa arrestare l'azione della legge di gravità; il processo economico, come la stessa vita biologica, è *unidirezionale*. Solo il denaro si muove in un flusso circolare, perché nessuno lo butta via anche se è solo un contrassegno artificiale”[54]. E, ancora, in un altro eloquente passaggio, egli afferma: “Che la legge di entropia sarà un giorno confutata, come è successo per molte altre leggi nella storia, è il ritornello preferito di molti ecologisti impegnati nel sostenere l'ottimismo di coloro che non riescono ad accettare la realtà per quello che è. Tuttavia, la storia sta dalla parte della permanenza della validità della legge. Non a caso tutte le volte che una mano tocca una pentola bollente, è la mano a scottarsi e non la pentola, confermando così la legge di entropia”[55].

Preso atto che le strutture che sostengono la vita sono soggette alla tirannia dell'irrevocabile degradazione entropica, e, quindi, dipendono inevitabilmente dall'energia e dalla materia disponibile - e accessibile[56] -, secondo Georgescu-Roegen, la formulazione della teoria bioeconomica assolve, allora, anche l'importante compito di disegnare un diversa cornice di significato, all'interno della quale riconciliare le dinamiche economiche con quelle dei processi naturali. Una simile presa di coscienza, infatti, invoca evidentemente un nuovo paradigma che consenta di reinterpretare il rapporto uomo-natura. La *bioeconomia*, pertanto, “deve studiare l'utilizzo da parte

[53]Ivi, p. 216.

[54]N. Georgescu-Roegen, *Processo agricolo e processo industriale: un problema di sviluppo bilanciato*, cit., pp. 190- 191.

[55]N. Georgescu-Roegen, *Quo vadis homo sapiens sapiens?,* cit., p. 217.

[56]La distinzione fra materia ed energia disponibile e non disponibile, secondo la prospettiva antropologica, non è sufficiente a garantirne l'effettivo sfruttamento da parte dell'uomo. A tal fine, occorre un'ulteriore qualità, l'*accessibilità*. Spiega Georgescu-Roegen: “La terra è immersa in un mare cosmico di energia disponibile (il flusso prodotto dal sole, per esempio), che non può essere utilizzata perché non è *accessibile*. Ecco dunque che l'energia che noi possiamo effettivamente utilizzare dovrà essere *sia* disponibile *sia* accessibile, una condizione di cui nessun esperto di analisi energetica è veramente consapevole” (N. Georgescu-Roegen, *Quo vadis homo sapiens sapiens?,* cit., p. 216).

dell'uomo delle diverse fonti energetiche e della materia del processo economico. Si avrebbe così un impianto teorico sul quale basare la ricerca di una nuova impostazione economica, in una rinnovata alleanza con la Natura, da attuare nell'attesa o nella ricerca di Prometeo III"[57]; ovvero nella speranza dell'intervento della scoperta di una nuova fonte di energia sfruttabile, dopo le rivoluzionarie scoperte del fuoco e della macchina termica.

Come denuncia il pensatore rumeno, "il fatto palese che tra il processo economico e l'ambiente materiale esista una mutua, ininterrotta influenza è irrilevante agli occhi dell'economista standard. E lo stesso è vero per gli economisti marxisti, i quali giurano sul dogma di Karl Marx secondo il quale tutto ciò che la natura offre all'uomo è un dono spontaneo"[58]; mentre, viceversa, "l'intera storia economica dell'umanità dimostra al di là di ogni dubbio che anche la natura svolge un ruolo importante nel processo economico, oltre che nella formazione del valore economico"[59]. Per questo motivo, conclude, a tal proposito, Georgescu-Roegen: "È tempo, io credo, che accettiamo questo fatto e ne consideriamo le conseguenze per il problema economico dell'umanità", poiché "alcune di queste conseguenze hanno infatti un'eccezionale importanza ai fini della comprensione della natura e

[57]S. Zamberlan, *Economia e biologia, la teoria bioeconomica di Nicholas Georgescu-Roegen*, in "Il pensiero economico moderno", anno XXVI, n. 4 –Ottobre-Dicembre 2006, p. 77. Secondo la ricostruzione offerta da Georgescu-Roegen, nell'ambito dell'articolata parabola della storia della specie umana, solo due fra le numerose innovazioni tecnologiche dell'uomo integrano gli estremi di "mutazioni bioeconomiche" vere e proprie: le cosiddette "innovazioni prometeiche", ovvero il controllo del fuoco e l'invenzione della macchina a vapore, che egli attribuisce simbolicamente a Prometeo I e a Prometeo II. Si tratta di scoperte di importanza enorme, proprio in quanto rappresentano due casi di "*conversione energetica qualitativa*". Il fuoco consente "la conversione dell'*energia chimica* delle materie combustibili in *calore*", e inaugura quella che potremmo definire l'*età del legno*. Quest'ultimo è stato per millenni la sola fonte di potere calorifico, fin quando, nella seconda metà del XVII secolo, venendo meno il combustibile alla tecnologia basata sul legno, a causa del feroce disboscamento, si andava configurando l'imminenza di una crisi energetica. Ma proprio a questo punto si è verificata la seconda innovazione prometeica, quella della macchina termica, che consente una nuova conversione energetica qualitativa, quella da *potere calorifico a energia meccanica*: "Con un po' di carbone e una macchina termica possiamo estrarre altro carbone e anche altri minerali con i quali fabbricare *diverse* macchine termiche, che a loro volta generano altre macchine termiche" (N. Georgescu-Roegen, *Analisi energetica e valutazione economica*, in Id., *Bioeconomia. Verso un'altra economia ecologicamente e socialmente sostenibile*, cit., pp. 180-181).

[58]N. Georgescu-Roegen, *La legge di entropia e il problema economico*, in Id., *Bioeconomia*, cit., pp. 79-80 (già pubblicato in N. Georgescu-Roegen, *Analisi economica e processo economico*, e in Id., *Energia e miti economici*, edizione italiana del 1998, cit.).

[59]Ivi, p. 80.

dell'economia umana"[60]. In breve, si tratta di un cambiamento di prospettiva che non può essere più rimandato.

Occorre intraprendere un cammino che si prospetta niente affatto agevole: il paradigma scientifico meccanicistico è talmente radicato nella mentalità comune da creare un'ostinata resistenza intellettuale all'accettazione dell'inesorabilità della legge dell'entropia, nonostante si tratti di una elementare verità fenomenologica. Al punto che, secondo Georgescu-Roegen, alcuni studiosi sono arrivati a coltivare l'illusione che la vita sfugga alla legge dell'entropia, incoraggiati dal fatto che "su archi temporali di breve durata gli organismi viventi rimangono pressoché immutati"[61]: tuttavia, in realtà, egli osserva ancora, "la vita avrà forse proprietà che non possono essere spiegate dalle leggi naturali, ma l'ipotesi stessa che possa violare qualche legge della materia (che è qualcosa di completamente diverso) è una mera sciocchezza. La verità è che ogni organismo vivente si adopera soltanto a mantenere costante la propria entropia. E ottiene il suo scopo (nella misura in cui l'ottiene) traendo bassa entropia dall'ambiente per compensare l'aumento di entropia cui, come ogni struttura materiale, l'organismo è ininterrottamente soggetto. Ma l'entropia del sistema totale – formato dall'organismo e dal suo ambiente – non può che crescere. In effetti, l'entropia di un sistema deve crescere più velocemente in presenza che non in assenza della vita. Il fatto che gli organismi viventi combattano la degradazione entropica della loro struttura materiale può ben essere una proprietà caratteristica della vita, che le leggi materiali non sono in grado di spiegare; ma ciò non costituisce una violazione di tali leggi"[62]. Né, tantomeno, l'attività economica, anche quando sembra creare ordine dal disordine - ad esempio attraverso la raffinazione di un minerale grezzo-, sfugge alla legge di entropia, poiché il bilancio entropico complessivo dell'ambiente circostante resta negativo, a causa del dispendio energetico innescato dal processo. In altri termini, la legge di entropia ci insegna che, in ogni caso, "il costo di qualunque intrapresa biologica o economica è sempre maggiore del prodotto. In termini di entropia, qualunque attività del genere ha inevitabilmente per risultato un deficit"[63].

È altrettanto vero, in ogni caso, che, nonostante la sua eccezionale attenzione all'incidenza del Secondo Principio della Termodinamica nella realtà, economica in particolare, per Georgescu-Roegen è assolutamente chiaro

[60] *Ibidem*.

[61] Ivi, p. 84.

[62] Ivi, pp. 84-85.

[63] Ivi, p. 85.

come non esista alcuna contraddizione, in termini di leggi naturali, tra il fatto che l'universo materiale sia costantemente soggetto a un processo irreversibile di degradazione e il fatto che all'interno di esso possano svilupparsi e anche espandersi delle strutture viventi. Egli ammette che la proprietà della vita di andare contro il flusso di degrado della materia inerte si giustifica senza ricorrere ad alcun tipo di misticismo[64]. E ciò, evidentemente, in quanto: "Primo, la legge dell'entropia si applica solo a sistemi completamente isolati, mentre invece un organismo vivente, come sistema aperto, scambia materia ed energia con il suo ambiente. Non si ha contraddizione con la legge di entropia in quanto l'aumento di entropia dell'ambiente compensa e supera la diminuzione di entropia dell'organismo. Secondo, la legge dell'entropia non determina la velocità della degradazione; questa può essere accelerata, come lo è da tutti gli animali, o addirittura rallentata, per esempio dalle piante verdi. Terzo, la stessa legge non determina i tipi di struttura che possono emergere da un caos entropico. Come esempio chiarificatore: la geometria determina la lunghezza delle diagonali di un quadrato ma non il colore del quadrato. Dire se il quadrato sarà, poniamo, verde, è una questione diversa a cui è impossibile rispondere"[65].

Com'è evidente, Georgescu-Roegen si avvale della "terminologia termodinamica" codificata da Ilya Prigogine, cui egli stesso fa esplicito riferimento[66]. Nell'accezione che utilizza, pertanto, mentre un sistema *aperto*[67] può scam-

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[64]A proposito del fatto che le leggi naturali dell'evoluzione biologica sembrano contraddire i principi della termodinamica, scrive Enzo Tiezzi: "I sistemi biologici sono una manifesta violazione della seconda legge, presentano strutture estremamente ordinate e si evolvono nella direzione di un più profondo ordine, di una minore entropia. In realtà la contraddizione è solo apparente. Il bilancio entropico deve essere globale e deve includere sia l'organismo biologico sia l'ambiente col quale l'organismo scambia continuamente energia e materia. Si vede così che gli organismi biologici si sviluppano e vivono in virtù dell'aumento di entropia che il loro metabolismo provoca nell'ambiente circostante. La variazione di entropia globale (sitema+ambiente) è positiva, l'entropia dell'universo è aumentata, la seconda legge non è stata violata". (E. Tiezzi, *Tempi storici e tempi biologici. La Terra o la morte: i problemi della 'nuova ecologia'*, Garzanti, Milano 1986, p. 52).

[65]N. Georgescu-Roegen, *Postfazione*, in J. Rifkin, *Entropia*, [1980], con la collaborazione di T. Howard, trad. di G. Gregorio, postfazione di N. Georgescu-Roegen, Baldini Castoldi Dalai, Milano 2004, p. 430.

[66]Cfr. N. Georgescu-Roegen, *Analisi energetica e valutazione economica*, in Id., *Bioeconomia. Verso un'altra economia ecologicamente e socialmente sostenibile*, cit., p. 135.

[67]Bertalanffy introdusse la distinzione tra sistemi *chiusi*, i soli presi in considerazione dalla fisica classica, e sistemi *aperti*, ovvero, in pratica, ogni organismo vivente, ma solo con Prigogine si è arrivati alla formulazione della nuova termodinamica dei sistemi aperti. Cfr. L. von Bertalannfy, *Teoria generale dei sistemi. Fondamenti, sviluppo, applicazioni*, cit., pp. 74 ss. e pp.

biare sia energia che materia con l'ambiente circostante, un sistema è *chiuso* se può scambiare soltanto energia, ma non materia; un sistema *isolato*, infine, non può scambiare niente[68]. Nel saggio *Lo stato stazionario e la salvezza ecologica*[69], in particolare, egli si riferisce alla Terra come sistema *chiuso*. In considerazione di ciò Georgescu-Roegen denuncia la disattenzione degli studiosi non soltanto in relazione al problema dell'esaurimento delle risorse energetiche disponibili - preso atto che l'uomo non è attualmente in grado di sfruttare in pieno l'energia solare - ma anche in relazione a quello derivante dall'usura della materia stessa, che con il semplice attrito si dissipa inevitabilmente, al pari dell'energia: questo è un passaggio chiave nell'impianto teorico bioeconomico, in quanto quella che può apparire una realtà fenomenologicamente evidente stenta a lasciarsi tradurre in una legge scientificamente ineccepibile. E, in realtà, il problema della rilevanza della degradazione della materia in un sistema chiuso ha impegnato Georgescu-Roegen in estenuanti polemiche sia contro i sostenitori del cosiddetto dogma energetico, secondo il quale con una quantità sufficiente di energia è possibile effettuare un riciclaggio completo della materia, sia contro il mito della salvezza ecologica mediante il raggiungimento dello stato stazionario, inteso come stato di crescita zero. Al punto che egli si è visto costretto a formulare provocatoriamente il cosiddetto ***quarto principio della termodinamica***[70], in base al quale *in un sistema chiuso l'entropia della materia deve tendere verso un massimo*[71].

Occorre tenere presente, infatti, che, sebbene l'economia sia un sistema aperto, e, pertanto, scambi energia e materia con l'ambiente, reintroducendovi gli scarti, le sue dinamiche devono tuttavia essere interpretate nel

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196 ss. Su ciò, si veda anche F. Capra, *La rete della vita* [1996], trad. di C. Capararo, BUR, Milano 2006, cit., pp. 61 ss. e I. Prigogine - I. Stengers, *La nuova alleanza. Metamorfosi della scienza*, cit., pp. 136 ss.

[68]Cfr. N. Georgescu-Roegen, *Analisi energetica e valutazione economica*, in Id., *Bioeconomia*, cit., pp. 135-136, con particolare attenzione alla nota n.10.

[69]Cfr. N. Georgescu-Roegen, *Lo stato stazionario e la salvezza ecologica,* in Id., *Bioeconomia*, cit., pp. 103 ss.

[70]La terza legge della termodinamica, secondo la quale *la temperatura dello zero assoluto non può essere raggiunta con un numero finito di trasformazioni*, è in effetti un teorema sviluppato da Walter Nernst sulla base del secondo principio della termodinamica (cfr. N. Georgescu-Roegen, *Analisi energetica e valutazione economica*, cit., p. 149).

[71]Su ciò, cfr. in particolare N. Georgescu-Roegen, *Lo stato stazionario e la salvezza ecologica*, cit.; Id., *Bioeconomia e degradazione della materia,* in R. Molesti (a cura di), *Economia dell'ambiente e bioeconomia*, cit.; Id., *Energia e miti economici*, cit.

complesso della loro integrazione all'interno del più ampio sistema naturale: quello della Terra, il quale, viceversa, si colloca fra i sistemi chiusi, cioè tra quelli che scambiano energia, ma non materia, con l'esterno. "Il fatto è", scrive Georgescu-Roegen, "che la Terra è un sistema termodinamico aperto solo per quanto riguarda l'energia: la materia meteorica che arriva, anche se in quantità non trascurabile, è già dissipata. Di conseguenza possiamo contare solo sulle risorse minerali, che, però, non sono né sostituibili né inesauribili"[72]. Il nostro pianeta, infatti, è esposto al continuo flusso dell'energia solare[73]. Tuttavia, dal punto di vista pratico, potrebbe addirittura assumere complessivamente i connotati di un sistema isolato, in quanto l'uomo non è attualmente in possesso degli strumenti adeguati per uno sfruttamento diretto dell'energia solare[74]. Pertanto, bisogna considerare che, se è vero che "il nostro pianeta riceve l'energia solare, della quale però non abbiamo ancora imparato a sfruttare che una minima parte", in effetti, "quanto meno dal punto di vista del processo economico", esso "è più simile ad un sistema isolato, e noi siamo costretti ad utilizzare l'energia fossile e le risorse minerali, che sono finite e non sostituibili"[75]. Bisogna, in definitiva, prendere atto che, da un lato, non esistono ricette fattibili per una tecnologia solare vitale, ovvero in grado di *auto-sostentarsi*[76] e, dall'altro, anche la stessa materia è soggetta a

[72]N. Georgescu-Roegen, *Energia e miti economici*, cit., p. 37.

[73]Nonostante ciò, allo stato attuale della tecnologia, è ancora impossibile risolvere il problema della carenza di risorse energetiche mediante il ricorso a questo tipo di energia, che è *disponibile*, secondo la terminologia di Georgescu-Roegen, ma non *accessibile*: "Forse quando diciamo che l'energia solare è gratuita vogliamo semplicemente dire che è 'estremamente abbondante', e in effetti lo è: il flusso annuale che raggiunge gli strati superiori dell'atmosfera è circa dodicimila volte superiore all'attuale consumo energetico mondiale da qualunque fonte! Sfortunatamente la sola abbondanza di energia *in situ* non costituisce necessariamente un vantaggio, e questo è proprio il caso dell'energia solare, che è abbondante, ma ha anche il grande difetto di essere estremamente debole quando ci raggiunge" (N. Georgescu-Roegen, *Analisi energetica e valutazione economica*, in Id. *Bioeconomia*, cit., p. 166). Per quanto riguarda le oggettive difficoltà di sfruttamento diretto e integrale dell'enorme quantità di energia solare si veda, in particolare, N. Georgescu-Roegen, *Energia e miti economici*, cit.

[74]Cfr. S. Zamberlan, *L'entropia come fondamento dell'economia nel pensiero di Georgescu-Roegen*, in "Il pensiero economico moderno", anno XXVI, n.1 – Gennaio-Marzo 2006, pp. 37-62.

[75]Ivi, p. 52.

[76]In sostanza, secondo Georgescu-Roegen, una tecnologia è fattibile quando, dati determinati ingredienti, *il metodo realizzabile può essere effettivamente realizzato per ottenere il risultato voluto*. Tuttavia, un metodo realizzabile non corrisponde necessariamente a un'iniziativa economica vantaggiosa. Su ciò, cfr., in particolare, N. Georgescu-Roegen, *Ricette fattibili contro tecnologie vitali*, in Id., *Bioeconomia*, cit., dove l'autore scrive: "Chiaramente il processo (o

degradazione, né, come sappiamo, esiste un flusso di materia proveniente dall'esterno che possa essere assorbito dalla Terra. Per questo motivo, allora, come spiega bene lo stesso Georgescu-Roegen in *Bioeconomia e degradazione della materia*, il processo economico è evidentemente aperto, mentre la Terra è un sistema chiuso, "pertanto non è escluso che in avvenire alcuni materiali possano divenire un fattore più critico dell'energia. Il sole come sorgente di energia durerà ancora almeno quattro miliardi di anni, più a lungo della più ottimistica durata della specie umana. Alcuni autori, tra tutti quelli, innumerevoli, che parlano oggi lungamente sulla energia, sostengono che 'l'idea di un possibile esaurirsi della materia è ridicola. L'intero pianeta è composto di minerali'. Questa affermazione ignora che il pianeta non è completamente composto di materiali utilizzabili. È la quarta legge della termodinamica che

ricetta) è fattibile se *al momento della discussione* ne conosciamo le coordinate specifiche di flusso e di fondo. Cuocere il pane, trasmettere messaggi mediante onde elettromagnetiche, fondere il minerale di ferro, sono tutte ricette fattibili. Ma controllare l'energia termonucleare o prevedere un terremoto non sono ricette fattibili. Inoltre, nonostante tutti i processi inclusi in qualsiasi tecnologia debbano essere fattibili, non tutte le tecnologie sono *vitali (viable)*. Per chiarire: una tecnologia è 'vitale' quando e solo quando è in grado di mantenere la corrispondente struttura materiale e, necessariamente, la specie umana. Un'illustrazione di ciò che intendiamo per 'vitale' si può trovare nell'organismo vivente o nella specie biologica. Quel che pare necessario sottolineare è che ogni tecnologia vitale è sostenuta da qualche 'carburante', da qualche risorsa naturale, ma nessuna tecnologia può creare il suo proprio carburante. Un esempio di tecnologia non vitale è il seguente. Immaginiamo una tecnologia in cui il capitale è costituito da un martello di pietra con il quale vengono costruiti altri martelli, utilizzando pietre liberamente disponibili. Lo stesso martello è usato anche per spaccare noci molto dure, che sono il solo cibo della popolazione di questo luogo. Se il martello non dura abbastanza per costruire gli altri martelli e per spaccare le noci necessarie a mantenere la popolazione allora quella tecnologia non è vitale. Questo esempio illustra i lati negativi dell'uso diretto di energia solare"; infatti "il difetto principale dell'energia solare è la bassa intensità con cui raggiunge la terra e (punto trascurato) l'assenza di qualunque proprietà di autoconservazione. Anche la pioggia arriva a terra con una bassa intensità media, ma si accumula naturalmente fino a raggiungere – gratuitamente – l'intensità energetica delle cascate del Niagara". E, in effetti, nonostante i mirabolanti progressi della tecnologia, solo due invenzioni nella storia intera dell'uomo hanno prodotto tecnologie vitali: la scoperta del fuoco e quella della macchina a vapore, che ha prodotto la tecnologia nella quale ancora oggi ci troviamo (cfr. ivi, pp. 208-209, e anche N. Georgescu-Roegen, *Bioeconomia e degradazione della materia*, cit.; Id., *Analisi energetica e valutazione economica*, cit.). Sul concetto di tecnologia vitale, cfr. anche N. Georgescu-Roegen, *Dogma energetico, economia energetica e tecnologie vitali*, in Id., *Energia e miti economici* [1998], cit., p. 172, nella edizione italiana più recente, citata nella precedente nota 25.

ne rivela l'assurdità. Certamente lo stock terrestre di palladio, per esempio, è praticamente costante, ma lo stock di palladio utilizzabile decresce"[77].

In effetti, solo ignorando quella sostanziale asimmetria, esistente nel mondo macroscopico, tra energia e materia, che, invece, fonda razionalmente la distinzione fra sistemi aperti e sistemi chiusi, il cosiddetto dogma energetico[78] può sostenere che non esistono vincoli materiali alla crescita economica, in quanto *con una sufficiente quantità di energia è possibile ottenere qualunque materiale si voglia e riciclare qualunque quantità di materia*. Viceversa, ribadisce Georgescu-Roegen, "come tutti sappiamo, l'energia disponibile e le strutture materiali ordinate rivestono due ruoli distinti nella vita del genere umano"[79]. E, nondimeno, "tale distinzione antropomorfica non sarebbe, da sola, decisiva"[80]. Ciò perché, in concreto, l'allettante miraggio del completo riciclaggio della materia è evidentemente incompatibile anche con le reali leggi del nostro universo, dove "non c'è creazione di materia a partire dalla sola energia in proporzioni minimamente significative"[81].

In definitiva, occorre ancora prendere in considerazione un ulteriore fatto fisico: "Nonostante l'equivalenza di Einstein fra massa ed energia, non ci sono motivi per credere di poter convertire energia in materia, se non su scala atomica, in un laboratorio, e solo per alcuni elementi speciali. Non possiamo, per esempio, produrre una lastra di rame solo dall'energia: tutto il rame di quella lastra deve esistere come rame fin dall'inizio (in forma pura o in qualche composto chimico)"[82]. Inoltre, non si può prescindere in questa analisi da un'altra elementare circostanza: "Nessuna macrostruttura materiale (sia essa un chiodo o un aereo a reazione) che abbia un'entropia più bassa di quella di ciò che la circonda può conservare per sempre la forma originale; neppure le singole organizzazioni caratterizzate dalla tendenza a sfuggire al decadimento entropico - le strutture biologiche - ci riescono. I manufatti che

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[77]N. Georgescu-Roegen, *Bioeconomia e degradazione della materia. Il destino prometeico della tecnologia umana*, in R. Molesti (a cura di), *Economia dell'ambiente e bioeconomia*, cit., p. 110.

[78]Su questo tema cfr. N. Georgescu-Roegen, *Bioeconomia e degradazione della materia. Il destino prometeico della tecnologia umana*, cit.; Id., *Analisi energetica e valutazione economica*, cit.; Id., *Dogma energetico, economia energetica e tecnologie vitali*, cit.

[79]N. Georgescu-Roegen, *Energia e miti economici*, cit., p. 36.

[80]*Ibidem*.

[81]N. Georgescu-Roegen, *Lo stato stazionario e la salvezza ecologica*, in Id., *Bioeconomia*, cit., pag. 106.

[82]N. Georgescu-Roegen, *Energia e miti economici*, cit., pp. 36-37.

costituiscono ora parte essenziale del nostro modo di vivere si devono continuamente rinnovare attingendo a qualche fonte”[83].

Peraltro, che il riciclaggio non possa essere completo è una verità innegabilmente tangibile nella vita quotidiana. Tuttavia, sebbene Georgescu-Roegen considerasse in principio ovvia l’evidente circostanza che anche la materia subisce un’irreversibile degradazione, l’esplosione di popolarità raccolta dal cosiddetto dogma energetico[84] intorno agli anni Settanta lo indusse a formulare specifiche argomentazioni, in merito a questo argomento, fino alla provocatoria enunciazione della citata quarta legge della termodinamica[85]: egli afferma, infatti, che “il dogma energetico ha fatto nascere altri sviluppi fallaci, che sono particolarmente dannosi per un mondo che oggi prova difficoltà economiche e demografiche senza precedenti”[86]; e aggiunge: “Nei miei primi lavori sulla relazione tra il processo economico e la legge della termodinamica, ho affermato semplicemente che ‘noi non possiamo utilizzare una quantità di bassa entropia che una sola volta’. A quell’epoca non potevo immaginare che la scienza potesse sostenere il contrario per ciò che concerne la materia. È per questo che non ho fatto sforzi per denunciare il dogma energetico che dopo averne preso coscienza molto più tardi”[87].

Sostanzialmente, sebbene sia realmente difficile negare che gli oggetti si usurino e la materia sia soggetta a dispersione, “ciò che caratterizza il dogma energetico è l’idea che con energia sufficiente si possano, per esempio, raccogliere tutte le parti di caucciù disperse per la frizione dei pneumatici sulle strade e anche rigenerare i pneumatici usati”[88]; e, tuttavia, commenta causticamente Georgescu-Roegen, “curiosamente nessun adepto del dogma energetico ha trovato necessario spiegare, almeno a grandi linee, come tale operazione potrebbe essere effettuata”[89]. La verità è, piuttosto, che anche la

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[83]Ivi, p. 37.

[84]Cfr. in proposito N. Georgescu-Roegen, *Analisi energetica e valutazione economica*, cit.

[85]In merito ai problemi teorici connessi al principio di degradazione della materia nell’ambito del pensiero ecologico e alle specifiche critiche rivolte da fisici, chimici ed economisti a questo particolare passaggio del pensiero di Georgescu-Roegen, si veda ancora M. Bonaiuti, *La teoria bioeconomica*, cit., pp. 97-104, e anche S. Zamberlan, *Economia e biologia, la teoria bioeconomica di Nicholas Georgescu-Roegen*, cit.

[86]N. Georgescu-Roegen, *Bioeconomia e degradazione della materia. Il destino prometeico della tecnologia umana*, cit., p. 102.

[87]*Ibidem*.

[88]Ivi, p. 103.

[89]*Ibidem*.

materia subisce una continua degradazione verso una forma non disponibile, ma che, ancora una volta, "è il fascino della *Weltbild* meccanicistica a indurci a credere che la materia possa essere senz'altro recuperabile"[90]. Com'è noto, infatti, il dogma meccanicistico ignora il cambiamento qualitativo a vantaggio della sola misura, pertanto "in meccanica la materia può cambiare solo di posto, non di qualità, e perciò un sistema può compiere spostamenti pendolari senza subire alcun cambiamento"[91].

Georgescu-Roegen, viceversa, interpreta in modo sostanzialmente differente le dinamiche innescate nel processo economico dall'ineluttabile interazione con le leggi naturali, e descrive un quadro che può essere così efficacemente sintetizzato: "In un sistema chiuso l'esistenza di una legge di degradazione della materia, unita alla non sostituibilità fra materia ed energia - sancita dalla IV legge della termodinamica appunto, in negazione del dogma energetico -, pone limiti ancor più stringenti, al sistema economico, di quelli connessi alla seconda legge della termodinamica. L'Autore afferma che il processo economico, potendo assorbire solo energia ma non materia dall'ambiente esterno alla Terra, non può compiere lavoro per un tempo infinito, in altre parole '*il movimento perpetuo di terza specie è impossibile*'[92], il che è un'altra definizione della quarta legge"[93].

Partendo da una premessa insostenibile, ovvero la presunta simmetria tra materia ed energia, il dogma energetico, come Georgescu-Roegen dimostra con una fitta serie di argomentazioni, è privo di ogni fondamento. Tra le argomentazioni decisive, contro l'idea che in presenza di una sufficiente disponibilità di energia sia possibile correggere completamente la dissipazione della materia, egli sostiene: "In ogni caso, si tratta di un'operazione che deve far ricorso a qualche strumento materiale, e dato che non esistono strutture materiali eterne, questi strumenti devono consumarsi per forza ed essere so-

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[90] N. Georgescu-Roegen, *Analisi energetica e valutazione economica*, cit., p. 139.

[91] *Ibidem*.

[92] A proposito di moto perpetuo, in *Energia e miti economici*, scrive Georgescu-Roegen: "Un tempo l'uomo credeva di poter spostare oggetti senza consumo di energia, il che costituisce il mito del moto perpetuo di primo tipo, senza dubbio un mito essenzialmente economico. Il mito del moto perpetuo di secondo tipo, quello per cui è possibile utilizzare più volte la stessa energia, continua ad aleggiare sotto forme velate. Un altro mito economico – quello secondo cui l'uomo riuscirà sempre a trovare nuove fonti di energia e nuovi modi per imbrigliarle a suo vantaggio – viene adesso sostenuto da alcuni scienziati, ma soprattutto da economisti di estrazione tradizionale e marxista" (N. Georgescu-Roegen, *Energia e miti economici*, cit. p. 26).

[93] S. Zamberlan, *L'entropia come fondamento dell'economia nel pensiero di Georgescu-Roegen*, cit., p. 45.

stituiti con altri, prodotti da qualche altro strumento che si logorerà a sua volta e dovrà essere sostituito, e così via, in una regressione senza fine. Questo è già un motivo sufficiente per negare la possibilità di un riciclaggio completo"[94].

Se il dogma energetico è privo di fondamento, del tutto valido è, viceversa, il principio contrario, ovvero quello che sostiene che "anche la materia conta"[95]. Si tratta appunto del principio che Georgescu-Roegen formula sotto la dizione di "quarta legge della termodinamica", proprio in quanto "sull'esempio della legge tradizionale dell'entropia, questa ultima legge è legata alla distinzione tra materia *utilizzabile* (cioè in uno stato tale che noi possiamo utilizzarla nella manipolazione fisico-chimica) e materia *non utilizzabile* (rappresentata dalle particelle di materia che si trovano disperse o senza possibilità di essere riunite in materia utilizzabile)"[96]: in verità, il fatto che delle piccole parti di materia possano considerarsi perdute per l'uomo non significa che esse siano annientate. E, nondimeno, è corretto dire, secondo la quarta legge della termodinamica, che "in ogni sistema chiuso la materia utilizzabile si degrada irrevocabilmente in materia non utilizzabile", ovvero, appunto, "il movimento perpetuo di terza specie è impossibile"[97].

Se queste sono le premesse corrette, allora, per affrontare la questione ecologica con una sana dose di realismo, non si può in alcun modo prescindere dalla quarta legge della termodinamica, la cui "importanza è capitale per la questione eminentemente pratica della relazione del processo economico con l'ambiente naturale fisico"[98].

In effetti, Georgescu-Roegen si vede costretto a insistere sulla evidente circostanza dell'incidenza della degradazione della materia sul processo economico soprattutto a causa dell' ingiustificato ottimismo che vizia irrimediabilmente il pensiero dello *sviluppo sostenibile* come l'allettante prospettiva dello *stato stazionario*: si tratta di soluzioni dell'irreversibile crisi economica in atto più che mai insostenibili alla luce del cambiamento radicale avviato, nella storia economica, dall'ascesa del capitalismo, che ha innescato

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[94]N. Georgescu-Roegen, *Analisi energetica e valutazione economica*, in Id., *Bioeconomia*, cit., 142.

[95]Cfr. ivi, p. 150; e anche Id., *Dogma energetico, economia energetica e tecnologie vitali*, cit., p. 172.

[96]N. Georgescu-Roegen, *Bioeconomia e degradazione della materia. Il destino prometeico della tecnologia umana*, cit., p. 107.

[97]*Ibidem*.

[98]Ivi, p. 108.

un'accelerazione imprevedibile dei processi di produzione e consumo, un vero e proprio "strappo socio-ecologico", dovuto allo straordinario sviluppo economico dell'Occidente a seguito della rivoluzione "termo-industriale"[99]. Come comprende lucidamente lo stesso Georgescu-Roegen, "la tesi secondo la quale lo stato stazionario costituisce la nostra salvezza economica, così brillantemente sostenuta da Herman Daly[100], urta anche contro la quarta legge. La sua grande popolarità nei paesi occidentali è soprattutto dovuta al fatto che la gente dei paesi sviluppati, che presentemente si sentono minacciati dalla crisi dell'energia, desidererebbe mantenere per sempre il loro attuale livello di vita"[101]. Ma, come sottolinea Georgescu-Roegen, non pare sia stato mai affrontato sistematicamente il problema se un sistema chiuso, come quello della Terra, possa configurarsi come uno stato stabile[102], sebbene, in base a quanto ritiene il dogma energetico, un processo economico chiuso è *riproduttivo*, ovvero può fornire lavoro *meccanico* interno a un tasso costante, purché riceva dall'ambiente un flusso costante di energia[103]: si tratta di quel sistema che nella terminologia di Georgescu-Roegen integra gli estremi del cosiddetto *moto perpetuo di terzo tipo*, la cui esistenza sarebbe tut-

[99]Cfr. J. Grinevald, *Georgescu-Roegen, bioeconomia e biosfera*, cit., p. 69.

[100]Daly, famoso teorico dello "stato stazionario", che ha ricevuto grande considerazione nell'ambito del pensiero ecologico, è stato uno dei principali allievi di Georgescu-Roegen. Tuttavia, la posizione di Georgescu-Roegen è il risultato di una spregiudicata analisi della realtà economica, e un onesto realismo in merito rende improponibile qualunque comodo assestamento all'interno del paradigma dello sviluppo sostenibile. Questa considerazione chiarisce i termini della controversia fra Georgescu-Roegen e il suo allievo Herman Daly - sostenitore, appunto in una determinata fase del suo pensiero, del cosiddetto *steady state* - il quale, peraltro, tributa ampi riconoscimenti al lavoro di Georgescu-Roegen (cfr., per esempio, H. Daly, *Il contributo di Georgescu-Roegen all'economia: un saggio commemorativo*, in Id., *Oltre la crescita. L'economia dello sviluppo sostenibile* [1996], trad. di S. Dalmazzone e G. Garrone, Edizioni di Comunità, Torino 2001, p. 262). Nell'epistemologia evolutiva del pensatore rumeno, in cui l'unica costante è il cambiamento, la proposta di una economia statica, a crescita zero, come soluzione per rallentare il degrado entropico, è ovviamente inconcepibile, ulteriore frutto dell'infatuazione ottimista degli economisti. Cfr. in merito N. Georgescu-Roegen, *Quo vadis homo sapiens sapiens*?, cit., pp. 221-222.

[101]N. Georgescu-Roegen, *Bioeconomia e degradazione della materia. Il destino prometeico della tecnologia umana*, cit., pp. 110-111.

[102]Cfr. N. Georgescu-Roegen, *Lo stato stazionario e la salvezza ecologica*, in Id., *Bioeconomia*, cit., p. 105.

[103]Cfr. N. Georgescu-Roegen, *Analisi energetica e valutazione economica*, in Id. *Bioeconomia*, cit., p. 135.

tavia smentita dalla validità della quarta legge della termodinamica[104]. E, in realtà, al di là del fatto che non tutta l'energia può essere convertita in lavoro effettivo - in quanto bisogna tener conto dell'incidenza della dissipazione -, resta ancora da considerare il dato che ogni conversione energetica si appoggia su un supporto materiale: ciò significa che non si può, poi, astrarre dalla circostanza che l'attrito dissipa non solo energia, ma anche materia, per quanto ciò possa, in alcuni casi, avvenire in modo impercettibile. Preso atto di questa ulteriore circostanza, diventa allora necessario concludere che "non ci sono strutture materiali immutabili, perché la materia come l'energia si dissipa continuamente e irrevocabilmente"[105]. Questa evidente, per quanto paradossalmente contestata, verità, ancora una volta, conferma la facile intuizione che l'idea di riciclaggio completo sia un *pericoloso miraggio*, alimentato dagli ecologisti con la descrizione di "schemi deliziosi" su "come l'ossigeno, l'anidride carbonica, l'azoto e qualche altra sostanza chimica vitale sono riciclati da processi naturali mossi dall'energia solare"[106]. Ma, la verità, come rivela Georgescu-Roegen, è che "se queste spiegazioni sono accettabili, è perché la quantità delle sostanze chimiche in questione è talmente immensa che il deficit entropico diventa visibile solo su lunghi periodi"[107]. Ciò significa che il riciclaggio completo è impraticabile. A proposito della possibilità di recuperare tutte le molecole necessarie a ricostituire una lastra di rame egli dice: "Quest'operazione non sarebbe concettualmente impossibile, ma in termini entropici è il progetto più fallimentare che si potrebbe escogitare. È questo che i promotori del contrabbando di entropia non sono arrivati a capire" [108].

Non si può ingannare la legge di entropia, pertanto "le 'transazioni' tra il processo economico e l'ambiente devono necessariamente includere, anche in uno stato stazionario, una certa quantità di materia disponibile per compensare la materia che viene continuamente e irrevocabilmente dissipata"[109].

[104]Ivi, p. 136.

[105]N. Georgescu-Roegen, *Lo stato stazionario e la salvezza ecologica*, in Id., *Bioeconomia*, cit., p. 106.

[106]Ivi, p. 107.

[107] *Ibidem.*

[108] N. Georgescu-Roegen, *Prospettive e orientamenti in economia*, cit., p. 115.

[109]N. Georgescu-Roegen, *Analisi energetica e valutazione economica*, in Id. *Bioeconomia*, cit., p. 150.

Indubbiamente l'enunciazione di questa cosiddetta quarta legge della termodinamica ha innescato una controversia inesauribile[110]. A ben vedere, in sostanza, questa polemica corre il rischio di assumere, a tratti, dal punto di vista pratico, un profilo lezioso. Anche perché, oltretutto, "viene attaccato il voler assurgere a legge una condizione di fatto, l'impossibilità attuale dell'uomo di recuperare completamente la materia che utilizza. Non viene però messo in discussione il ruolo critico che questa incapacità può avere sul nostro sviluppo futuro"[111].

In sintesi, i termini della questione possono essere riassunti come segue.

Secondo Georgescu-Roegen è palese che in un sistema chiuso anche l'entropia della materia, oltre che quella dell'energia, deve tendere verso un massimo. Tuttavia, sebbene la degradazione della materia resti una verità di fatto incontestabile, molti pensatori, tra cui discepoli[112] dello stesso Georgescu-Roegen, ma anche chimici e fisici[113], ritengono che questa circostanza non possa essere stigmatizzata attraverso il rigore formale di una legge fisica. Cioè, in breve, se la degradazione della materia resta, in pratica, un dato inconfutabile, la irreversibilità di tale degradazione non è una acquisizione teorica certa e dimostrata. Infatti, sebbene secondo Georgescu-Roegen sia impossibile recuperare completamente la materia dispersa nell'ambito di un

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[110] Come scrive Molesti, "si è discusso a lungo se tale enunciato possa, per così dire, essere elevato al rango di legge scientifica. I fisici, in generale, non si sono mostrati entusiasti nel considerare l'asserzione di Georgescu-Roegen come una possibile quarta legge della termodinamica: in ogni caso, si possa o non si possa parlare di una quarta legge della termodinamica, il problema che pone l'Autore è un problema reale. Oltre all'energia anche la materia si degrada: il riciclaggio completo non è possibile, anche ammesso che si disponga di energia a sufficienza. Gli elementi di cui l'uomo può avvalersi subiscono un'usura progressiva, perciò anche il voler mantenere uno stato stazionario, potrebbe rivelarsi, nel lungo periodo, un'utopia. Il poter continuare a coltivare due spighe di grano dove ne nascevano altrettante sarebbe già un miracolo. Che sia accettabile o meno la cosiddetta quarta legge della termodinamica, il problema che ci sta davanti è, in ogni caso, un problema da cui non si può prescindere, al di là dei meri nominalismi" (R. Molesti, *La rivoluzione della scienza e la bioeconomia*, in Id., *I fondamenti della bioeconomia. La nuova economia ecologica,* prefazione di N. Georgescu-Roegen, Franco Angeli, Milano 2006, p. 235).

[111] S. Zamberlan, *Economia e biologia, la teoria bioeconomica di Nicholas Georgescu-Roegen*, cit., p. 83.

[112] Il riferimento è in particolare a K. Mayumi, che contesta la quarta legge in via teorica, ma anche a H. Daly, il cui *steady state* è con essa praticamente incompatibile. Su ciò cfr. ancora M. Bonaiuti, *La teoria bioeconomica*, cit. e S. Zamberlan, *Economia e biologia, la teoria bioeconomica di Nicholas Georgescu-Roegen*, cit.

[113] Cfr. in proposito E. Tiezzi, *Fermare il tempo. Un'interpretazione estetico-scientifica della natura,* prefazione di Ilya Prigogine, Cortina, Milano 1996, pp. 59 ss.

lavoro meccanico o in conseguenza di una frizione, indipendentemente dalla quantità di energia e di lavoro spesi nel tentativo di recupero, secondo Tiezzi, per esempio, la fotosintesi (recupero selettivo di molecole di anidride carbonica disperse nell'atmosfera da parte delle piante verdi per mezzo dell'energia solare) mostra il contrario. Ovvero, il riciclaggio della materia è completamente possibile con una sufficiente quantità di energia disponibile. E, un'operazione di tal tipo, secondo alcuni, potrebbe presto essere resa verosimile dai nuovi orizzonti raggiunti dal progresso tecnico. Pertanto, la razionalità economica e un adeguato sistema di prezzi sono gli strumenti idonei per risolvere qualunque problema ecologico. In altri termini, la quarta legge della termodinamica sarebbe ridotta a un'estrapolazione dal contesto del secondo principio, in quanto un riciclaggio completo sarebbe realizzabile a patto di avere la disponibilità di una sufficiente quantità di energia, e sempre a costo di un cospicuo aumento dell'entropia dell'ambiente circostante.

Resta, tuttavia, il fatto che lo stesso Georgescu-Roegen, in realtà, non nega affatto che sia realmente possibile raccogliere le perle di una collana spezzata, ma sostiene pure che l'operazione diventa assai più dispendiosa se esse sono disperse per la città di Roma intera, o se, addirittura, sono state dissolte nell'acido, nel qual caso occorrerebbe, anche disponendo di tutta l'energia necessaria, un tempo pressoché illimitato. Cioè, secondo lui, nulla osta alla ricomposizione di una struttura materiale parziale, purché si disponga di sufficiente energia libera (e di un tempo infinito, anche!). Per cui, a suo parere, la verità è, piuttosto, che la legge dell'entropia non distinguerebbe, in tal senso, tra materia ed energia.

Quindi, in conclusione, per Georgescu-Roegen, in presenza di elementi e processi ad alta dissipazione, come nel caso dell'usura per attrito delle molecole di una moneta o di quelle della gomma degli pneumatici, il riciclaggio è praticamente improponibile.

Ma vale la pena seguire direttamente dai testi di Georgescu-Roegen, sia pur brevemente, i termini in cui si articola la questione.

Si tratta di una controversia che ha coinvolto numerosi interlocutori appartenenti a diverse discipline, tra cui, come si è accennato, anche un fisico come Tiezzi, il quale afferma: "Georgescu-Roegen assume l'esistenza di un'entropia della materia che tende verso un massimo (massimo disordine e miscelazione di materia) in modo tale che, alla fine, tutta la materia non è più disponibile. Il suo enunciato stabilisce che è impossibile recuperare completamente la materia coinvolta nella produzione di lavoro meccanico o dispersa a causa di frizione, indipendentemente dalle quantità di energia e materia spese per il recupero. Ma *la fotosintesi mostra il contrario*: recupero selettivo di molecole di anidride carbonica disperse nell'atmosfera da parte delle piante verdi per mezzo dell'energia solare. Oppure: recupero dell'azoto disperso da parte dei batteri fissatori nelle radici delle leguminose. E ancora: recupero della limatura di ferro dispersa tramite energia elettromagnetica. La 'legge' di Georgescu-Roegen è tutta dentro il contesto del secondo principio! Il punto è che per recuperare il materiale disperso è necessario un passaggio da forme ordinate di energia (meccanica, elettromagnetica, chimica) a forme meno ordinate (calore). La gomma consumata dei copertoni o il metallo disperso per frizione delle monete potrebbero essere recuperati solo a costo di un grande aumento di entropia dell'ambiente circostante (e di un'enorme spesa economica). In altri termini, il riciclaggio completo della materia è fisicamente possibile se una sufficiente quantità di energia è disponibile! Il problema è che tale spreco di energia porterebbe a un tremendo aumento di entropia della biosfera, certamente non sostenibile"[114]. E, d'altra parte, Georgescu-Roegen è innegabilmente consapevole della plausibilità di una simile ipotesi teorica. Egli scrive: "Si potrebbe sostenere, pensando all'interpretazione statistica della termodinamica[115], che è sicuramente possibile riunire le perle di una collana spezzata. Il riciclaggio non è per l'appunto un'operazione di

[114]Ivi, p. 61.

[115]Il riferimento è qui al tentativo del fisico austriaco Ludwig Boltzmann di "spiegare i fenomeni irreversibili fondendo il determinismo perfetto delle leggi reversibili della meccanica di Newton con la probabilità. Questa costruzione ibrida è di interesse cruciale per gli economisti: sostenendo che la rigenerazione dell'energia non disponibile è molto *improbabile* ma non *impossibile*, i fautori della teoria probabilistica inducono a credere che sia possibile barare al gioco entropico […] È spiacevole quindi che non tutti i fisici sappiano che la costruzione di Boltzmann è stata criticata in modo irrefutabile da alcuni dei più grandi fra i loro colleghi […]. Ancora peggiore è il fatto che non sappiano che pionieristici contributi di Ilya Prigogine hanno dimostrato che la 'teoria meccanica di Boltzmann sull'evoluzione della materia si basa su argomenti intuitivi e che quanto sostiene non è stato mai stato realizzato, nonostante frequenti affermazioni in senso contrario'[…]. Solo chi non è andato oltre Boltzmann può sostenere […] che la legge dell'entropia non pone ostacoli a una crescita economica infinita" (N. Georgescu-Roegen, *Analisi energetica e valutazione economica*, p. 139, nota 14). Con il fisico Ludwig Boltzmann, in effetti, la termodinamica diventa una meccanica statistica, in quanto viene posta su basi newtoniane: il comportamento dei sistemi meccanici complessi viene affrontato col ricorso al concetto di probabilità e può essere spiegato nei termini di leggi statistiche. In tale costruzione l'entropia viene definita come una misura del grado del disordine. I tentativi, inaugurati da Boltzmann, di ridurre la legge di entropia all'interno della meccanica statistica sono un vistoso sintomo della dittatura intellettuale ancora esercitata dal paradigma meccanicistico. Su ciò si veda F. Capra, *La rete della vita*, cit., p. 210. Cfr., ad esempio, L. Boltzmann, *Modelli matematici, fisica e filosofia* [1905], a cura di C. Cercignani, trad. di A. Cercignani, Bollati Boringhieri, Torino 1999.

questo tipo? Per scoprire l'errore che nasce estrapolando da una scala all'altra, supponiamo che quelle stesse perle siano state prima dissolte in qualche acido e che la soluzione sia dispersa negli oceani – esperimento che riproduce quel che accade effettivamente alle diverse sostanze minerali, le une dopo le altre. Anche disponendo di tutta l'energia che vogliamo, avremmo bisogno di un tempo fantasticamente lungo e pressoché infinito per rimettere insieme le perle. Questa conclusione ricorda uno degli insegnamenti che figurano nella parte introduttiva di tutti i manuali di termodinamica: tutti i processi che si svolgono a una velocità infinitamente piccola sono reversibili, perché in tali condizioni l'attrito è pressoché nullo. Tuttavia, un simile movimento richiede un tempo praticamente infinito. È questa in effetti, scientificamente parlando, la ragione per cui nella realtà i processi reversibili non sono possibili. Ed è anche la vera ragione per cui la materia non può essere completamente riciclata"[116]. Un simile passaggio si trova in *Bioeconomia e degradazione della materia*, dove egli scrive: "Immaginiamoci che una collana si rompa e che le sue perle si spandano in una stanza. Si potrebbero certamente raccogliere tutte in un lasso di tempo relativamente breve se si è sufficientemente pazienti. Ma se si rompe in qualche parte di Roma durante la visita alla città, la stessa operazione è quasi impossibile. Non solo ciò prenderà un tempo quasi infinito, ma in più un certo numero di oggetti dovranno essere utilizzati a questo fine e questi si usureranno a loro turno e conseguentemente dovranno essere ricostituiti se si vuole che il riciclaggio sia completo"[117].

Il profilo squisitamente teorico di questa sottile discussione è ulteriormente confermato dalle parole dello stesso Tiezzi, quando, ammettendo, in qualche modo, la natura del tutto fantastica dell'ipotesi del riciclaggio totale, dichiara: "In fondo, Nicholas Georgescu-Roegen (ma *non* la sua quarta legge) ha ragione"[118].

Ma una completa onestà intellettuale impone un' ultima incursione in merito nel pensiero di Georgescu-Roegen, la cui analisi risulta puntuale nel suo assoluto realismo. Egli commenta: "Poiché la materia, quanto l'energia, è sot-

[116] N. Georgescu-Roegen, *Lo stato stazionario e la salvezza ecologica*, in Id., *Bioeconomia*, cit., p. 107.

[117] N. Georgescu-Roegen, *Bioeconomia e degradazione della materia. Il destino prometeico della tecnologia umana*, in R. Molesti (a cura di), *Economia dell'ambiente e bioeconomia*, cit., p. 104. Sullo stesso tema si veda anche N. Georgescu-Roegen, *Analisi energetica e valutazione economica*, in Id., *Bioeconomia*, cit., p. 145.

[118] E. Tiezzi, *Fermare il tempo. Un'interpretazione estetico-scientifica della natura*, cit., p. 61.

toposta alla degradazione entropica, dovrebbe esserci una formula generale per l'energia della materia analoga a quella che si applica all'energia. Attualmente l'accertamento di una simile formula sembra al di fuori di ogni possibilità. L'ostacolo è la differenza fondamentale tra l'energia e la materia. L'energia è una 'sostanza' omogenea che può sempre essere convertita da una forma in un'altra. Per esempio l'elettricità può trasformarsi in calore, il calore in lavoro, il lavoro in calore e così di seguito. La materia macroscopica, al contrario, è profondamente eterogenea, ogni elemento, ogni sostanza ha il suo proprio carattere"[119].

La conseguenza ineluttabile di questa analisi è che, in un sistema chiuso, secondo la quarta legge della termodinamica, l'entropia della materia deve tendere verso un massimo[120].

L'idea promossa dagli economisti ortodossi è, in effetti, che il progresso tecnologico costituisca la risorsa sufficiente a spostare indefinitamente in avanti la frontiera della produzione, in quanto, mediante la cosiddetta *dematerializzazione del capitale* si configurerà la reale possibilità di produrre sempre più beni con progressivo minor dispendio di materia ed energia, grazie al fenomeno su cui si fonda la *new economy*[121]: essa preconizza un'economia

[119]N. Georgescu-Roegen, *Bioeconomia e degradazione della materia. Il destino prometeico della tecnologia umana*, cit., p. 108. In merito, si vedano anche M. Bonaiuti, *La teoria bioeconomica*, cit., p. 103 e G. C. Dragàn - M. C. Demetrescu, *Entropia e bioeconomia*. *Il nuovo paradigma di Nicholas Georgescu-Roegen*, Nagard, Milano 1996, pp. 123-124. In *Analisi energetica e valutazione economica*, Georgescu-Roegen scrive anche: "Nel processo economico non si considera la massa in quanto tale, ma la materia in blocco (e naturalmente l'energia), e il problema è che, a differenza della massa e dell'energia, la materia costituisce una categoria assai eterogenea: quasi tutti gli elementi chimici hanno perlomeno una proprietà che li caratterizza completamente e quindi li rende indispensabili in certe applicazioni tecniche. Ci si deve quindi aspettare che, a differenza della teoria generale dell'energia (termodinamica), lo studio delle trasformazioni della materia aggregata sia complicato, come abbiamo visto sopra per il caso dell'attrito. È piuttosto semplice capire come l'energia si degradi, con la dissipazione del calore dai corpi più caldi ai più freddi di un sistema, diventando sempre meno disponibile per una conversione in lavoro meccanico" (N. Georgescu-Roegen, *Analisi energetica e valutazione economica*, in Id., *Bioeconomia*, cit., p. 143).

[120]Cfr. N. Georgescu-Roegen, *Lo stato stazionario e la salvezza ecologica*, in Id., *Bioeconomia*, cit., p. 110.

[121] Questa corrente di pensiero, che si sviluppa negli anni Novanta, si basa sull'ipotesi di un mercato globale che sfrutta le nuove tecnologie informatiche e telematiche e ha prevalentemente come punto chiave i beni immateriali. Si veda, in proposito, per un approccio anche critico, J. Rifkin, *L'età dell'accesso. La rivoluzione della new economy* [2000], trad. di P. Canton, Mondadori, Milano 2009. Si veda anche F. Capra, *La scienza della vita. Le connessioni nascoste fra la natura e gli esseri viventi*, [2002], trad. di D. Didero, Rizzoli, Milano 2004, pp. 206 ss.

leggera, a basso impatto ambientale, in cui il capitale naturale può essere sostanzialmente sostituito dal capitale umano[122].

In breve, ci si entusiasma all'idea che il progresso tecnologico, conquistando una maggiore efficienza nello sfruttamento delle risorse, possa integralmente sostenere e abbattere il peso dell'impatto ambientale: ma, ancora una volta, ci si affida a una prospettiva geneticamente viziata da riduzionismo e determinismo. Infatti, nonostante le ottimistiche aspettative, se si accede a una visione sistemica, in cui si valuta l'interazione tra impatto sull'ecosistema, produzione-consumo e progresso tecnologico, si perviene alla costatazione del sorprendente risultato di un aumento del complessivo consumo energetico parallelamente alla superiore efficienza conquistata dall'evoluzione della tecnica. In quanto, in realtà, non solo la maggiore accessibilità economica e il miglioramento delle prestazioni garantite dal progresso tecnologico, sollecitano, piuttosto che inibire, il maggiore consumo dei prodotti - dall'automobile al rasoio elettrico -, con conseguente aumento del dispendio energetico; ma, inoltre, la manutenzione dell'enorme comples-

[122]Ma, come spiega Bonaiuti, la teoria bioeconomica è appunto in grado di dimostrare la natura illusoria anche di questo ulteriore auto-inganno in cui trovano conforto gli economisti. Infatti, egli dice, "legato al fenomeno della degradazione della materia/energia è senz'altro il tema, sovente sbandierato dai fautori dell'ottimismo tecnologico, della *smaterializzazione del capitale.* In particolare, si sente spesso affermare che la *new economy,* basata sull'utilizzo sempre più diffuso delle nuove tecnologie, consentirà di sviluppare un'economia leggera, caratterizzata da consumi sempre minori di risorse e da minore inquinamento. La teoria bioeconomica, tuttavia, presenta significative obiezioni su questo punto. In particolare, utilizzando il modello *flussi/fondi* elaborato da Georgescu-Roegen, è possibile mostrare come i beni prodotti dalla *new economy* necessitino di significativi apporti di capitale. Tale capitale, per essere mantenuto in condizioni di 'efficienza costante', richiede quantità crescenti di input di risorse naturali ed energia. Questo spiega come mai, mentre l'impiego di risorse per *unità di prodotto* è effettivamente diminuito negli ultimi anni [dati OCSE], i consumi *assoluti* delle risorse chiave continuino invece ad aumentare (energia in testa). La teoria bioeconomica consente dunque di comprendere a fondo per quali ragioni il miraggio di un'economia leggera e pulita, che sembra effettivamente realizzarsi per alcuni settori delle economie avanzate, non sia estensibile ad altri settori e tantomeno ai paesi meno avanzati"(M. Bonaiuti, *La teoria bioeconomica. La "nuova economia" di Nicholas Georgescu-Roegen*, cit., p. 13). Il modello *flussi/fondi* è stato elaborato da Georgescu-Roegen all'interno della sua riflessione sulla teoria della produzione. Cfr., in particolare, N. Georgescu-Roegen, *The Entropy law and the Economic Process*, cit., cap. IX; Id., *Analisi energetica e valutazione economica*, cit.; Id., *Ricette fattibili contro tecnologie vitali*, cit.; Id., *Processo agricolo e processo industriale: un problema di sviluppo bilanciato*, cit. Si vedano anche M. Bonaiuti, *La teoria bioeconomica*, cit., pp. 108 ss. e Id., *Introduzione*, in N. Georgescu-Roegen, *Bioeconomia*, cit., pp. 35 ss.; R. Molesti, *Ambiente e produzione: il modello a fondi e flussi*, in Id., *I fondamenti della bioeconomia. La nuova economia ecologica,* cit., pp. 195 ss., p. 196. Cfr. anche D. Donato, *I fisici della Grande Vienna. Boltzmann Mach Schrödinger*, Le Lettere, Firenze 2011.

so di strutture materiali e prestazioni intellettuali, necessario ad alimentare la nuova tecnologia, incide in misura imprevedibilmente elevata sul consumo energetico: è evidente, infatti, che un professionista a elevata specializzazione è il risultato di un investimento assai più consistente rispetto a quello destinato a un semplice operaio.

A questo punto sembra evidente come il pensiero di Georgescu-Roegen si riveli dirimente in merito alla possibilità di coltivare una fiducia indiscriminata nel progresso tecnologico come via di uscita dalla crisi economica, ambientale ed energetica. Infatti, come si è tentato di dimostrare, allo stato attuale delle conoscenze umane, non si può contare sulla possibilità di un riciclaggio totale, né sull'ipotesi che strumenti tecnologici più efficienti garantiscano una maggior produzione di manufatti riducendo l'output di rifiuti: "Macchine più efficienti", ricorda infatti Georgescu-Roegen, "hanno bisogno di quantitativi maggiori di energia e di materia per completare il processo produttivo"[123].

Tutto ciò considerato, allora, sembra il momento di affrancare la scienza economica dalla miopia che la affligge consegnandola direttamente all' illusione di concilianti prospettive, in quanto "i progressi tecnologici troppo vantati e propagandati nella nostra epoca non dovrebbero renderci ciechi. Dal punto di vista dell'economia delle risorse terrestri - base del modo di vita industriale dell'umanità - la maggior parte delle innovazioni rappresenta uno spreco di bassa entropia. In proposito, che i rasoi siano gettati tutti interi quando la loro lama ha perso il filo o che montagne di fotocopie siano buttate senza essere nemmeno degnate di uno sguardo, è poca cosa rispetto alla meccanizzazione dell'agricoltura e al ricorso alla 'rivoluzione verde'. Automobili, vetture per il golf, falciatrici ecc. 'più grandi e migliori' significano necessariamente un inquinamento e un esaurimento delle risorse 'più grandi e migliori'"[124].

Georgescu-Roegen con il paradigma bioeconomico, allora, intende offrire un'interpretazione del processo economico più aderente alla realtà sotto due profili fondamentali e interdipendenti: la considerazione dell'ineluttabile interferenza delle leggi naturali nell'economia, in quanto processo integrato nel più ampio metabolismo terrestre, e la conseguente percezione dell'impossibilità di uscire dalla crisi facendo affidamento sull'aspettativa che con una quantità sufficiente di energia si possa compiere lavoro all'infinito.

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[123]N. Georgescu-Roegen, *Ricette fattibili contro tecnologie vitali,* cit., p. 207.

[124]N. Georgescu-Roegen, *Lo stato stazionario e la salvezza ecologica*, in Id., *Bioeconomia*, cit., pp. 111-112.

La lucidità con cui Georgescu-Roegen affronta l'analisi delle dinamiche economiche dischiude, pertanto, una diversa prospettiva, dalla quale è possibile affacciarsi sull'inevitabile crisi ecologica: occorre, in definitiva, abbandonare il mito dell'onnipotenza della tecnologia e decolonizzare il nostro immaginario per riportare l'economia al suo giusto posto nella scala dei valori comuni.

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Article

The Influence of Thermodynamic Ideas on Ecological Economics: An Interdisciplinary Critique

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Abstract: The influence of thermodynamics on the emerging transdisciplinary field of 'ecological economics' is critically reviewed from an interdisciplinary perspective. It is viewed through the lens provided by the 'bioeconomist' Nicholas Georgescu-Roegen (1906–1994) and his advocacy of 'the Entropy Law' as a determinant of economic scarcity. It is argued that exergy is a more easily understood thermodynamic property than is entropy to represent irreversibilities in complex systems, and that the behaviour of energy and matter are not equally mirrored by thermodynamic laws. Thermodynamic insights as typically employed in ecological economics are simply analogues or metaphors of reality. They should therefore be empirically tested against the real world.

Keywords: thermodynamic analysis; energy; entropy; exergy; ecological economics; environmental economics; exergoeconomics; complexity; natural capital; sustainability

"A theory is the more impressive, the greater the simplicity of its premises is, the more different kinds of things it relates, and the more extended is its area of applicability. Therefore the deep impression that classical thermodynamics made upon me. It is the only physical theory of universal content that, within the framework of applicability of its basic concepts, it will never be overthrown."

Albert Einstein, "Autobiographical Notes", 1949

"What do you know of the Second Law of Thermodynamics? ... This law is one of the greatest depth and generality: it has its own sombre beauty: like all the major scientific laws, it evokes reverence. There is, of course, no value in a non-scientist just knowing it by the rubric in an encyclopaedia. It needs understanding, which can't be attained unless one has learnt some of the language of physics."

C P Snow, "The Two Cultures: A Second Look", 1964

"An orthodox economist ... would say that what goes into the economic process represents valuable natural resources and what is thrown out of it is valueless waste. But this qualitative difference is confirmed, albeit in different terms, by a particular (and peculiar) branch of physics known as thermodynamics. From the viewpoint of thermodynamics, matter-energy enters the economic process in a state of low entropy and comes out of it in a state of high entropy."

Nicholas Georgescu-Roegen, "The Entropy Law and the Economic Process", 1971

1. Background

1.1. Introduction

Thermodynamic concepts or laws underpin the operation of energy systems that heat and power human development. Their scientific 'beauty', depth and generality (identified by C P Snow [1]) has inspired engineers and physical scientists over the last two centuries, including some of the very greatest, such as Albert Einstein. In the modern era, thermodynamic methods provide an important means of identifying process improvement potential, although heuristic developments have arisen in the past without the aid of science; as in the case of Watt's steam engine (which predated the development of the formal 'Laws of Thermodynamics' [2]). They utilise concepts like 'enthalpy' to represent the quantity of energy consumed, as well as 'exergy' to reflect its quality. But the related Second Law concept of entropy (an extensive property of matter) is not easy to grasp, particularly when it has been so widely used and abused. It was originally postulated by Rudolf Clausius (circa. 1864) via an analysis of the Carnot cycle for an ideal heat engine. This original 'energetic' (Clausius) entropy reflects the fact that, although heat can flow down a temperature gradient unaided, shaft work or an electrical energy input is required in order to induce heat transfer to take place from a cold to a hot reservoir: Clausius' inequality. However, idea of entropy has fascinated writers in disciplines far removed from engineering and the physical sciences.

Perhaps the first discipline outside engineering to seriously adopt thermodynamic ideas was economics; actually the sub-set that has become known as environmental economics [3,4]. The system studied in economics is the individual firm or the consumer. Transactions between the firm (or consumer) and the rest of the world are described in terms of the quantities and prices of the commodities exchanged. Prices in this neoclassical economic model are supposed to reflect the 'value' that society places on an economic good. Thus, economic practitioners claim that their discipline is 'normative': it suggests the optimal course of action to be taken in the allocation of resources, whereas thermodynamic analysis is 'descriptive'. However, environmental economists have employed thermodynamic ideas to devise alternative accounts of sustainability by analogy to physical or natural processes, such as energy usage. There is a well-developed literature, dating back to the early 1970s, that amounts to the postulation of an 'Energy Theory of Value' [5], although this has been largely rejected because choices about (First Law) energy use do not reflect the full complexity of human behaviour and value judgements. However, it was soon recognised that it is Second Law properties, such as entropy (and, by coupling with the First Law, exergy), which more realistically reflect dissipative processes. Nicholas Georgescu-Roegen (1906–1994), who in the latter part of his career regarded himself as a 'bioeconomist', was at the forefront of this movement with his advocacy of 'the Entropy Law' (his favoured expression for the Second Law of Thermodynamics; see Georgescu-Roegen [6]) as a measure of economic scarcity. Tribute is paid here to his contributions to the study of energy-matter as part of the economic process, although rather different conclusions are drawn about the utilisation of thermodynamic ideas in an attempt to understand natural resource scarcity and substitutability.

1.2. The Issues Considered

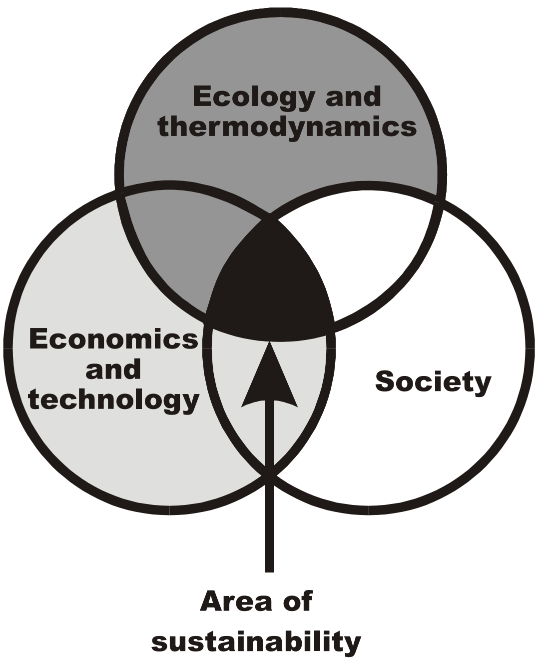
Thermodynamic concepts have been utilised by practitioners in a variety of disciplines with interests in environmental sustainability, including ecology, economics and engineering. It has been argued that resource depletion and environmental degradation are reflected in thermodynamic parameters and methods of analysis. But outside the realm of energy systems, thermodynamic concepts are typically employed by way of analogy [3], or as a metaphor [5]. Some resource economists, including Georgescu-Roegen [6], have viewed economic systems as ones in which energy is conserved, but in which entropy increases or exergy degrades. More recently, engineers in Europe and North America have proposed the coupling of exergy analysis with financial cost accounting; yielding the so-called 'exergoeconomic' approach. However, Hammond and Winnett [3] have recently cast doubt on such methods, which attempt to merge schema that may in large measure be incompatible—trying to mix 'chalk and cheese'. In this context, the influence of thermodynamic ideas on the development of the emerging, transdisciplinary field of 'ecological economics' will be critically reviewed from an interdisciplinary perspective.

2. Science and Sustainability in a Complex World

Over a period of some 15–20 years, the international community has been grappling with the task of defining the concept of 'sustainable development'. It came to particular prominence as a result of the so-called Brundtland Report published in 1987 under the title "Our Common Future"; the outcome of four years of study and debate by the World Commission on Environment and Development [7] led by the former Prime Minister of Norway, Gro Harlem Brundtland. This Commission argued that the time had come to couple economy and ecology, so that the wider community would take responsibility for both the causes and the consequences of environmental damage. It thereby attempts to balance economic and social development with environmental protection (encapsulated in the 'strapline' for the 2002 Johannesburg World Summit on Sustainable Development of "people, planet, prosperity"); the so-called 'triple bottom line' [8], or what others term 'The Three Pillars'. Many writers and researchers have acknowledged that the concept of 'sustainable development' is not one that can readily be grasped by the wider public (see, for example, Hammond [9]). However, no satisfactory alternative has thus far been found. Further confusion is added by the large number of formal definitions for sustainable development that can be found in the literature; Parkin [8] refers to more than two hundred.

The Brundtland Commission envisaged sustainable development as a means by which the global system would satisfy "the needs of the present without compromising the ability of future generations to meet their own needs" [7]. It therefore involves a strong element of intergenerational ethics; what John Gummer, former UK Secretary of State for the Environment (1993–1997), encapsulated in the popular phrase "don't cheat on your children" [8]. The interconnections between engineering constraints and the economic and social domain are illustrated by the sustainability Venn diagram shown in Figure 1 (Hammond [10]; adapted from a version originally developed by Clift [11] and extended by Parkin [8]). Here thermodynamic limits are represented as underpinning the environmental sphere. But the notion of sustainable development is not without its critics. Meredith Thring (Emeritus Professor of Mechanical Engineering at Queen Mary's College, London) regards the term as an oxymoron; arguing that development *per se* cannot be sustainable. He would prefer humanity to strive for a creative and stable world with the aid of 'equilibrium engineering' [12]. Similar views can be found in developing countries, where their debt burden and inequalities in global income distribution are seen as serious obstacles to sustainable development.

Figure 1. Venn diagram representation of 'The Three Pillars' of sustainability. Source: Hammond [10]; adapted from Clift [11] and Parkin [8].



Both Sara Parkin [8] and Jonathan Porritt [13], British environmental campaigners and now co-Directors of *Forum for the Future*, have recently stressed that sustainable development is only a process or journey towards a destination: 'sustainability'. This end-game cannot easily be defined from a scientific perspective, although Porritt [13] argues that the attainment of sustainability can be measured against a set of four 'system conditions'. He draws these from 'The Natural Step' (TNS); an initiative by the Swedish cancer specialist, Karl-Henrick Robèrt (see, for example, Broman *et al.* [14]). One of TNS system conditions, for example, suggests that finite materials (including fossil fuels) should not be extracted at a faster rate than they can be redeposited in the Earth's crust. This contrasts with the present rapid rate of fossil fuel depletion on the global scale: 20–40 years for oil, 40–70 years for natural gas, and 80–240 years for coal [9]. Such sustainability requirements would put severe constraints on economic development, are extremely difficult to achieve in engineering terms, and they may therefore be viewed as being impractical; or 'utopian' (see, for example, Hammond [10]). They certainly imply that the ultimate goal of sustainability is rather a long way off when compared with the present conditions on the planet. Parkin [8] suggests 2050–2100 or beyond.

3. Thermodynamics, Analogy and Metaphor

Practitioners in a variety of disciplines with interests in environmental sustainability, including ecology, economics and engineering, have drawn on thermodynamic concepts (as noted in Section 1.2 above). Widespread concern about resource depletion and environmental degradation are common to them all these areas of study. It has been argued that the deleterious consequences of human development are reflected in thermodynamic ideas and methods of analysis (see, for example, the early work of Mueller [15] at the US Goddard Space Flight Center); they are said to mirror energy transformations within society. Mueller [15] draws a parallel between the resource flows in economics and energy (as well as implicitly exergy) flows in thermodynamics. This led him to an, arguably rather dubious, analogy between the "technology of man" and heat engines. Such ideas have inspired Parkin [8] and others to believe that thermodynamic principles or laws may act as a guide for engineers in the quest for environmental sustainability. In the context of 'The Natural Step', energy and matter are seen as having a tendency to disperse. Entropy (a Second Law extensive property of thermodynamic systems; see Section 4.5 below for further discussion) is regarded as a measure of this dispersal in a closed or isolated system. The Earth is such a closed system in terms of matter, but an open one from the perspective of the incoming solar energy that drives living plants via photosynthesis. This underpins the notion of 'capital' and 'income' energy resources for the planet (such as fossil fuels and solar energy respectively), and is behind TNS system condition that relates to the conservation of materials and fossil fuels. Outside the realm of energy systems, thermodynamic concepts are typically employed in terms of an analogy with, or resemblance to, physical processes [10]. Alternatively, their use may be regarded as metaphorical (see Scott and Gough [16] and Mirowski [17]): being imaginatively, but not literally, applicable.

An interesting feature of the advocacy of 'The Natural Step' system conditions in the present context is the claim that they reflect thermodynamic limits. Broman *et al.* [14] and others suggest that TNS conditions address the tendency of energy and matter to spread spontaneously. They in turn view this as mirroring the Second Law of Thermodynamics or what they, in common with

Georgescu-Roegen [6], term 'The Entropy Law'. In reality, the latter property is what the distinguished American mechanical engineer Stephen J Kline (1922–1997) refers to as the 'vulgar' entropy; reflecting the generic, but vague or ill-defined, application of entropy to various kinds of disorder (see Kline [18], or the review of his book by Hammond [19]). The Natural Step, in effect, uses the Laws of Thermodynamics (according to Hammond [10]) only by way of a rather loose analogy, or as a metaphor. Indeed Upham [20] argues that TNS moves beyond (scientific and other) knowledge in signposting action for the business sector. He contends that it represents a political and ethical statement rather than any justifiable scientific consensus.

4. The Mathematical and Physical Framework Provided by the 'Laws of Thermodynamics'

4.1. Energy Analysis

The First Law of Thermodynamics is simply based on the principle of energy conservation, which in turn provides the foundations for 'energy analysis'. It may be represented for a steady-state process by the balance Equation [21]:

$$\sum (\mathrm{h} + \mathrm{ke} + \mathrm{pe})_{\mathrm{in}} \mathrm{m}_{\mathrm{in}} - \sum (\mathrm{h} + \mathrm{ke} + \mathrm{pe})_{\mathrm{out}} \mathrm{m}_{\mathrm{out}} + \sum \mathrm{Q} - \mathrm{W} = 0 \quad (1)$$

where $\mathrm{m_{in}}$ and $\mathrm{m_{out}}$ denote the mass flow across the system inlet and outlet respectively, Q represents the heat transfer across the system boundary, W is the work (including shaft work, electricity, and so on) transferred out of the system, and h, ke, and pe denote the specific values of enthalpy, kinetic energy, and potential energy respectively. This energy balance (represented schematically in Figure 2 [10]) can be simplified, assuming negligibly small changes in kinetic and potential energy and no heat or work transfers, to [21]:

$$\sum \mathrm{H}_{\mathrm{i,in}} = \sum \mathrm{H}_{\mathrm{j,out}} \quad (2)$$

where $\mathrm{H_{i.in}}$ represents the enthalpies of the various incoming flow streams for the system, and $\mathrm{H_{j,out}}$ the different enthalpies outputs. Enthalpy is an extensive property of matter, which represents the energy content of the flow stream (or 'energy carrier' in lay person's terms), defined by:

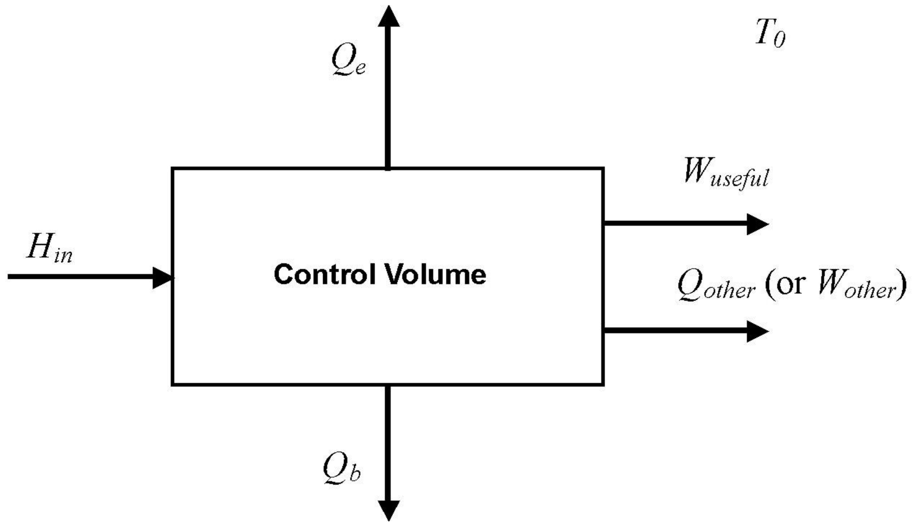
$$H_2 - H_1 = mc_p(T_2 - T_1) \quad (3)$$

where m is the mass flowrate of the stream, and c_p is the specific heat at constant pressure of the working fluid. The suffices 1 and 2 indicate the start and end conditions for the cycle or process. It can be seen that there is an almost direct connection between enthalpy and the experimental measurements needed to determine its value. The mathematical manipulations associated with these measurements involve only linear algebra. These characteristics, and nearness of enthalpy to the direct human experience of heat transfer, make it easy to accept that its value is worth knowing [22].

If all these energy inputs and outputs for a system are taken into account (whether or not all the outputs are actually 'useful') then the First Law energy efficiency becomes:

$$\eta = \sum \mathrm{E}_{\mathrm{j,out}} / \sum \mathrm{H}_{\mathrm{i,in}} = \mathrm{H}_{\mathrm{out}} / \mathrm{H}_{\mathrm{in}} = 1 \quad (4)$$

Figure 2. An energy balance for a simple control volume or unit operation. Source: Hammond [13]; upgraded.



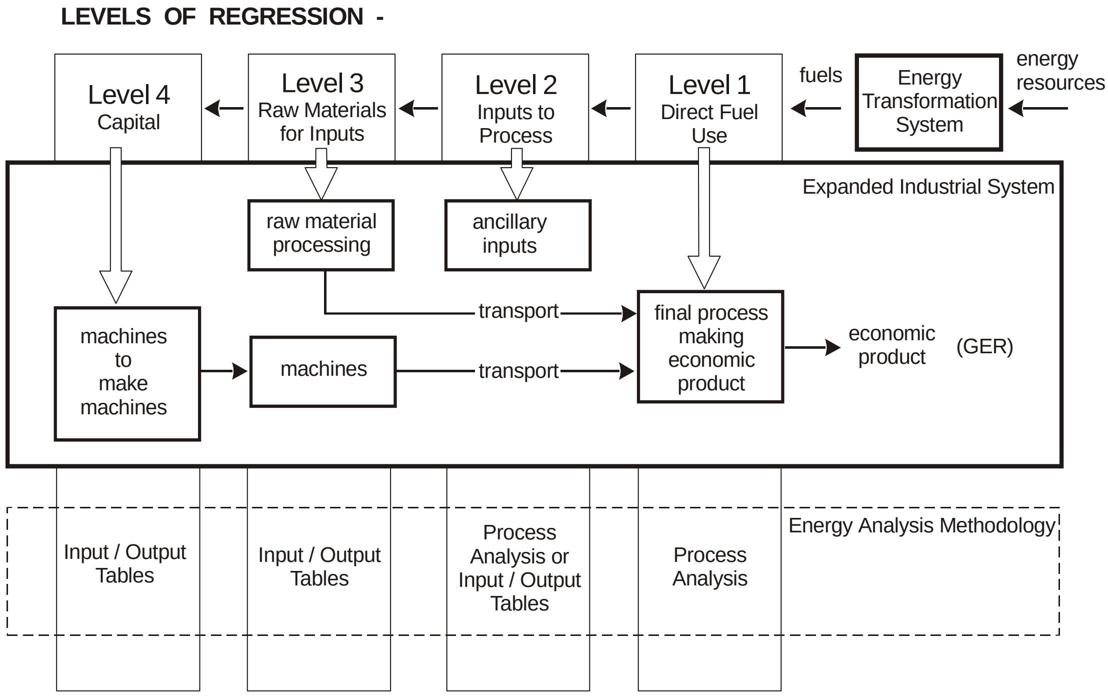
This is not a very helpful expression, as many of the energy output streams will be in the form of 'waste heat'. Excluding waste streams, then energy efficiency may be rewritten in more realistic terms as:

$$\eta = (H_{out})_{useful} / H_{in} < 1 \quad (5)$$

The First Law was the basis of a techniques developed in the mid-1970s that became known as 'energy analysis' [23]. In order to determine the primary energy inputs needed to produce a given amount of product or service, it is necessary to trace the flow of energy through the relevant industrial system. This involves the entire life-cycle of the product or activity from "cradle-to-grave". The system boundary for energy analysis should strictly encompass the energy resource in the ground (for example, oil in the well or coal at the mine), although this is often taken as the national boundary in practice [10,22,23]. Thus, the sum of all the outputs from this system multiplied by their individual energy requirements must be equal to the sum of inputs multiplied by their individual requirement.

This process consequently implies the identification of feedback loops, such as the indirect, or 'embodied', energy requirements for materials [24] and capital outputs. This procedure is illustrated schematically in Figure 3 [3], which was adapted from one given by Slesser [23]. Different 'levels of regression' may be employed, depending on the extent to which feedback loops are accounted for or the degree of accuracy wanted. There are several different methods of energy analysis; the principal ones being statistical analysis, input-output table analysis and process analysis [23,25]—again illustrated in Figure 3 [3]. The first method is limited by the available statistical data for the whole economy or a particular industry, as well as the level of its disaggregation. Statistical analysis often provides a reasonable estimate of the primary energy cost of products classified by industry. However, it cannot account for indirect energy requirements or distinguish between the different outputs from the same industry [3]. The technique of input-output table analysis, originally developed by economists [24], can also be utilised to determine indirect energy inputs and thereby to provide a much

Figure 3. Schematic representation of the energy analysis process. Source: Hammond [10]; adapted from Slesser [23].



better estimate of 'primary energy' use. This approach is constrained only by the level of disaggregation that is available in national input-output tables [24]. Process energy analysis is the most detailed of the methods, and is usually applied to a particular process or industry. It requires process flow-charting using conventions originally adopted by the International Federation of Institutes of Advanced Studies in 1974–1975 [23,25]. The application domains of these various methods overlap. They can be used to determine the least energy-intensive industrial process from amongst a number of alternative options.

4.2. The Foundations of Exergy Analysis

First Law or 'energy' analysis takes no account of the energy source in terms of its thermodynamic quality. It enables energy or heat losses to be estimated, but yields only limited information about the optimal conversion of energy. In contrast, the Second Law of Thermodynamics indicates that, whereas work input into a system can be fully converted to heat and internal energy (via dissipative processes), not all the heat input can be converted into useful work. [This Second Law 'asymmetry' also dictates that, although heat can flow down a temperature gradient unaided, shaft work or an electrical energy input is required in order for heat transfer to take place from a cold to a hot reservoir (as in the case of a heat pump)]. The Second Law therefore suggests the need for the definition of parameters that facilitate the assessment of the maximum amount of work achievable in a given system with different energy sources. 'Exergy' is the available energy for conversion from a donating source (or reservoir) with a reference to a specified datum, usually the ambient environmental conditions (typically 1 bar and 5–25 °C). This quantity or its close relatives have been given a variety of names in the literature, including availability, available energy, available work and essergy [21]. In a sense it represents the thermodynamic ‘quality’ of an energy carrier, and that of the waste heat or energy lost in the reject stream. Electricity, for instance, may be regarded as an energy carrier having a high quality, or exergy, because it can undertake work [10]. In contrast, low temperature hot water, although also an energy source, can only be used for heating purposes. This distinction between energy (strictly enthalpy) and exergy is very important when considering a switch, for example, from traditional internal combustion engines to electric, hybrid, or fuel cell vehicles. Thus, Hammond [3,10] has argued that it is important to employ exergy analysis alongside a traditional First Law energy analysis in order to illuminate these issues. It provides a basis for defining an exergy efficiency, and can identify exergetic ‘improvement potential’ within systems.

Exergy is lost or degraded in every irreversible process or system. Consequently an exergy budget on a control volume can be formulated in an analogous manner to the First Law energy balance, Equation (1), as [10,26]:

$$\sum \varepsilon_{in} m_{in} - \sum \varepsilon_{out} m_{out} + \sum \left(E^{Q} - E^{W}\right) - I = 0 \tag{6}$$

where E^Q and E^W denote the exergy transfer associated with Q and W respectively, I is the system exergy consumption or irreversibility, and ε represents the specific exergy. This exergy budget is represented schematically in Figure 4 [10]. Here heat transfer at a constant temperature (say T_p) the ‘thermal exergy’ is given by [21,26]:

$$E^Q = (1 - T_o/T_p)Q \tag{7}$$

Equation (6) can also be simplified like its First Law equivalent to yield [21]:

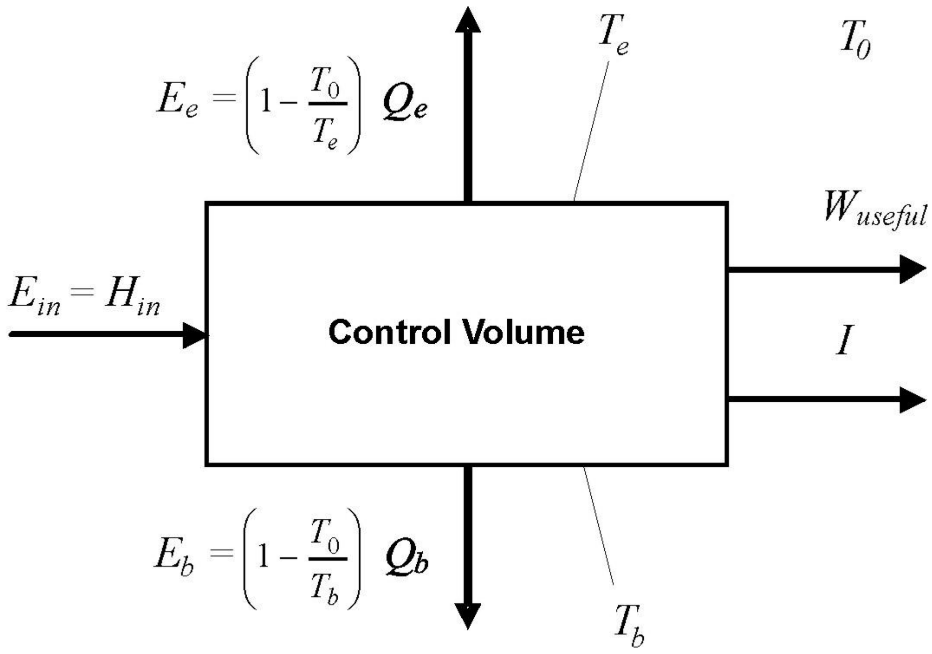
$$\sum E_{i,in} > \sum E_{j,out} \tag{8}$$

Thus, the exergy loss or irreversibility rate [27] of the system is given by:

$$I \equiv \Delta E_{lost} = E_{in} - E_{out} > 0 \tag{9}$$

Kline [18] argues that this ‘irreversibility’, perhaps better denoted by the term exergy ‘degradation' or ‘destruction’ [19], can be interpreted as the dissipated ‘available energy’ (or exergy) that ends up as random thermal fluctuations of the atoms and molecules in the exit flow of mechanical devices. He illustrates this process by way of examples drawn largely from the sort of rotating fluid machines with which he was most familiar (essentially kinetic energy converters). According to Kline [18] dissipated ‘available energy’ (or exergy) ends up, in the context of fluid flow, as random thermal fluctuations of the atoms and molecules. This implies that diffusion phenomena can only be understood as an interaction between processes at both the macroscopic and microscopic levels (see also Hammond [19]). In contrast, the detailed mechanisms involved in combustion processes are not well understood. Several studies have investigated the sources of irreversibility, or exergy destruction, resulting from such phenomena. They indicate that between about one quarter and one third of the useful exergy in the fuel (E_{in}) is destroyed during the combustion of fossil fuels [10]. Dunbar and Lior [28] identified three hypothetically distinct subprocesses: (i) combined diffusion/fuel oxidation, (ii) internal thermal energy exchange (or heat transfer), and (iii) the mixing process associated with the combustion products. They employed a simplified, ‘zonal’ computational model, which indicated that about three quarters of the exergy degradation was linked to heat conduction. In contrast, chemical reaction was found to be quite efficient; the exergy efficiency of this subprocess was typically 94%–97%.

Figure 4. An exergy budget for a simple control volume or unit operation. Source: Hammond [10]; upgraded.



The exergy function itself is another 'extensive' property [21,26], which is defined by reference to a "dead" or equilibrium state (in terms of temperature T_o, pressure P_o, and species component μ_{io}):

$$E = (H - H_o) - T_o(S - S_o) + \sum_i N_i(\mu_i - \mu_{io}) \quad (10)$$

where S denotes Clausius entropy and N_i is the number of moles of species i. Variations in species, or matter, concentration are therefore reflected in the last term on the right hand side. This is where material exchange appears in the thermodynamic domain. Hence, matter does not physically mirror the way in which energy transfer takes place. Such changes in species concentration are not usually significant in problems related to the macro-scale analysis of energy systems. Consequently, a truncated mathematical expression can be used to calculate 'physical' or 'thermomechanical' exergy states:

$$E = (H - H_o) - T_o(S - S_o) \quad (11)$$

The choice of the reference state has been the subject of some divergence of opinion in the literature. Many use the standard temperature and pressure (T_o = 298 K (25 °C) and P_o = 1 atm), whereas Wall [29] adopted 15 °C as the datum for his country study of Sweden. Nevertheless, a more common basis for heat load calculations in mainland Britain is to assume a winter outside design temperature of about −1 °C. This was the reference condition adopted by Hammond and Stapleton [21] for their exergy analysis of the UK energy system. It is the same as the "dead state" temperature adopted by Reistad [30] for exergy analysis of space heating in the USA.

4.3. The Exergy Method in Practice

An exergy efficiency, ψ, can be defined in much the same way as its energy counterpart [21]:

$$\psi = E_{out}/E_{in} = 1 - I/E_{in} < 1 \quad (12)$$

It should be noted that this expression is strictly analogous to Equation (4), rather than the practical First Law (energy) efficiency defined by Equation (5). Comparison with the former equation indicates that, in any real world system (which is irreversible) exergy is degraded and the exergy efficiency is consequently less than unity. Van Gool [27] has noted that the maximum improvement in the exergy efficiency for a process or system is obviously achieved when ΔE_{lost} is minimised; see Equation (9). Consequently, he suggested that it is useful to employ the concept of an exergetic 'improvement potential', IP, when analysing different processes or sectors of the economy. It is given by [27]:

$$IP = (1 - \psi)\,(E_{in} - E_{out}) \quad (13)$$

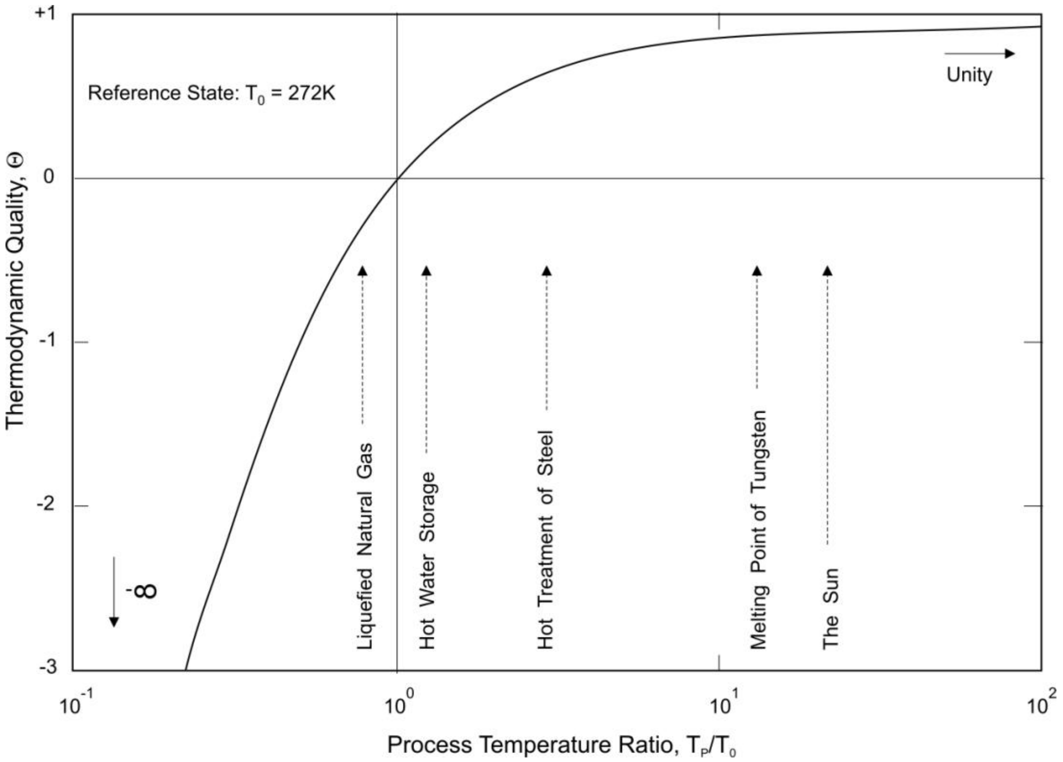
This expression was recently used, for example, by Hammond and Stapleton [21] to evaluate the improvement potential within critical elements of the UK economy.

Now, it was suggested above that exergy analysis provides an indication of the thermodynamic quality of an energy carrier. This was formally defined by van Gool [31] as the ratio of exergy to enthalpy in the flow:

$$\Theta \equiv \frac{E}{H} \quad (14)$$

Now, for electricity: Θ = 1 and for process heat: $\Theta = \left(1 - \frac{T_0}{T_p}\right)$(the derivation of which is explained by Hammond and Stapleton [21]; Reistad [30]; Rosen and Dincer [26]). Electricity is essentially a 'capital' resource that is normally generated in advanced, industrialised countries using either depleting fossil or nuclear fuels (see, for example, Hammond [32]). These latter sources may be contrasted with the renewable (or 'income') energy sources, such as solar energy and tidal, wave and wind power. In contrast to electricity (a high quality energy carrier with Θ = 1 as indicated above), low temperature hot water (Θ ≈ 0.2) can only be used for heating purposes. Hammond [10,33] recently devised a graphical representation of the variation in van Gool's thermodynamic quality (Θ) with the process temperature ratio (T_p/T_0): see Figure 5. This was produced using the environmental datum temperature adopted by Hammond and Stapleton [21] for their energy analysis of the UK: −1 °C (or T_0 = 272 K). They indicated that the exergy efficiency of various domestic heating appliances was quite sensitive to the choice of this reference temperature, when the process temperature is close to the selected environmental datum. However, both the exergy efficiency (Ψ) and the thermodynamic quality (Θ) are insensitive when plotted against the process temperature ratio; as depicted by Hammond [10] in Figure 5. Here a very wide variation in T_p/T_0 is displayed, and various heat sources are shown for comparison purposes. The associated process temperatures span the range from liquefied natural gas (LNG) at about −50 °C to the optical temperature of our Sun at around +5,500 °C.

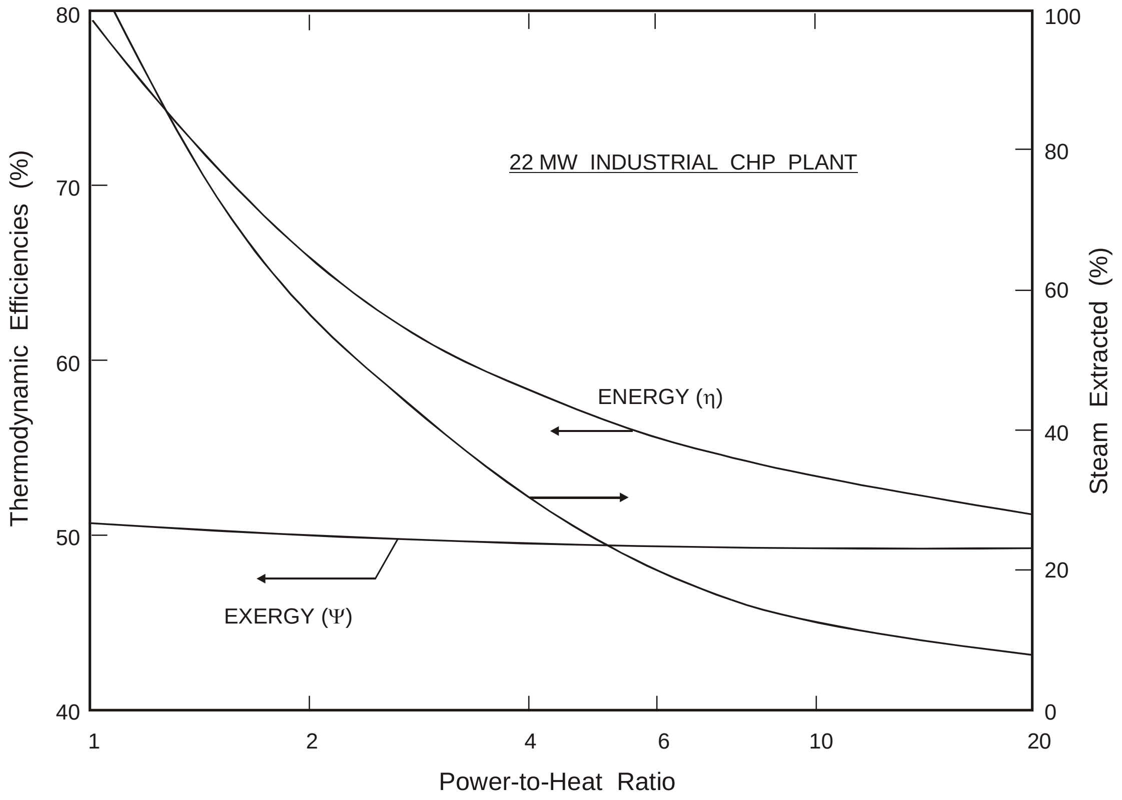
Figure 5. Temperature dependence of thermodynamic quality. Source: Hammond [10]; with a minor correction.



The use of the exergy method of analysis has grown rapidly since the mid-1970s, particularly for optimising individual energy conversion systems and process plant. Van Gool [34] used the example of a gas boiler plant for space heating, which is normally regarded as having quite a high energy efficiency, but is found to have a very low exergy efficiency. Another example is the identification of the true nature of losses in power plant. The major ‘energy’ losses arise in the condenser, whereas ‘exergy’ losses occur in the steam generator [30]. Losses in the condenser would suggest little prospect of improvement other than by way of a 'bottoming cycle'. However, exergy analysis indicates that the main improvement potential is associated with combustion processes and with heat exchangers. Making improvements at the ‘top end’ of the cycle will have the ‘knock-on’ benefit of also giving rise to higher First Law efficiencies [21]. The feasibility of such changes is arguably not as important as a proper comprehension of the thermodynamic processes involved [35].

Large energy losses occur during electricity generation unless used in conjunction with combined heat and power (CHP) systems. Thus, the only ways to improve the efficiency of the ‘energy transformation system’ significantly, in the absence of new large-scale hydropower sites, is either to restrict the use of electricity to power applications (and not for relatively low-temperature heating) or to adopt a greater proportion of CHP plants. Such schemes have an overall First Law efficiency (η) of some 80 per cent in contrast with the best recuperative CCGT plant of 59–61 per cent. The results of a recent Canadian parametric study by Bilgen [36] of a CHP cycle (or what the North Americans term a ‘cogeneration’ plant) are illustrated schematically in Figure 6 [10]. This study examined a nominal 22

Figure 6. Thermodynamic performance of combined heat and power plant. Source: Hammond [10]; adapted from Bilgen [36].



MW industrial turbine set manufactured in the USA, which typically operates on a power-to-heat ratio of 0.92. It can be seen from Figure 6 that the First Law (energy) efficiency falls sharply with power-to heat ratio and the proportion of process steam extracted. In contrast, the exergy efficiency (ψ) is insensitive to these parameters. This is because it reflects the *ability to perform work* and the efficiency of power generation only. However, CHP plants are obviously desirable on fossil fuel resource productivity grounds. It is therefore evident that this is a situation where exergy analysis on its own is insufficient, and needs to be used in parallel with energy analysis in order to reflect the interrelated constraints imposed by the First and Second Laws [10,35].

4.4. The Gibbs Free Energy

In the field of ecology, strictly the branch of the natural sciences that deals with the relation between biological organisms and their physical surrounding, the concept of Gibbs free energy or function (G) is used in preference to exergy [37]. It is defined mathematically as:

$$G = H - TS \tag{15}$$

The connection between this thermodynamic property and the physical (or thermomechanical) part of exergy can to seen by way of comparison of this expression with the truncated expression for exergy; Equation (9). Gibbs free energy is again the maximum work that is available from a natural or other system, but it is not determined by reference to the surrounding environmental conditions. The dead state temperature is effectively taken to be absolute zero (–273 °C). However, in many cases, it is the change in free energy (ΔG) that is significant to the problem being considered, and this is nearly the same as the corresponding change in physical exergy (ΔE)—Hammond [10] noted that they are identical when $T = T_o$. Exergy and Gibbs free energy therefore play a similar in thermodynamic analysis; they are simply alternative choices for most practical purposes.

4.5. Entropy

Dissipative processes in mechanical systems give rise to 'irreversibilities' (or exergy destruction). If a process or cycle, for example, involves either friction or heat transfer across a finite temperature difference, then they cannot be considered reversible. Chemical processes that involve a spontaneous change of material structure, density or phase are also irreversible. The 'energetic' or Clausius entropy is a Second Law extensive property that is a measure of such irreversibilities, and is defined as:

$$S_2 - S_1 = \int_1^2 \frac{dQ_R}{T} \qquad (16)$$

It can be seen that entropy is the integral quantity measured from some starting condition (1). Entropy rises whenever irreversible processes take place; as in all real world systems. It can be contrasted with nature of the First Law 'enthalpy' described in Section 4.1 above [22,38]. In order to determine entropy changes, there is a complicated experiment implied by Equation (16), as well as the need for mathematical manipulation. The experimental measurements needed to determine the heat exchange would need to be carried out under the ideal conditions of reversibility; a requirement that is almost impossible to satisfy. In addition, the numerical manipulation of the results of such an experiment would require relatively advanced mathematics (that is, integral calculus), and not the sort of elementary arithmetic needed to evaluate First Law enthalpy. Spalding and Cole [22] note that there is no 'physical picture' of entropy and that it is not obvious that it has an important role, for example, in engineering calculations. Furthermore, Hammond [13] and Hammond and Stapleton [21] have argued that enthalpy can be readily seen to represent the 'quantity' of energy required for the provision of a product or service, and that exergy reflects its corresponding 'quality'. Exergy is thus a more easily understood thermodynamic property than is entropy to represent system irreversibilities [38]. Its value falls (or degrades) in real world systems; in contrast to that for entropy.

It is apparent from the discussion above that the concept of entropy is not an easy concept to grasp, although it has been so widely used and abused [19,38]. Many analogous properties have been proposed. In addition to the energetic or Clausius entropy, Kline [18] identified five microscopic 'entropies' (including Gibbs' statistical entropy), two information functions (Shannon's and Brillouin's so-called 'entropies'), and what he amusingly denoted as the 'vulgar' entropy (see Hammond [19]). Kline [21] interprets Gibbs' statistical entropy as a useful measure of the "spread-outness" of random molecular fluctuations amongst various microstates within the constraints of the physical boundaries of a system. However, he criticises the attribution of the term 'entropy' to information functions as an error of typology; saying it is like equating "apples with oranges". These are not unique criticisms, and Kline points to earlier reservations by the likes of Denbigh, Fast, Pierce, and Popper [18,19].

5. From Classical to Ecological Economics

5.1. The Limits to Micro-Economic Analysis

In the neoclassical study of economics the system studied is founded on actions of, and interactions amongst, individual producers or consumers (‘agents’). This is a system that may well be sub-optimal in natural resource and environmental terms [25]. The transactions between these agents and the rest of the world are economically described in terms of the quantities and prices of (broadly defined) commodities that are exchanged. Prices in this classic economic model are supposed to reflect the ‘value’ that society places on an economic good. Thus, economics is claimed to be a ‘normative’ discipline: it suggests the optimal course action to be taken in the allocation of resources. For the price of commodities to give information that will lead to an efficient use of resources, it is necessary to assume that the prices are determined in complete and perfectly competitive markets. Obviously there may be imperfections in the structure of the market; for example, social costs (notably environmental externalities) may not be transacted and therefore remain unpriced. There are also likely to be uncertainties about the future, restricted information about technological possibilities and time-lags, all of which might cause prices to deviate from those which would lead to optimal investment decisions [3,9,25].

5.2. From Environmental to Ecological Economics

Over the past twenty years or so environmental economics has moved from being a fringe activity to become one of the most active fields of economic research. It is now a major, even dominating, influence within significant areas of policy debate, including global issues such as climate change and biodiversity loss. Mainstream environmental economics is primarily influenced by the neoclassical paradigm in the ways in which it formulates and analyses the two key issues of concern: the valuation of ecological assets and the design of policy instruments to manage those assets [4]. These are brought together in the contemporary study of sustainable development. Thus, environmental economics is essentially a branch of applied welfare economics. In some respects environmental economics represents a rather extreme interpretation of the neoclassical economic paradigm, with its belief in the possibility of extending individual valuations to all sorts of non-marketed ‘commodities’. Here environmental problems are essentially defined as flowing from ‘market failures’, and incentive-based policy instruments are advocated to correct such failures with efficacy.

In the neoclassical view, environmental problems are just one species of externality that should be costed at the price which an efficient market would impute to them: they would not exist if markets were complete and in equilibrium. This seems to fail to grasp the existence of real environmental problems independent of their specification in an economic model [4]. Nevertheless, it might be a reason for adopting one of the alternative accounts of what may be called environmentally-embedded sustainability in order to clearly define the nature of such problems.

In many, perhaps most, of the cases which are of interest to environmental economists, there are no observable or even imputable prices of any sort to use in such valuations. The various methods that have been proposed for valuing external costs and benefits are all open to criticism (see, for example, Hammond and Winnett [3]). Choice of different valuation methods can lead to a wide variation in the supposed costs and benefits. This valuation process is uncertain and potentially controversial, often relying on the determination of shadow prices. In the extreme, they result in methods for valuing human life and well-being that are quite at odds with that perceived by the individual or by society as a whole [3]. Similar difficulties arise in valuing other elements of the biosphere. One widely adopted procedure is to invoke the so-called 'contingent valuation method'; eliciting prices by questioning people about their "Willingness to Pay" (WTP) for ecological benefits or to accept environmental losses. However, the answers given in contingent valuation surveys could simply represent an attempt by respondents to formulate a response based on prices that people know in their everyday economic lives [4], rather than a properly formulated reaction based on the nature of environmental assets.

Partly owing to its somewhat extravagant faith in the neoclassical paradigm, and partly because of the necessary interface between environmental economics and the natural sciences, mainstream environmental economics has had its critics. Some of this criticism is simply misplaced (for example, that it cannot account properly for the life-cycle of products), and is easily rebutted by any well-trained neoclassical economist (see, for example, Winnett [4]). But some are fundamental. This is especially true of those critics who challenge the foundations of neoclassical approaches to the environment. The same goes for those proposals for the use alternative accounts of sustainability based on physical or natural processes intrinsic to the biosphere, such as energy usage [6,39] or biological resilience [40]. Such accounts often aspire to create an entirely new form of economics based, for example, on a redefinition of the concept of scarcity or value.

Dissatisfaction amongst scholars with the ecological limitations of environmental economics has led to the development of the emerging transdisciplinary field of 'ecological economics'. At the forefront of this activity have been individuals like Robert U. Ayres, Jeroen C.J.M. van der Bergh, Cutler J. Cleveland, Robert Costanza, Herman Daly, Nicholas Georgescu-Roegen, John M. Gowdy, Charles Hall, Kozo Mayumi, Howard T. Odum, R. Kerry Turner, and Matthias Ruth: to name but a representative few. They come from a wide range of disciplines, including various branches of biology, ecology, economics, engineering, and geography. Some, like eminent ecologist and systems analyst H.T. Odum [41,42], laid the foundations for more than one new area of ecologically-related study. Odum was engaged in the instigation of two interdisciplinary fields: 'ecological economics' and 'ecological engineering' [42]. Interestingly in the present context, he was fully engaged with others in the discourse about Second Law concepts in the 1980s. He attended a Gordon Research Conference in New England around 1984 [43], during which he gave one of the preliminary talks; along with Georgescu-Roegen and the distinguished geologist M. King Hubbert. Odum asserted that at that time [43] thermodynamicists were intent on taking what he regarded as a wrong direction in favour of exergy analysis to evaluate the qualitative features of energy systems. He later devised his own method for analysing energy systems, both physical and biological, known as EMERGY analysis [42]. The heterodox nature of field can be judged by the content of the journal titled '*Ecological Economics*' [sponsored by the *International Society for Ecological Economics*]. It sets out its domain of study as being "concerned with extending and integrating the study and management of 'nature's household' (ecology) and 'humankind's household' (economics)." The editors argue that this integration is necessary "because conceptual and professional isolation have led to economic and environmental policies which are mutually destructive rather than reinforcing in the long term." The journal aims to be "transdisciplinary in spirit and methodologically open".

5.3. Sustainability and Economic Thought

The concept of 'sustainability' is regarded by many economists (see, for example, Winnett [4]) as a highly debatable notion. Its status within neoclassical-oriented environmental economics is not entirely clear: it is essentially a side-condition, rather than being intrinsic to the logic of the model. The core of the concept is that some measure of welfare; often expressed in terms of maintaining an appropriate aggregate capital stock. Welfare is ultimately dependent on the return to stock. The capital stock is very broadly defined, to include natural resource and environmental assets, alongside physical, human, and even social capital [3]. It should be noted that this framework is very widely used, even by those who are dismissive of neoclassical-oriented environmental economics. Indeed, one of the common (but mistaken) criticisms of this branch of economics is that it does not use a comprehensive enough definition of capital. This should to be distinguished from the argument that the market-based values utilised in aggregation are inappropriate [3].

Many of the mainstream accounts of sustainability-as-maintaining-aggregate-capital strengthen the criterion by requiring some individual components of the aggregate to be maintained as well. This is on the grounds that the weaker criterion overestimates the possibilities of substitution within the economy, though others are more sanguine. But introducing it as an assumption does raise questions about the coherence of the neoclassical model of sustainability, which do not seem to be very clearly appreciated. Economists are fond of arguing that prices are uniquely efficient descriptors and aggregators. A little reflection will show that it implies that prices are not the efficient aggregators fundamental to the neoclassical paradigm.

6. Early Attempts to Link Thermodynamics and Economics

The development of First Law 'energy analysis' in the 1970s (see Section 4.1 above) led to a great deal of interdisciplinary debate in the literature over the link between energy and value, involving both physical scientists and economists. For example, Costanza [44] utilised the 1967 US, 92-sector, input-output table to calculate the total (process plus embodied) energy requirements for products and services [24]. He took account of solar energy input into the economy that was previously ignored by energy analysts. This resulted in a strong relation between embodied energy, including the energy required to produce labour and government services, and the dollar ($) value. Costanza suggested that embodied energy, defined in this way, yield accurate indicators of market values that incorporate 'externalities', and might constitute a means for natural resource valuation. He further argued that embodied energy could therefore provide a common denominator in both ecological and economic systems. Other environmental economists have employed thermodynamic ideas to devise alternative accounts of sustainability by analogy with physical or natural processes, such as energy usage (see, for example, Costanza and Daly [39]). Reference was made in Section 1.1 above to the literature that postulates an 'Energy Theory of Value'. Söllner [5] contends that this was largely rejected because choices about (First Law) energy use do not reflect the full complexity of human behaviour and value judgements. Ideas of this type have also been criticised by Georgescu-Roegen [45,46] and Mirowski [47], with the latter viewing the proponents as 'neo-energeticists'. The former dissociated himself from proposed links between embodied energy and economic value (as suggested by Costanza [44] and others) largely because it takes no account of Second Law degradation. Mirowski [47] observed that the neo-energeticists were almost entirely "engineers who have taken it upon themselves to improve the scientific tenor of economics". While not wanting to advocate an 'energy theory of value', the present authors would wish to see a greater interchange between economists and engineers in order to stimulate mutual understanding across the economy-environment system boundary.

Chemists and chemical process engineers have long been concerned with the need to achieve optimal performance from heat exchange and process plant, including minimising their environmental impact. The distinguished Dutch physical chemist Willem van Gool (1926–1998), for example, recognised the significance that the financial costs of process plant play in equipment selection (see the memorial review by Hammond [33]). Van Gool studied, with various collaborators, the trade-off between energy use and financial costs of various processes, or 'unit operations'[48,49]. This initially involved evaluating the minimum product (direct or 'process', plus the indirect or 'embodied') energy required for different types of process equipment. He recognised [48] that the embodied energy is not really recoverable from the equipment, except via materials substitution. However, a typical trade-off between process and embodied energy is illustrated in Figure 7. Here the process energy curve is similar to that later derived by Cleveland and Ruth [50], although with its axes transposed, to represent the trade-off between energy and materials inputs per unit of outputs. The more significant finding by van Gool was that embodied energy is a fundamental or intrinsic part of the total energy needed to construct and operate process equipment (see Section 4.2). He went on [34,48] to study the trade-off

Figure 7. Product (process + embodied) energy consumption associated with unit operations. Source: Hammond [33]; adapted from van Gool [49].

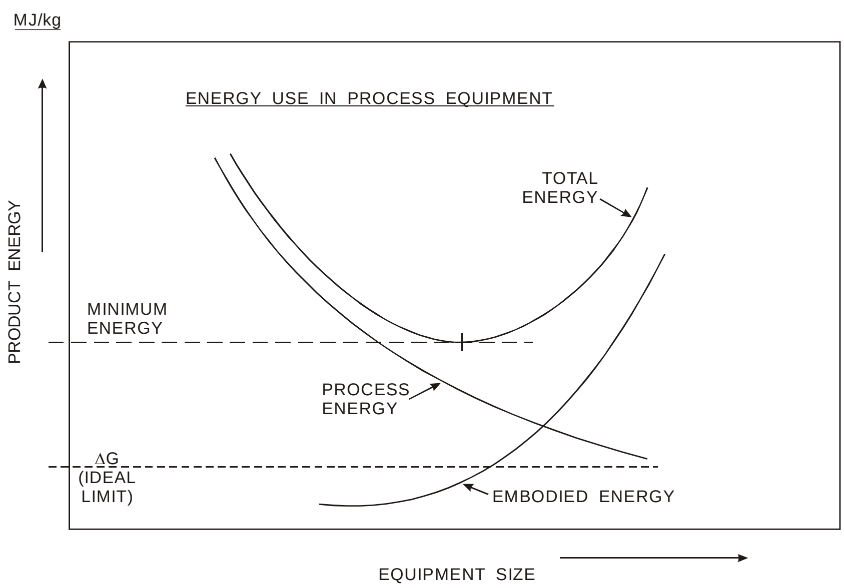
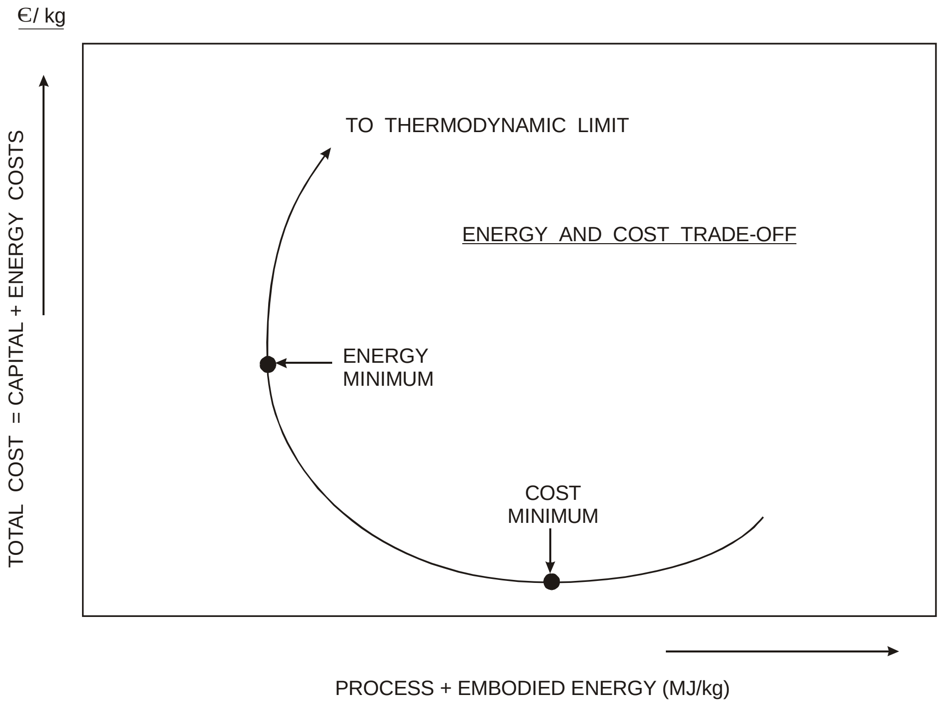


Figure 8. Trade-off between product energy use and financial costs associated with unit operations. Source: Hammond [33]; adapted from van Gool [34].

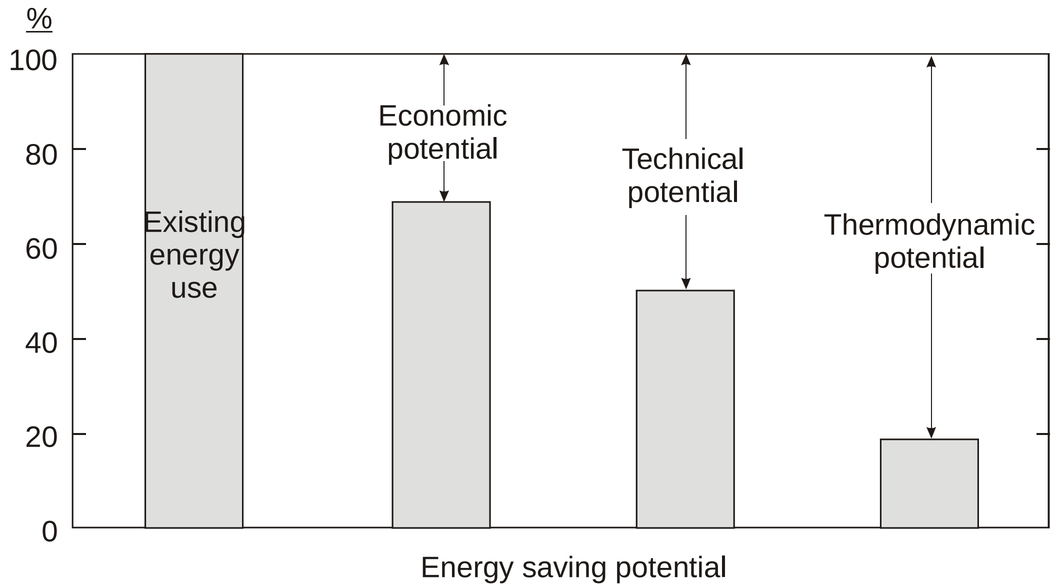


between the total energy requirements for investment in process plant and the consequent lifetime financial costs. These are shown in Figure 8, where minima associated with the total energy requirement and financial costs are depicted.

van Gool's later work highlighted the insights that could be provided by exergy analysis in terms of determining the theoretical energy saving potential of a product or activity (see Hammond [33]). However, there is a need to distinguish between thermodynamic optimal plant or product design and what can be feasibly achieved in practice [3,35]. This is illustrated schematically in Figure 9 (adapted from Jaffe and Stavins [51]), which depicts the economic and technical barriers (as well as the thermodynamic limits) that must be faced in securing energy efficiency savings in practice. Roughly this implies that, although the thermodynamic (or exergetic) improvement potential is around 80%, only about 50% of energy currently used could be saved by technical means and, when economic barriers are taken into account, this reduces to perhaps some 30%. Nevertheless, this still implies that there is very significant scope for innovation in energy efficiency over the longer-term [3,35] within the sort of trade-offs and constraints reflected in Figure 8.

A brave attempt to investigate interdisciplinary approaches to long-term energy problems and the employment of thermodynamic concepts was made in a workshop organised under the auspices of the Dutch Energy Study Centre in the mid-1980s (see van Gool and Bruggink [52]). Here similarities and differences between the physical sciences and economics were explicitly investigated, and many enduring insights obtained. This attempt at interdisciplinary discourse has not received universal acclaim, and Mirowski [47] protested that many of the contributors were advocates of the identity between energy and economic value: the 'neo-energeticists'. Nevertheless, it is interesting to see that in his commentary van Gool noted that there were nearly as many interpretations of the theme as participants in the workshop.

Figure 9. The energy efficiency gap between theory and practice. Source: Hammond [35]; adapted from Jaffe and Stavins [51].



7. Georgescu-Roegen, 'The Entropy Law' and Ecological Economics

7.1. Nicholas Georgescu-Roegen (1906–1994)

Borne in Rumania into modest family circumstances just prior to the First World War, Nicholas Georgescu-Roegen excelled in mathematics and statistics. His university education included periods at the University of Bucharest, and had a two-year fellowship at the Sorbonne's Institut de Statistique in Paris (working with Emile Borel and Georges Darmois), extended for a further two years of postgraduate study with Karl Pearson in London (for a fuller description of Georgescu-Roegen's life and work, see Mayumi and Gowdy [53]). Georgescu-Roegen held an appointment as Professor of Statistics at the University of Bucharest from 1932–1946, during which time he gained a Rockefeller Fellowship at Harvard (1934–1937), where he came under the influence of the economists Joseph Schumpeter and Wassily Leontief, amongst others. He played a role back in Rumania on the National Council of the Peasant Party, and also held the post of Secretary-General of the Rumanian Armistice Commission during 1944–1945. Georgescu-Roegen and his wife (Otilia) escaped from the turmoil of the post-Second World War Communist takeover of Rumania stowed abroad a foreign freighter, eventually returning to Harvard in 1948 via Turkey and France. Vanderbilt University (in Nashville, Tennessee) subsequently offered him a post within their Faculty of Economics in 1949, where he remained for the rest of his career. Georgescu-Roegen became the Distinguished Professor of Economics in 1967, and formally retired from the faculty in 1976. His academic studies can be divided into contributions to the 'normal' and 'revolutionary' economic sciences [54]. In the former category can be listed agrarian economics, consumer theory, and Leontief-type linear activity models [55]. They were all underpinned by Georgescu-Roegen's mathematical strength in neoclassical economics. But it is his revolutionary or unorthodox work on thermodynamic insights for economic theory, leading to what he later called 'bioeconomics', that is of interest in the present context.

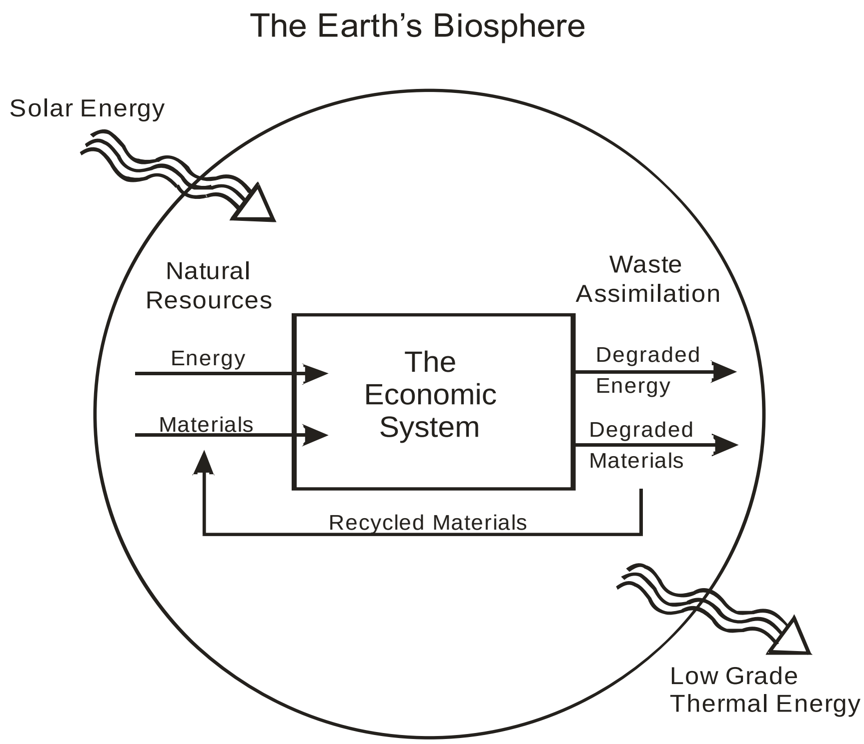
There have been many published tributes to Georgescu-Roegen and his work before and after his death; see, for example, Mirowski [47], Daly [54], Maneschi and Zamagni [55] and Mayumi and Gowdy [53]. He was elected a Distinguished Fellow of the American Economics Association [55], but resigned in later life in a protest over the publication of material that Georgescu-Roegen regarded as of questionable merit, as well as perceived “cavalier treatment by some prominent economists” [53]. Although the likes of Nobel economics laureate Paul A. Samuelson have given fulsome praise to his many contributions (writing, for example, the ‘Foreword’ to a collection of essays in Georgescu-Roegen’s honour edited by Mayumi and Gowdy [53]), his more revolutionary ideas have not permeated the mainstream economics literature. His *magnum opus,* ‘The Entropy Law and the Economic Process’ [6], was viewed by Mirowski [47] as “one of the great unsung classics of economics in the twentieth century”. Maneschi and Zamagni observe that Georgescu-Roegen’s attempts to convert neoclassical economists to his bioeconomic ideas were not helped by his tendency to refer to them as ‘standard’ economists.

7.2. Real World Economics and Thermodynamics

The neoclassical model of the economic process postulates an isolated circular flow of money from firms to households (see also Section 5.1 above). Daly [54] argues that, although this model has its uses for analysing monetary exchanges, it fails to account for maintenance and replenishment of resources; ‘externalities’ as far as the neoclassical paradigm is concerned. In practice, production and consumption rely on a one-way, irreversible, flow of natural resource inputs (from global sources) and outputs of products and wastes (to global sinks) that are therefore extracted and deposited from and to the environment. The interrelation between the economic system and the Earth’s biosphere is illustrated in Figure 10; adapted from Cleveland and Ruth [50]. Here the economy is represented as an open sub-system within the larger global ecosystem. [A consistent, but more elaborate, alternative representation of the economy-environment relationship is provided by Söllner [5].] The economic process is sustained by the unidirectional flow of energy and materials that enters the sub-system as low entropy/high exergy inputs, which are then degraded via system irreversibilities, and leave as high entropy/low exergy outputs: low grade waste heat and waste materials. Cleveland and Ruth [50] view the Earth’s biosphere as being principally a ‘closed’ system, whereas the natural environment on which all species depend is actually driven by solar energy inputs; the principal ‘income’ energy source mentioned in Section 3 above. Consequently, the planet is an open system in respect to solar energy, but effectively closed in terms of matter. [leveland and Ruth draw a distinction between a closed system (in which energy can cross the boundary, but matter could not) and an isolated one.] ndeed peasant economies depend on extraterrestrial, short-wave solar radiation: an abundant energy source of low entropy or high exergy (see Figure 5). The output of such predominately agricultural societies is typically encapsulated in the form of livestock [54]; such as goats and cattle of various sorts. In contrast, industrialised economies depend on terrestrial resources laid down over geological timescales: depleting fossil fuels and minerals of relatively poor ore grade. Georgescu-Roegen [6] regarded the throughput of the economic sub-system as an ‘entropic flow’ that is subject to the physical constraints of natural resource depletion, environmental pollution, and consequent disruption of the biosphere. He argued that Second Law properties, such as entropy (and, by implication, exergy), more realistically reflect dissipative processes.

The dissipative nature of the entropic process emphasises the essential dissimilarity between space and time, in contrast to much of conventional economics. This treats them as analogous: just as commodities can be labelled according to where they are located—the foundational Arrow-Debreu general-equilibrium model handles time by labels according to the date at which commodities are available. This has consequences for the ways in which economists approach problems such as irreversibility and uncertainty, which obviously have implications for their treatment of ecological problems. The entropy law was regarded by Georgescu-Roegen [6] as the 'taproot' of economic scarcity: an American expression that refers to the main root of a plant or tree, growing downwards, from which the smaller roots spread out. Economic systems are thereby seen as ones in which energy and matter is conserved, whilst entropy increases. The major contribution of ecological economics from the 1970s onwards has been to embrace the interaction of the economic process with the constraints imposed by the natural environment; along the lines of the model depicted in Figure 10. Practitioners continue to argue about the mechanisms involved and methods of analysis, but this basic model has been generally accepted by those who consider themselves to be 'ecological economists'.

Figure 10. A simplified representation of energy and material flows across the biosphere and the economic system. Source: Adapted from Cleveland and Ruth [50].



Söllner [5] more recently produced a comprehensive review and critique of the use of thermodynamic ideas in ecological economics. He again drew attention to the insight that energy and related properties can bring to economics and sustainability via the use of *analogies* and the setting of absolute limits respectively. An important medium-term example of the latter (suggested independently by Slesser [23] and Söllner [5]) is the dominant use and finite nature of fossil fuel resources. But there is no direct link between thermodynamic properties and the characteristics of economic systems. The former cannot explain the latter, let alone forecast the future paths of complex economies. Söllner's review [5] was influential in terms of the evolution of the first author's view of the use of thermodynamic concepts outside the realm of energy systems [10], and subsequently on the interdisciplinary discourse of Hammond and Winnett [3] over the application of these concepts in the field of environmental appraisal and valuation.

7.3. The Appropriateness of Second Law Quantities

A debate has recently erupted in the literature about the choice of Second Law properties for use in ecological economics; see, for example, Gillett [56] and Lozada [57]. In the context of the findings of the present work, this must be seen as something of a futile exercise. Given that it has been argued here that the application of thermodynamic ideas in the economic domain only amount to a rather loose analogy or metaphor, the precise choice of thermodynamic quantities that are required to reflect the irreversibilities in economics is of only marginal concern. Nevertheless, the debate between the proponents of entropy or exergy as appropriate Second Law properties is likely to persist in the field of ecological economics. Gillett [56] argues in favour of the use of Gibbs free energy; see Section 4.4 above. He suggests that concern about entropy accumulating in the biosphere (see Figure 10) is unwarranted, as waste heat is eventually reradiated out into space in the form of long-wave radiation. In his view, the main use of thermodynamic analysis is for identifying promising technological opportunities, or improvement potential, in common with Hammond [10,33,35] and Hammond and Stapleton [21]. In his response, Lozada [57] expresses a preference for 'entropy maximisation', although he effectively acknowledges that there is a certain interchangeability between exergy, entropy, and free energy [see Equations (10), (11) and (15) here]. The present authors advocate the use of exergy as a measure of thermodynamic quality in physical systems. In part, that is because exergy is an easier Second Law property to measure and understand than, for example, entropy (see Sections 4 above). But they have also argued that <u>both</u> First and Second Law properties (enthalpy and exergy, say) are needed to characterise the quantitative and qualitative thermodynamic consequences of energy systems (see Section 4.3 above). More importantly, Lozada points out that free energy (or, alternatively, exergy) are not directly related to economic value any more than energy is; see Section 6 above.

7.4. "Matter Matters Too": A Fourth Law of Thermodynamics?

A major concern of Georgescu-Roegen [6] was about the incorporation of 'matter' (minerals or materials) into what he viewed as the thermodynamics underpinning the economic system. He asserted that matter underwent similar irreversible processes to that of energy. Indeed, he felt that whenever energy is degraded in order to perform mechanical work, matter had to be consumed by way of 'friction', combustion, and the like [46]. Thus, he argued that macroscopic matter could be degraded like energy, and therefore required a property analogous to entropy that would reflect these processes. Matter too, he hypothesised, is subject to irrevocable degradation. These considerations led Georgescu-Roegen [46] to formulate a 'Fourth Law of Thermodynamics' [the Third Law, that has not been explicitly dealt with here, simply sets physical entropy to be zero at the absolute zero of temperature (0 K)]: "matter also consists of two states, available (low entropy/high exergy) and unavailable (high entropy/low exergy), and that, just like energy, it degrades continuously and irrevocably from the former to the latter". Here he viewed matter in 'bulk', rather than in microscopic, terms. In regard to a national economy, such as that of the USA, minerals would be dispersed, scattered, or wasted, in the course of production. Some of these waste materials might be recycled, but only subject to limits of a similar type to those imposed by the Second Law of Thermodynamics. Such material degradation would ultimately lead to some finite terrestrial minerals, within an effectively closed system, becoming extremely scarce. In the end, the prospect of increasing 'matter entropy' led him to view mineral availability as being a more important constraint on human development than energy security.

Georgescu-Roegen's Fourth Law of matter entropy represents dubious physics, let alone economics. The dispersion of materials during the production process arises mainly because of various types of machining and processing activities that lead to the generation of 'scrap' (that is potentially recyclable as illustrated schematically in Figure 10). It <u>does not</u> occur principally because of a concentration (or potential) gradient in an analogous manner to heat transfer caused by temperature gradients. Matter therefore behaves like energy only by way of a very loose analogy or parallel. It was indicated in Section 4.2 above that matter has a peripheral role in the definition of exergy [see Equation (10)]: this is where physical material exchange actually appears in the thermodynamic domain. Cleveland and Ruth [50] have reviewed many of the criticisms of the Fourth Law by analysts in both economics and the physical sciences. They note that chemical elements are quite wildly distributed over the Earth's crust and need to be concentrated, or refined, before raw (or 'virgin') materials are turned into useable ones. Likewise, Ayres [58] argued that, in principal, perfect recycling of materials from a waste sink could take place provided there is an adequate energy source of sufficient high exergy, although he acknowledged that, in practice, recycling would be an energy-intensive process [59]. He noted that carbon, oxygen and nitrogen, as well as other elements, are naturally recycled with aid of solar energy in the biosphere. Indeed, Cleveland and Ruth viewed the concentration of dispersed wastes, via recycling, as being unlikely to be any more difficult than extracting raw minerals at the average crustal abundance or oceanic concentration. Perfect recycling is clearly impractical, from both an economic and technological perspective. But significant extraction from wastes is possible provided that there is sufficient energy, of high enough quality, available to do so. Consequently, it can be argued that it is <u>energy</u> (or exergy) and not matter, as Georgescu-Roegen contended, that ultimately provides the resource constraints on production [50,58]. Notwithstanding the weaknesses in the concept of a Fourth Law, Cleveland and Ruth [50] suggest that Georgescu-Roegen's emphasis on the physical limits to materials recycling presaged many recent and useful ideas emanating from the new field of industrial 'ecology' or 'metabolism'.

8. 'Exergoeconomics': the Close Coupling of Exergy and Economic Costs

The popularity of 'exergy' analysis in Central Europe and North America from the 1980s onwards led to attempts to merge the technique with financial cost accounting. This arose because exergy began to be viewed as a measure of the <u>true</u> quality or value of energy carriers [60,61], notwithstanding the recent criticisms of this view by Hammond [10] and Hammond & Stapleton [21]. The combined approach with monetary costing has been described using various terms in the engineering literature: 'exergy accounting', ‘exergy costing’, or 'exergoeconomics'. Although the term 'thermoeconomics' is often used for this purpose, it also encompasses the combination of First Law energy analysis with financial costing; sometimes called ‘heat economy’ [3]. The idea of exergy costing actually stretches back to the early 1930s, when one of the American pioneers of engineering thermodynamics, Joseph Keenan, implicitly suggested that it be used as a means for apportioning costs from the cogeneration of steam heating and power: CHP schemes in European terminology. However, it was only in the 1980s and 1990s that exergy accounting procedures became formalised and more widely adopted [3] led by the pioneering research of George Tsatsaronis and his co-workers, amongst others).

Exergoeconomics attributes unit costs to the exergy associated with each of the material and energy streams entering or leaving an engineering device, or its subsystems [62]; a procedure sometimes called the ‘cost formation process’ [3]. Exergy has been seen as providing a means for determining the sources of exergy losses, or ‘irreversibilities’, within thermal or chemical process plants. It is argued that the exergy function is closely related to the economic value of the carrier [61]; as users may be viewed as wishing to pay for the maximum useful work. Advocates assert that exergy destruction represents what the layperson views as ‘waste’ energy or heat [62]. Its cost is ‘hidden’, but no less important for that. The monetary costs are therefore allocated to system irreversibilities, and these are compared with (annualised) capital and operating costs for individual ‘unit operations’. The mathematical formalism is provided within a general systems framework, and optimisation then yields possibilities for design changes and improvement [62]. It makes product costs, those associated with both capital equipment and exergy losses in process flow streams, and fuel savings more visible.

The various proposals to marry thermodynamic concepts with financial cost accounting represent attempts to couple what might be viewed as two incompatible disciplines. Economics claims to be 'normative', suggesting optimal courses of action, whereas thermodynamic analysis is 'descriptive'. Prices in economic markets are supposed to reflect value judgements, whilst exergy accounting deals only with essentially invariant 'costs'. The system boundaries are also arguably different: micro-economic units (such as the factory or the firm) versus an integrated supply chain encapsulated by the cradle-to-grave (or ‘cradle-to-gate’) concept. [‘Arguably’, since these tight boundaries are really a product of conventional accounting practices. Economic models, such as input-output matrices, can have wide boundaries—even wider than those of life-cycle models—although these may not be empirically realisable at fine levels of detail.] Exergoeconomics was therefore viewed by Hammond and Winnett [3] as attempting to blend "chalk and cheese". This is perhaps not surprising as the technique has been developed largely by specialist engineers and scientists talking amongst themselves. There is clearly a need to engage economists in a multidisciplinary discourse and to publish in the economics literature, as well as the engineering one. Nevertheless, this approach may yield practical benefits in terms of the optimisation of power plant even if the theoretical basis is open to question. Hammond and Ondo Akwe [63], for example, recently evaluated natural gas combined cycle power plants with and without carbon capture and storage using exergoeconomics. This yielded useful insights in terms of the most significant sources of exergy degradation and irreversibility. It illustrated that major improvements can potentially be achieved by considering power generation systems as a whole, rather than concentrating on enhancing the performance of individual components.

9. Concluding Remarks

Thermodynamic concepts (such as energy, entropy, and exergy) have been utilised by researchers in a variety of disciplines with interests in environmental sustainability. Energy transformations within society have been viewed as mirroring resource depletion and environmental degradation by practitioners in, for example, ecology, economics and engineering. These consequences of human development are said to reflect thermodynamic ideas and methods of analysis; they are believed to mirror energy transformations within society. Mueller [15] drew an early parallel between the resource flows in economics and energy (as well as implicitly exergy) flows in thermodynamics. Such ideas have encouraged some [8,13,14] to believe that thermodynamic principles or laws may act as a guide for engineers and others in the quest for environmental sustainability. Indeed, the property known as exergy is viewed as providing the basis of a tool for resource and/or emissions accounting even by various thermodynamicists [3,10]. It is also seen as indicating natural limits on the attainment of sustainability [10]. But these applications simply draw an analogy, or a metaphorical link, between one domain of study and another [5,10,17]. Caution therefore needs to be used when seeking real-world insights for ecological economics.

The significance of employing thermodynamic analysis in engineering and the physical sciences, and the insights it provides, are as useful today as they were when Albert Einstein advanced their merits. However, there is a tendency amongst a few thermodynamicists to elevate exergy analysis to a pivotal position in the array of technology assessment methods (see the discussion by Hammond and Stapleton [21]). Some US analysts, for example, view exergy as representing thermodynamic 'value', and regard the Second Law efficiency as the true efficiency. This is in effect to postulate an 'exergy theory of value'; analogous to the "monetary theory of value" in economics. It is not warranted, and Hammond and Stapleton [21] argue that it should be discouraged. Exergy is simply a measure of the maximum theoretical useful work that is obtainable from a thermal system (as it is brought into equilibrium with its surrounding environment) and this may not be the only, or necessarily most relevant, criteria in any given situation. Thus, exergy analysis should be employed as one tool amongst several quantitative approaches to study energy systems, in addition to the more traditional First Law energy analysis.

Thermodynamics methods of analysis can clearly form an important part of a 'sustainability toolkit', whilst economics and the environmental sciences will provide other complementary tools [3]. Energy and exergy analysis are 'descriptive' methods that highlight thermodynamic constraints in complex biological and physical systems. They also provide a means for evaluating the energy saving potential of various sectors of the economy and types of thermal plant. By contrast, economics as a 'normative' discipline, and its practitioners like to feel that it is the only technique or approach that is necessary to obtain an optimum solution. This is misguided (see Hammond and Stapleton [21]; Hammond and Winnett [3]), although there will clearly be economic and political barriers to the attainment of technical energy savings. It has been argued here that (i) exergy is a more easily understood thermodynamic property than is entropy to represent irreversibilities in complex systems; (ii) energy and exergy analysis need to be performed in parallel in order to accurately reflect the interrelated constraints imposed by the First and Second Laws; (iii) the behaviour of energy and matter are not equally mirrored by thermodynamic laws; (iv) thermodynamic insights for the economic process and natural resource scarcity are simply analogues or metaphors of reality; and (v) such insights should therefore be empirically tested against the real world. Georgescu-Roegen and other pioneers of ecological economics drew many valuable, qualitative insights from thermodynamics. But a new vocabulary for ecological economics is needed that stands on its own; one that evolves a unique terminology, rather than co-opt that of thermodynamics. The latter can mislead as much as enlighten when applied outside the realm of energy systems. In a similar vane, Mirowski [47] viewed Georgescu-Roegen's application of thermodynamic laws to economics as being "tantalisingly vague". In an attempt to 'close the circle' between thermodynamic and economic analysis, proposals have been made to couple the results of exergy analysis with financial cost accounting; yielding the so-called 'exergoeconomic' approach. Doubt has been cast on the use of exergoeconomic analysis by Hammond and Winnett [3], which they regard as attempting to merge the two qualitatively different approaches; one descriptive and the other normative. They argue that they may be in large measure incompatible—like trying to blend 'chalk and cheese'. Nevertheless, this approach may yield practical benefits in terms of the optimisation of power and process plant even if the theoretical basis is open to question.

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The authors' names appear alphabetically.

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