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Entropy and Economics: A Bioeconomic Perspective on Economic Development and Sustainability

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Abstract

This paper investigates the integration of the thermodynamic concept of entropy into economic theory, with a particular focus on the development of bioeconomics. After introducing the physical foundations of entropy, we explore how these principles have been adapted into economic thought to address key challenges related to resource scarcity, ecological constraints, and the irreversible nature of economic processes. Among others, we highlight Georgescu-Roegen’s bioeconomic approach, grounded in the Second Law of Thermodynamics, and discuss how it contrasts with the assumption of neoclassical economics, which traditionally focuses on equilibrium and efficiency without fully accounting for the physical and thermodynamic constraint of resource use. In addition, we review specific applications of entropy-based techniques into the economic field, including production, growth theories, and policy evaluation. While entropy provides valuable insights for sustainable economic modelling, we also highlight its limitations; particularly, in addressing the complexities of socio-economic systems, accounting for technological change, and applying entropy-based concepts in empirical economics, where their integration into measurable models remains methodologically and computationally challenging. Finally, we propose possible directions for future research, particularly concerning the integration of entropy into post-growth frameworks, to develop a more comprehensive understanding of sustainable economic development.

JEL classification: A12, B4, B20, E61, Q32, Q4

Keywords: entropy in economics, circular economy, energy efficiency, bio economics, policy implication

Outline

1. Introduction

Entropy is a fundamental concept in physics that reflects how energy is spread out in a system and how many microscopic configurations a system can have. It captures the natural tendency of isolated systems to evolve toward thermodynamic equilibrium, where energy becomes more evenly distributed and less available to perform useful work. As concentrated, usable energy (such as heat or chemical energy) transforms into diffuse, less useful forms, many physical processes become irreversible unless external energy is introduced to restore order. The term itself derives from the Ancient Greek word *entropía,* meaning "a turning toward" or "transformation," thus reflecting the concept of change and the evolution of energy. The notion was later formalized in thermodynamics, where entropy quantifies irreversible energy transformations in a closed system.

The scientific understanding of entropy is grounded in the two fundamental laws of thermodynamics, which together provide its conceptual framework and scientific derivation. The First Law of Thermodynamics, also known as the law of energy conservation, states that energy within a closed system remains constant; it can change form, but it cannot be created nor destroyed (Clausius, 1850; Atkins, 2010). This principle therefore implies that, while energy transformations occur, the total quantity of energy remains unchanged. The Second Law introduces the concept of entropy by emphasizing the directionality and irreversibility of these energy transformations. It states that in any isolated system, entropy tends to increase over time, reflecting the system’s natural progression towards thermodynamic equilibrium (Clausius, 1867; Boltzmann, 1872; Nicolis & Prigogine, 1977). Thermodynamic equilibrium is reached when a closed system exhibits no net macroscopic flows of energy or matter and when temperature and chemical potential are uniformly distributed throughout. At this point, entropy reaches its maximum value, indicating a state in which energy and matter are spread out as evenly as possible given the constraints[1]. For a fixed total energy, the system is in equilibrium, and no further spontaneous changes or internally useful work can occur. Entropy captures the irreversibility and inherent wastefulness of physical transformations. When energy is converted from one form to another (for instance, in the operation of an engine or in metabolic processes) part of it becomes unavailable for further work, resulting in irreversible dissipation, often in the form of heat or material waste (Kamiński & Okólski, 1980). As usable energy is progressively converted into a less concentrated form of energy, it spontaneously disperses throughout the system. Such a diffusion leads to a more homogeneous temperature distribution, increasing entropy. As thermal gradients vanish, the system loses its ability to perform useful work, illustrating how rising entropy fundamentally constrains the efficiency and reversibility of physical processes (Georgescu-Roegen, 1971; Jakimowicz, 2020).

Over time, the concept of entropy has been applied beyond physics, offering valuable insights across a variety of disciplines such as information theory, biology, economics, and social sciences (Shannon, 1948; Nicolis & Prigogine, 1977; Georgescu-Roegen, 1971; Ulanowicz, 1986; Martyushev & Seleznev, 2006). This paper explores its relevance through the lenses of bioeconomics, which emphasizes the connection between biological systems and the economic modelling of growth. This link assumes that economic models are governed by the same laws as biological and physical systems. Therefore, the dynamics of economic processes can be described using principles such as energy flows, system

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[1] In classical physics, mass and energy are treated as distinct and separately conserved quantities. In relativistic physics, however, mass is understood as a form of energy (as expressed by Einstein’s equation $E = mc^2$), and total energy is conserved as a single entity (Einstein, 1905). This total energy represents all its possible forms - kinetic, potential, rest mass energy - and remains constant within a closed system according to the constraints given by the system’s boundary conditions and conservation laws (Gibbs, 1982).

equilibrium, and entropy. Since entropy governs the degradation of energy and matter in all physical and biological processes, the economy (like any living system) must operate within the constraints of finite energy and material resources. Rather than presenting new empirical results or applied modelling, our aim is to examine how entropy has been interpreted and employed within this interdisciplinary field. We have therefore chosen to review the existing literature, by concentrating on those contributions that explicitly ground the notion of entropy in its thermodynamic roots, and thus leaving aside other domains such as finance, game theory, or social sciences, where the concept is often used in a more analogical or metaphorical sense, frequently without a clear physical or measurable basis. This decision reflects the goal of our work, which seeks to contribute conceptually to the understanding of entropy as a constraint on economic processes, especially in relation to the limits of resource use and the sustainability of growth patterns.

It is worth noting that entropy, as originally defined in physics, possesses well-defined mathematical properties, such as scalability and differentiability. The concept of scalability means that entropy scales proportionally with the irreversibility of the system, allowing us to assume that the principles observed at the micro level might inform dynamics at the macro level. Differentiability, meaning that partial derivatives of entropy with respect to state variables such as energy and volume exist, enables us to isolate individual factors to understand its influence on a system's disorder or complexity. By borrowing this conceptual framework, fields like biology, economics, and the social sciences employ entropy as an analytical metaphor. In these contexts, related ideas like disorder, dissipation, and complexity are used to capture emergent patterns or hidden instabilities. While these applications may not adhere to a strict quantitative framework, they provide an invaluable conceptual toolkit. In the context of economics, its interpretation through the lens of thermodynamics enables us to look at the production and consumption processes as the transformation of ordered, low entropy resources into goods designed to satisfy human needs (Kamiński & Okólski, 1980). However, as free energy becomes bound and less available, economic activity faces inevitable thermodynamic limits. These constraints have gained renewed relevance today in light of escalating ecological degradation and resource depletion.

Nevertheless, entropic reasoning alone cannot provide complete knowledge about economic systems. At this point, the adoption of a bioeconomic perspective offers a natural extension of the framework. For instance, biological systems, governed by biophysical limits, demonstrate that maximization, whether of growth, resource extraction, or population spread, does not always lead to optimal or stable outcomes. In fact, pushing systems toward their maximum capacity can result in instability, collapse, or irreversible degradation, challenging the traditional economic assumption that more is always better. Instead, they demonstrate that stability is often a goal for living systems. A clear example is the regulation of oxygen, where extremely high or low values can be harmful. From this angle, the pursuit of unchecked profit or output maximization appears not only questionable but potentially maladaptive. This rethinking also extends to classical economic competition, often justified by Darwin's principle of the "survival of the fittest" (Darwin, 1869). Recent biological research has emphasized the role of cooperation, not only competition, as vital to the survival of species. Recognizing these dynamics invites economists to rethink assumptions about efficiency, competition, and growth in light of the cooperative and adaptive strategies observed in nature—all of which are ultimately governed by entropic constraints.

The literature reviewed in this paper was selected through a reconstructive and theoretically grounded approach, aimed at ensuring both coherence and conceptual relevance. Rather than conducting a systematic review based solely on keyword searches, we focused on genealogical and thematic connections, prioritizing contributions that engage with the thermodynamic foundations of economic processes. Specifically, we included works that address the application of entropy within economic systems, with particular attention to resource scarcity, limits to growth, and sustainability challenges. Foundational works from both classical economic thought (such as Georgescu-Roegen, Daly, Robbins, and Latouche) and the physical sciences (including Clausius and Boltzmann) were considered essential for framing the theoretical background. At the same time, we integrated more recent empirical studies and methodological innovations, including entropy-based approaches to sustainability assessment (such as the Entropy Weight Method), as well as emerging perspectives from fields like econophysics, complexity economics, and microeconomic models.

The paper is structured as follows. *Section 2* introduces the concept of entropy as defined in physics, emphasizing the aspects that are most relevant for its economic application. *Section 3* retraces the historical and conceptual transfer of physical and biological principles into economic theory, with a particular focus on Georgescu-Roegen's pioneering integration of entropy into economics and the resulting development of bioeconomics. *Section 4* then presents the direct applications of entropy in economics, including its use in economic models of production, growth, and policy evaluation. Finally, *Section 5* provides concluding remarks, synthesizing the key insights and proposing directions for future research.

2. Entropy in Physics

The concept of entropy originates from the study of heat engines, which played a fundamental role in the development of thermodynamics in the 19th century. One of the earliest key insights came from Carnot's Principle (1824), which showed that the efficiency of a reversible engine depends only on the temperatures of the heat reservoirs, not on the working substance. This principle was refined by Thomson (1853), who demonstrated that no cyclic process can fully convert heat into work without energy dissipation. These insights led to the formulation of the Second Law of Thermodynamics. As discussed earlier, the First Law of Thermodynamics ensures energy conservation, while the Second Law addresses the directionality and irreversibility of energy transformations. To quantify this irreversibility, Clausius developed in 1854 the mathematical concept later termed entropy, which he initially referred to as "equivalence-value" (Jakimowicz, 2020).

In 1865, he formally used the term *entropy*, which serves as a measure of the thermal energy that is unavailable to perform useful work, thus quantifying the system's energy dissipation (1). [2]

$$\Delta S = \frac{1}{T}\Delta Q \tag{1}$$

where ΔQ represents the amount of heat transferred reversibly divided by absolute temperature T at that moment, and ΔS stands for the change in entropy (Fermi, 1956). This concept can also be applied to a closed and isolated system, such as the Universe, to describe fundamental properties of its behaviour: directionality and irreversibility of the processes. When heat Q flows from a hotter body at temperature $T1$ to a colder one at $T2$, the total entropy change can be described as:

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[2] Strictly speaking, the entropy differential is defined as dS=δQ/T, where δQ denotes the infinitesimal heat exchanged in a reversible process and T is the absolute temperature. The symbol δQ is used because heat is path-dependent and not a state function, whereas entropy S is a state function. For simplicity, the main text reports the relationship in its integrated form.

$$\Delta S = \left(\frac{1}{T2} - \frac{1}{T1}\right) Q \qquad (2)$$

Since heat naturally flows from hot to cold, we know that $T1 > T2$, which means $\frac{1}{T2} > \frac{1}{T1}$. Therefore, the change in entropy is always positive, leading to an increase of the total entropy. This expresses the irreversibility of spontaneous processes. Clausius formalised previously described properties into what became known as the Second Law of Thermodynamics, which encapsulates the tendency of isolated systems to evolve irreversibly toward states of higher entropy (Truesdell, 1980). In other words, a spontaneous transfer of heat from a cold body to a hot one violates the Second Law of Thermodynamics, because this would lead to the decrease of the system's entropy. However, such a transfer is possible if we are no longer acting in a closed and isolated system; in that case, external work is required. Yet performing this work leads to energy dissipation, as some energy is inevitably lost as unusable heat in the surroundings (Jakimowicz, 2020).

This irreversible dissipation of energy is closely linked to the statistical behaviour of the system at the microscopic level. In thermodynamic, what appears in a single macroscopic state—defined by variables such as temperature, pressure, volume and density—corresponds to a vast number of microscopic configurations (microstates), each representing a different arrangement of the system’s particles (in terms of position and momentum). The macrostate is thus a statistical summary of these possibilities. The Second Law reflects the statistical tendency of isolated systems to evolve toward macrostates with the largest number of microstates—the most probable configurations. This explains the macroscopic irreversibility of processes such as heat transfer. In this sense, entropy quantifies the number of microstates within a macroscopic state, and it is proportional to the logarithm of that number. The greater the number of such configurations, the higher the entropy. Figure 1 schematically illustrates particle microconfigurations corresponding to low and high-entropy macrostates.

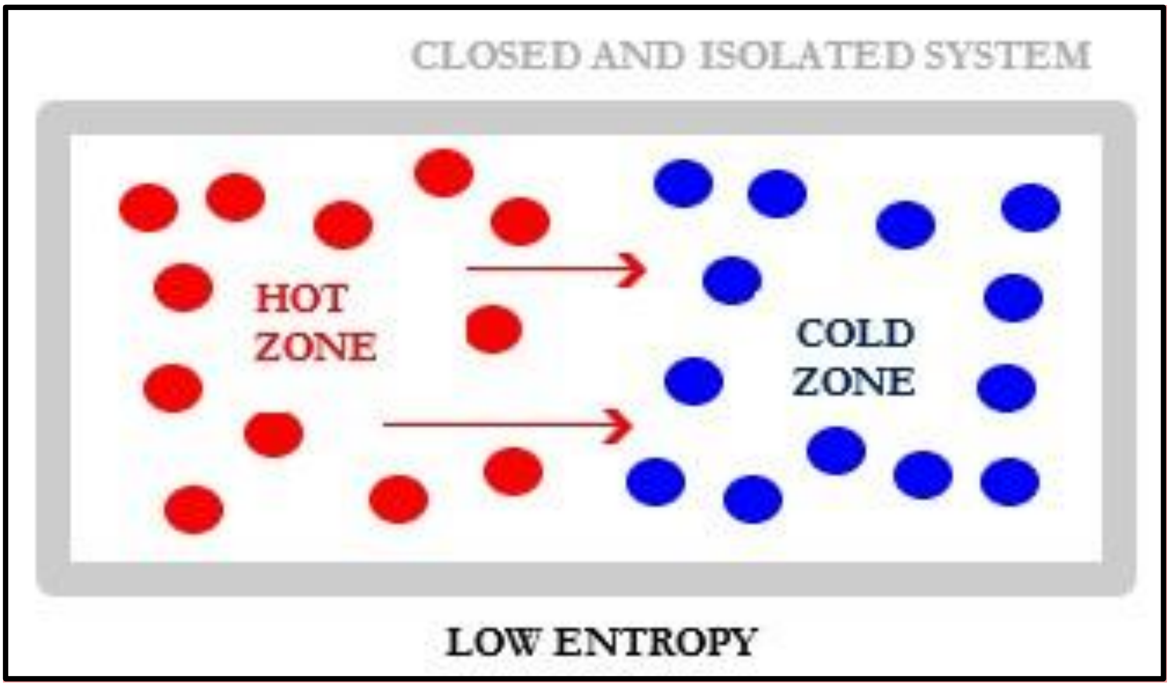

Figure 1. In the low-entropy case, particles are concentrated and heat flows from hot (red) to cold (blue) regions, as shown by directional arrows. In the high-entropy case, particles are more disordered and uniformly distributed, indicating thermal equilibrium where no net heat flow occurs. *Source*: authors’ own development.

From the perspective of classical physics, however, such a probabilistic behavior emerges from underlying deterministic rules: although gas molecules may appear to move chaotically within a volume, each molecule still follows Newton's Laws of Motion. The apparent randomness at the microscopic level arises only from our inability to track all particles simultaneously. The behavior of a collection of gases thus can be described by macro magnitudes, which represent average properties derived from the probability distributions of the motions, such as velocities and the average time between collisions. In this classical physics framework, randomness is not inherent, but rather reflects our limited knowledge of initial conditions, which entirely determines the future behavior of the system. In contrast, quantum physics introduced a fundamentally different perspective: at the microscopic level, particles do not follow deterministic trajectories but are instead governed by probability amplitudes and principles of randomness. Here, uncertainty is intrinsic to the system itself, and physical quantities can only be predicted probabilistically, even with complete knowledge of the system's wavefunction, which describes the probabilities of all possible outcomes.

Despite these differences, both classical and quantum perspectives agree that the organization of gases in a closed system tends to evolve from less probable distributions to more probable ones, allowing the change to be measured. This statistical evolution, from fewer to more numerous microstates, is what entropy quantitatively captures. Although entropy is often described as a measure of 'disorder,' this term can be conceptually ambiguous, as it lacks a precise physical definition. A more accurate interpretation, pioneered by Boltzmann (1872), defines entropy as the number of microscopic configurations (or microstates) compatible with a given macroscopic state. In this sense, entropy measures the degree of multiplicity or statistical likelihood of that state, rather than any subjective notion of chaos or randomness. Boltzmann demonstrated that the probability distribution of the microstates resulting from the thermal motion of gas molecules can be used to characterize each thermodynamic macrostate of a gas (Brătianu, 2020). He later showed that such a process has a stochastic nature rather than a deterministic one (Boltzmann, 1877). Thus, he provided a statistical formulation for entropy, defining it as the logarithm of the total number of microstates required to determine a specific macrostate for the gas contained within a given space (Brătianu, 2020). Even though it was initially underestimated, his statistical approach gradually gained such notoriety that many researchers attempted to apply it to other fields of study.

The formulation is rather simple but effective. Boltzmann formula expresses entropy S as:

$$S = k_B ln W \tag{3}$$

where k_B is the Boltzmann constant, a proportionality coefficient, and W represents the number of distinct microstates corresponding to a given macrostate. The value W depends on the macroscopic properties defined by such parameters as the number of molecules, volume, energy, and pressure. This formulation is utilized in statistical mechanics to connect the macroscopic property of entropy with the microscopic behavior of particles through probability.

In classical mechanics, the thermodynamic probability W in the Boltzmann entropy formula is treated as an integer (Jakimowicz, 2020). Nevertheless, Boltzmann's formulation can be generalized by incorporating probability distributions. More specifically, the total number of microscopic states of the system W can be represented combinatorially by calculating how N molecules within an isolated system are distributed among n energy levels. This calculation assumes a constant number of molecules and a fixed value for the total energy (Jakimowicz, 2020):

$$W = \frac{N!}{\Pi_{i=1}^{n} N_i!} \tag{4}$$

Substituting it in the previous formula we obtain Boltzmann's entropy in the form, which is known as the Gibbs entropy formula (Gibbs, 1902):

$$S = k_B \ln \frac{N!}{\Pi_{i=1}^{n} N_i!} \approx \; - k_B \, N \sum_{i=1}^{n} p_i \ln \, p_i \qquad (5)$$

where $p_i = N_i \, / \, N$ is the probability of a molecule to be in the i-th energy state. For large N the system's behaviour becomes well-described by a probability distribution over microstates. Entropy is therefore associated with the degree of dispersion of a system's components: it increases as the system transitions from a concentrated configuration to a more evenly distributed one. Boltzmann (1877) argued that the tendency of any structure toward greater dispersion, or higher entropy, reflects a fundamental drive to increase its stability. When all microstates are equally probable, entropy reaches its maximum value, corresponding to thermodynamic equilibrium (Brătianu, 2020).

Extrapolated to the Universe, this principle gave rise to the theory of heat death. When treating the universe as an isolated thermodynamic system, the implication is that, over time, it will evolve toward a state of maximum entropy and of thermodynamic equilibrium (Thomson, 1852). In other words, the universe will reach a state of uniform temperature and evenly distributed energy, making it impossible to perform any mechanical work and thus becoming lifeless. For decades, this scenario concerned both scientists and philosophers. However, the advent of modern Big Bang cosmology, which frames the evolution of the universe in terms of perpetual space-time expansion, has shifted the perspective on this issue (Adams & Laughlin, 1997). Unlike in classical thermodynamics, this modern theory claims that the temperature of an expanding universe never stabilizes and never reaches complete thermodynamic equilibrium (Barrow & Tipler, 1978; 1986; Frautschi, 1982). Because of this continuous evolution, classical heat death is avoided. Yet, if the Universe's expansion eventually becomes fully adiabatic (meaning no heat is exchanged), then the entropy within any given comoving volume may approach a constant value. In this case classical heat death may not occur; nevertheless, the Universe could still become a lifeless and stagnant place with its temperature approaching zero. This is because the endless expansion of space will cause matter and energy to become so spread out that no useful energy transformations would be possible. This alternative fate is known as cosmological heat death (Adams & Laughlin, 1997).

3. Entropy in economics: a theoretical framework

The concept of entropy in physics has significant applications in economics, particularly bioeconomics, in relation to irreversibility, energy degradation, and systemic constraints. The idea of aligning human activity with natural limits has deep historical roots, dating back to Ancient Greece. Philosophers such as Plato (Laws, 740–41; Republic, 424, 546) and Aristotle (Politics, 11.2; V.3, 6–7; VII.14) already argued that a society must maintain demographic and material balance to ensure its survival. These early reflections anticipate the modern idea of a steady-state economy, emphasizing the necessity of respecting natural limits. Building upon these foundations, economic thought has long attempted to connect economics with physical sciences, using different approaches over time. While early classical economists such as Adam Smith (1776) and Jean-Baptiste Say (1803) viewed the economy as a closed self-regulating system, John Stuart Mill (1848) offered a markedly different vision, introducing a more explicit interpretation of growth limits. He developed a vision of economic stationarity in which neither capital accumulation nor population growth would continue indefinitely. He argued that prosperity does not require endless expansion and that, beyond the satisfaction of basic material needs, further increases in production contribute little to human happiness. Rather than viewing a stationary state as a condition of stagnation or misery, Mill (1848) regarded it as an opportunity for society to redirect its focus toward cultural, intellectual, and moral advancement. His vision emphasized sustainable resource use, social justice, and a fairer distribution of wealth—themes that would later become central to ecological economics and bioeconomics (Daly & Farley, 2011). Building on Mill's (1848) pioneering work, Robbins (1930) introduced a key distinction between two interpretations of the stationary state: one in which stationarity represents a final equilibrium achieved through an evolutionary process, and another in which a system is deemed stationary simply because its internal elements remain unchanged over time. This concept can also be extended to ecology, where stationarity implies that ecosystems remain stable as long as matter and energy resources remain equally available. However, this equilibrium relies on the assumption of a materially closed Earth: a condition that, as we will argue later, does not guarantee long-term stability. As previously discussed, not all energy or matter can be fully converted into useful work; part of it is inevitably dissipated as unusable thermal energy due to friction and other irreversible processes. This implies that true stationarity is not achievable in the long term, as the continuous increase in entropy, used here by analogy with physics, progressively degrades the availability of useful energy and matter. In other words, even in a materially closed system, the impossibility of fully recycling degraded materials and the irreversible dissipation of energy prevent a perfectly steady state from being maintained indefinitely without external inputs or compensatory mechanisms. This convergence between biological and economic thought was further strengthened by Alfred Marshall (1961), who proposed moving beyond the mechanistic and descriptive economics of his time, in favor of a biological approach. He argued that the economic process should be understood in evolutionary and organic terms capable of explaining qualitative changes that classical mechanics could not address. In this sense, his perspective supports a conception of the economy as a living and adaptable system, governed by physical and biological laws. This approach thus makes it possible to integrate physical concepts such as entropy into economic analysis. In contrast, neoclassical economics, rooted in mechanical equilibrium concepts dating back to the physiocrats, assumes that markets operate like closed, isolated systems that naturally return to equilibrium after external shocks (Jakimowicz, 2020; McMahon & Mrozek, 1997). Within this framework, economic models focus on rational behavior and the allocation of land, labor, and capital, while largely neglecting energy as a production factor (Kümmel & Lindenberger, 2020). Production functions within this framework generally omit environmental inputs and fail to account for interactions with other systems, particularly the natural environment (McMahon & Mrozek, 1997). As a result, neoclassical models tend to ignore physical deterioration and the concept of entropy as the irreversible degradation of energy and the consequent loss of system order over time. This view has profound implications, as it suggests an economic system that can continue functioning smoothly without considering the degradation of the biophysical resources it depends upon. Influenced by this conceptualisation, many economists in the early to mid-twentieth century (particularly, in the context of recovery from the Great Depression) focused on developing models of long-term growth linked to continuous, smooth economic operation (Vozna, 2016). Despite methodological differences, these various growth models shared the common goal of identifying a "golden" formula that would ensure the constant expansion of a mature capitalist economy. For example, the Harrod-Domar model introduced the concept of a justified growth rate required to maintain full employment, while Solow's neoclassical growth model defined the "golden rule" of capital accumulation, which maximises steady state consumption per worker (Harrod 1939; Domar 1946; Solow 1956). Both frameworks attempted to mathematically determine the ideal proportion of savings, investment, and capital to achieve stable and non-inflationary growth trajectories, effectively preventing recessions and economic instability (Vozna, 2016). However, these theories are based on a closed-system perspective that abstracts from the biophysical foundations of economic activity, thereby ignoring the thermodynamic constraints of real-world processes. They overlook the Second Law of Thermodynamics, focusing solely on the conservation of energy (First Law), which fails to account for the inevitable degradation of energy and the associated increase in entropy (McMahon & Mrozek, 1997). This conceptual omission has drawn strong criticism from scholars in ecological economics, who argue that neoclassical growth models, including those employing the golden rule, fail to account for the physical limits imposed by resource depletion, energy degradation, and environmental deterioration (Georgescu-Roegen, 1971; Ayres, 1999). Additionally, neoclassical economics has been criticised for its monetary reductionism, as it tends to reduce complex ecological and social phenomena into purely financial metrics, ignoring systemic complexity, material flows, and irreversible processes (Daly & Farley, 2011). In contrast, entropy economics challenges this framework by integrating ecological, social, and political dimensions into economic rationality, emphasizing that long-term growth models cannot be decoupled from the biophysical constraints imposed by the laws of thermodynamics (Kamiński & Okólski, 1980).

This critique represents a fundamental departure from the classical equilibrium models first developed in the late 19th and early 20th centuries by economists such as Léon Walras (1874) and Irving Fisher (1892). These pioneers developed equilibrium models inspired by mechanics and mathematical formalism. At the same time, Marx (1867) and early political economists started to recognize capitalism's entropic tendencies, acknowledging resource depletion during industrial expansion. While their observations did not explicitly rely on thermodynamic laws, they anticipated some of the consequences that would later be formalized through the concept of entropy in bioeconomics[3]. The mid-twentieth century marked a pivotal shift in economic and scientific thinking, moving beyond classical equilibrium models toward a systemic perspective that better captures complexity and irreversibility. Norbert Wiener's cybernetics introduced the concepts of feedback loops and adaptive regulation into economic thinking, while Claude Shannon's information theory provided a rigorous way to measure communication, uncertainty, and systemic complexity (Wiener, 1948; Shannon, 1948).

Building on these advances, Kenneth Boulding (1966) also contributed significantly to legitimizing the extension of physical concepts to socio-economic systems. Through his well-known distinction between "cowboy economics", based on the idea of unlimited resources, and "spaceship economics", which acknowledges ecological limits and the finiteness of the planet, Boulding (1966) proposed a systemic vision of the economy as a subsystem of the global ecological system. This perspective entails the need to incorporate entropic constraints, even if treated in a more qualitative form, as an essential framework for a sustainable economic theory.

These interdisciplinary perspectives set the stage for the work of Nicholas Georgescu-Roegen (1906–1994), who was the first economist to formally integrate entropy into economic theory. In his seminal work, *The Entropy Law and the Economic Process* (1971), he argued that economic activity involves the irreversible transformation of low-entropy (high-quality) resources into high-entropy (less useful) waste, consistent with the Second Law of Thermodynamics (Jakimowicz, 2020). This challenged the conventional assumption of economic processes as circular and endlessly recyclable, highlighting that human systems cannot be explained solely by deterministic cause-and-effect models due to their anticipatory and adaptive behaviors. For instance, while a stone kicked by a person follows predictable mechanical laws, humans and biological systems display anticipatory and adaptive behavior (Bateson, 1972). These cybernetic interactions suggest that living systems pose challenges that often go beyond the scope of traditional deterministic models as used in classical physics. To better understand these phenomena, concepts from chaos theory[4] and non-linear dynamics can be helpful. Chaos theory

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[3] Many scholars have debated whether Marx fully grasped the significance of the Second Law of Thermodynamics. The controversy concerns not the existence of entropic limits as such, but whether Marx can be considered a precursor of ecological economics in a strict sense. In particular, the debate focuses on his interpretation of material limits and resource depletion, rather than on a direct adoption of thermodynamic principles (Burkett & Foster, 2008).

[4] Chaos theory is a branch of mathematics and physics that studies complex dynamic systems characterized by sensitivity to initial conditions. Small differences in the initial state may lead to large divergences in future outcomes, making long-term prediction difficult even when the system is deterministic. A classic example is the "butterfly effect" (Lorenz, 1963).

shows that small changes in initial conditions can lead to radically different outcomes over time, a characteristic often observed in ecological, biological, and economic systems. These insights reinforce Georgescu-Roegen's argument that conventional economic models, which rely on linear assumptions and mechanical equilibrium, are inadequate to describe the real-world complexity of socio-economic interactions. By highlighting the sensitivity and dynamic instability of complex systems, chaos theory provides a valuable framework for exploring the adaptive and emergent behaviours characteristic of living organisms, which would be overly complex to account for in purely deterministic models.

Georgescu-Roegen's contribution laid the foundation for ecological economics and bioeconomics. Mohammadian (2000) described the discipline of bioeconomics as a paradigmatic shift addressing the environmental impacts of socio-economic activities. The Earth, in fact, can be considered a materially closed system, as it exchanges energy with its surroundings by receiving solar radiation and emitting heat, but absorbs only minimal amounts of matter from the external environment (McMahon & Mrozek, 1997). Within this closed planetary system, the economy operates as an open subsystem that interacts continuously with the environment through the extraction of low-entropy resources (materials and energy that are concentrated, organised, and thus capable of performing work) and the emission of high-entropy waste, which is disordered, dispersed, and no longer usable. This openness enables socioeconomic systems to maintain their internal structure and functionality. In thermodynamic terms, order refers to the organised and concentrated state of energy or matter, whereas disorder indicates their random, diffuse distribution which inhibits any further productive use. For example, fossil fuels are low-entropy resources because their chemical energy is highly ordered and concentrated, whereas the CO_2 released by combustion represents high entropy: its energy has been dissipated as heat into the environment, making it unavailable for further work. This systemic transformation is visually summarised in Figure 2, which shows how the economic system receives solar energy and natural resources, and outputs waste heat and degraded materials, reflecting the entropic nature of production and consumption.

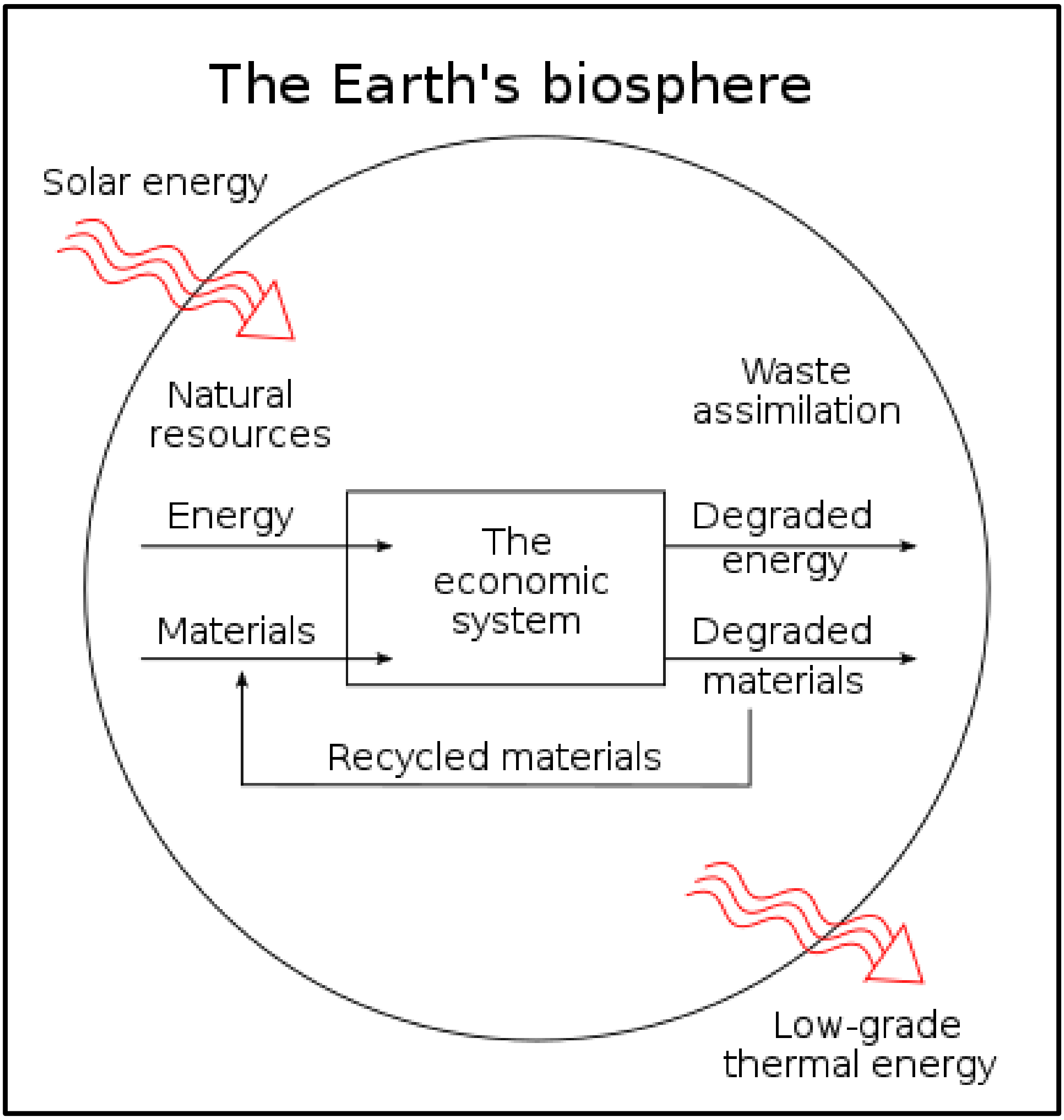

Figure 2. Diagram of natural resource flows within the Earth's biosphere. The figure illustrates the inputs of solar energy and natural resources into the economic system, and the resulting output of degraded materials and low-grade thermal energy. *Source*: Gu and Chen, 2021.

Georgescu-Roegen (1971) emphasised that economic processes are inherently entropic transformations, as they convert ordered, valuable resources into disordered waste, thus increasing the entropy of the overall system. A continuous inflow of low-entropy inputs is necessary for maintaining order and functionality within socioeconomic systems, which would otherwise experience increasing disorder (Kamiński & Okólski, 1980; Ruth, 2007). He argued that the law of entropy applies not only to biological processes but also to all economic processes, even though different production methods may follow distinct economic rules (Georgescu-Roegen, 1971; Kamiński & Okólski, 1980). Building on these insights about entropy and disorder, Kondepudi & Prigogine (2015) contributed a fundamental perspective on how irreversible processes, typically associated with increased disorder, can paradoxically generate new forms of order in systems far from equilibrium. His theory of dissipative structures provided a theoretical framework to understand how complexity and organisation emerge from thermodynamic disequilibrium; a concept applied in biological and socio-economic contexts.

Georgescu-Roegen (1971) also defined this fundamental and irreversible degradation as the “Fourth Law of Thermodynamics”, underlining that degraded matter and energy cannot be fully recycled or restored to their original low-entropy state. Recognizing the entropic nature of economic activity challenges the core assumptions of neoclassical models and underscores the need to integrate ecological perspectives into economics to address sustainability within the biophysical limits of our finite planet. This view would later resonate in more popular and critical discourses, most notably in the work of Jeremy Rifkin (1980), who expanded on similar entropic principles to propose a critical reading of industrial civilization through the lens of the Second Law of Thermodynamics. Rifkin interprets entropy as a tool to describe the inevitable degradation of resources and the structural instability of modern economic and social systems. While less formal than Georgescu-Roegen’s framework, Rifkin’s interpretation helped disseminate the implications of the Second Law of Thermodynamics to broader audiences, strengthening the argument for a fundamental rethinking of modern economic paradigms.

The implications of Georgescu-Roegen’s work challenged classical growth theories. He aimed to demonstrate that unrestricted expansion is impossible, as it inevitably leads to the depletion of Earth's resources, thus highlighting the unsustainability of current development models. In fact, while knowledge and technology may enhance resource efficiency, they cannot eliminate waste or bypass thermodynamic constraints (Ruth, 2007).

However, such a principle is critically re-examined by Ayres (1999), who, while acknowledging the constraints imposed by the Second Law of Thermodynamics on process efficiency, challenges the necessity of introducing a so-called "Fourth Law" that would categorically prohibit complete recycling. He argues that, under certain thermodynamically ideal conditions (specifically, in the absence of dispersion, contamination, or loss) materials could theoretically be recycled indefinitely, as the Second Law applies strictly to energy transformations, not to matter itself. His model suggests that a steady-state economy might be sustained despite entropy buildup, provided there is access to a large inert waste reservoir and a continuous external energy input, for example, from solar energy. By shifting the focus from absolute entropic limits to more pragmatic concerns, such as environmental degradation and the social and technical capacity for material recovery, -Ayres redefines the terms of the debate. Rather than viewing entropy as an insurmountable barrier to growth, his perspective suggests it can be managed through effective control of energy inputs and waste reservoirs. In doing so, he offers a more flexible interpretation that challenges the deterministic pessimism often linked to thermodynamic constraints. In ecological economics, his study highlights the importance of trash stockpiles and energy availability in maintaining circular material flows. By rephrasing policy implications from inexorable decline towards regulating energy inputs and waste reservoirs to ensure systemic viability, Ayres' contribution therefore emphasises how entropy constrains economic processes but does not prevent long-term sustainability and stationarity. Furthermore, a few years earlier Smulders (1995) offered a crucial theoretical link between endogenous growth theories and biophysical constraints, contending that although the laws of thermodynamics naturally limit the accumulation of physical resources, economic value can increase through the advancement of technology and knowledge. His approach distinguished between the economic dimension of value creation, which depends on repeatable and non-rival inputs like knowledge, and the physical component of growth, which is limited by entropy and resource depletion. According to his theory, if natural resources are managed within ecological bounds and investments in human capital and technical innovation consistently increase resource productivity, sustainable growth is achievable. He highlighted that in order to match financial incentives with environmental sustainability; public policies should encourage resource conservation and pollution reduction in addition to knowledge development. His approach advanced ecological economics by demonstrating that thermodynamic restrictions do not necessarily prohibit economic development in and of itself; rather, they influence the institutional framework and routes that allow for it to continue.

Another significant contribution to growth alternatives comes from Serge Latouche (2004), who emphasised the need for alternative metrics such as circular economy indicators to assess economic performance beyond GDP. He argued that economic growth primarily generates non-recyclable, high entropy waste and energy, thereby accelerating resource depletion and environmental degradation. The liberal paradigm prioritises profit maximisation, which is however an objective that does not necessarily lead to optimal social or ecological outcomes. Contrarily, in his view, Latouche (2004) argued for a more rational strategy for economic agents, which would involve minimising regret and cultivating greater awareness of the consequences of their actions and production choices. This critique laid the foundation for the development of degrowth theories. Degrowth is not merely an economic strategy but a broader philosophical and political approach that advocates for a deliberate reduction of economic activity to realign human needs with the planet's ecological limits (Charonis, 2021). It promotes a shift in focus from material accumulation toward enhancing public and social wealth, including ecosystem health, justice, social cohesion, equality, democratic institutions, and welfare systems. These dimensions constitute essential outcomes generated by economic processes, yet they remain largely invisible within conventional monetary statistics, which measure development solely in material and financial terms. However, the degrowth paradigm has faced significant criticism, particularly from Neoclassical and Marxist schools of thought. While Neoclassical economists question its feasibility in sustaining welfare, Marxist theorists often argue that it risks neglecting structural inequalities inherent in capitalist modes of production (Van den Bergh, 2011; Huber, 2022). Despite such critiques, degrowth perspectives continue to emphasise that a paradigm shift away from perpetual growth is necessary to achieve long-term ecological sustainability and social well-being. In response to the challenges and political resistance associated with degrowth implementation, an alternative perspective has emerged in the debate: a-growth. It is an approach that may prove more politically pragmatic, as it allows for targeted interventions to reduce environmental impact and improve social well-being without necessarily rejecting any form of conventionally measured economic growth - especially in contexts of greater poverty (Haddad & Solomon, 2024). From this viewpoint, any technical or economic regulations aimed at safeguarding the local or global climate and environment should be realistically evaluated, not only in terms of their ecological effects and financial costs to the stakeholders, but also regarding their effects on energy production and cycling, entropy production, and other relevant factors (Van den Bergh 2011). The entropy production factor may thus serve as a stand-in for unanticipated political and economic factors (Jenkins, 2005).

Given today's global challenges, revisiting traditional economic frameworks has become more critical than ever. Issues such as fossil fuel dependence and climate change dominate the international agenda, underscoring how governments have long overlooked the consequences of resource exploitation for future generations and developing nations (Stern, 2007).

It is important to further distinguish between bioeconomics and bioeconomy, two concepts that are often used interchangeably but refer to different analytical frameworks. Bioeconomics, as developed by Georgescu-Roegen, is a theoretical approach grounded in thermodynamic principles, emphasizing entropy, irreversibility, and the biophysical limits of economic processes. By contrast, the bioeconomy refers to a policy-oriented framework that focuses on economic activities based on renewable biological resources, including agriculture, forestry, and bio-based industries. While the bioeconomy provides practical strategies for resource use and sustainable production, bioeconomics offers the underlying theoretical foundation by highlighting the physical constraints within which such activities must operate. In this sense, the two perspectives are complementary.

In this context, bioeconomy offers a comprehensive perspective by examining all economic activities that rely on renewable bioresources from both land and sea (including agricultural crops, forests, animals, and microorganisms) to produce essential goods, services, and energy (McMahon & Mrozek, 1997; Lucia and Grisolia, 2021). Rather than focusing solely on GDP growth, bioeconomics emphasises human development in terms of enhanced well-being and reduced environmental impact. Central to this approach, alongside rethinking growth theories, is the development of policies that promote lower entropy (lower-waste) activities, minimising resource degradation. This perspective provides a crucial foundation for rethinking resource management theories to achieve sustainability within the planet's ecological limits.

For instance, the law of entropy has been widely applied to economic theories concerning resource management. In thermodynamic terms, human activities are irreversible processes, as they involve energy dissipation that increases the overall entropy of the system (Kamiński & Okólski, 1980). Technologies that raise energy demand further exacerbate this trend (Georgescu-Roegen, 1971; Ruth, 2007). However, in the late 19th century, Podolinsky argued that human labour plays a unique role by capturing solar energy and preventing its immediate dissipation, thus facilitating the accumulation of additional usable energy on Earth (Vozna, 2016). Despite this, the long-term viability of economic systems depends on the availability of low-entropy energy and materials, as well as the capacity to harness solar energy for productive purposes. While solar energy flows remain abundant, the finite supply of material resources needed to convert this energy into usable goods is becoming a pressing issue, raising concerns about how long Earth's natural capital can sustain current or higher levels of resource consumption (McMahon & Mrozek, 1997).

As we already stated, scholars argue that entropy imposes an absolute physical limit on economic growth, because even if resources are used efficiently, waste and dissipation inevitably increase. Although specific resources can sometimes be substituted—such as replacing one fuel with another—this does not eliminate thermodynamic constraints. As Daly (1991) notes: "*Substitutability among different varieties of low entropy does not suggest that there can be a substitute for low entropy itself*." In other words, while particular materials can be replaced, the fundamental principle that all energy transformations increase entropy remains unavoidable (McMahon & Mrozek, 1997).

In ecological economics, Daly's (1991) concept of sustainable scale is central: it refers to the physical volume of throughput—the flow of matter and energy extracted, transformed, and returned as high entropy waste—that can be maintained without compromising essential ecosystem functions. Achieving a sustainable scale requires respecting the regenerative capacity of renewable resources and the assimilative capacity of ecosystems to absorb waste (Haddad & Solomon, 2024). Nevertheless, awareness is growing that natural resource scarcity is not always accurately perceived or valued in markets (McMahon & Mrozek, 1997). The intrinsic value of environmental elements is often overlooked, while market systems that misjudge scarcity tend to promote technologies that foster economic growth at the cost of environmental degradation.

As cited in McMahon and Mrozek (1997), Carpenter (1995) highlights that the strong sustainability approach rejects the Axioms of Material Value, Abundance, and Technological Abundance, which underpin conventional economic thinking.
Norton (1989) further clarifies these axioms. The Axiom of Material Value assumes that resources have no intrinsic value beyond market price, leading to the undervaluation of essential environmental services. The Axiom of Abundance presumes that Earth's vastness prevents resource depletion within human timescales. The Axiom of Technological Abundance claims that technological innovation will

always enable substitution between natural and man-made capital, making entropy constraints irrelevant (Kamiński & Okólski, 1980). In contrast to these optimistic assumptions, Georgescu-Roegen (1971) adopted a more cautious stance, arguing that the technological solution is only viable if it can sustain the material structures that support resource flows and essential ecosystem functions (Vozna, 2016). Therefore, sustaining economic expansion requires continuously absorbing low-entropy resources from Earth's surface and interior (e.g. fossil fuels, minerals) and relying on the constant flow of solar energy that fuels biological and ecological processes.

The strong sustainability approach rejects the idea that natural capital can always be substituted by human-made or human capital. As Buriti (2019) explains, weak sustainability assumes that what matters is the maintenance of the aggregate stock of capital over time, allowing for substitution between natural, human and manufactured capital. Strong sustainability, by contrast, argues that some components of natural capital are critical and non-substitutable, since they provide essential ecological functions, life-support services and welfare benefits that cannot be reproduced by other forms of capital. From this perspective, technological innovation may improve resource efficiency, but it cannot make entropy constraints irrelevant or guarantee full substitution for degraded ecosystems and depleted natural resources."

Finally, economists have debated whether the Second Law of Thermodynamics applies exclusively to energy or also to material resources. From a physical standpoint, this distinction is often considered artificial, as entropy governs both energy and material processes. It influences fields ranging from thermodynamics and quantum mechanics to information theory, biology, and cosmology. As such, entropy is a central factor in both energy and material constraints, and understanding its implications is crucial for achieving long-term economic sustainability (McMahon & Mrozek, 1997).

4. The application of entropy in economics: prospects, models and policies

The recognition of entropy as a structural and unavoidable constraint on socio-economic systems opens the way to significant applications across various economic domains. In this section, we aim at reviewing some applications of the entropy law in micro and macroeconomic modelling, resource management and policy evaluation. In terms of public policy, it calls for a reformulation of development strategies, which can no longer pursue unlimited linear expansion but must instead focus on resource regeneration, systemic resilience, and the optimal management of energy and informational dissipation. On a theoretical and modelling level, the entropic approach encourages the integration of thermodynamic limits into traditional macroeconomic models, in line with the principles of bioeconomics and ecological economics—through tools such as entropy-constrained input-output models and dissipative efficiency curves (Smulders, 1995). Finally, in the realm of environmental initiatives, this perspective provides a solid conceptual foundation to strengthen frameworks like the circular economy, the energy transition, and selective degrowth practices, steering design toward systems with low internal entropy and high systemic efficiency. In this sense, entropy is not only a physical limit but also a guiding principle for rethinking economic and ecological sustainability in structural terms (Lucia & Grisolia, 2021).

Entropy has been widely applied in economics, especially in resource management and sustainability assessment. One of the most straightforward applications is the Entropy Weight Method (EWM), a quantitative tool that assesses sustainability based on multiple indicators. The core idea of this method is to assign weights to each indicator based on its variability: those that vary more across regions or time are considered to carry more information and are given more weight in the analysis. The process begins with the construction of a decision matrix, which contains the values of various sustainability indicators for different regions, sectors, or time periods. This matrix is then normalized to ensure comparability. Next, the entropy of each indicator is calculated: this statistical measure reflects how uniformly an indicator's values are distributed. An indicator with high variability has higher entropy and thus provides more discriminating power. Such indicators are assigned greater weight in the composite index. Once the weights are determined, they are used to compute scores for specific subsystems and eventually to derive an overall sustainability index. This method ensures that the indicators contributing most to differences in sustainability performance are given more importance, making the evaluation more objective and data driven.

For example, Cunha-Zeri et al. (2022) apply the EWM method to assess nitrogen management in Brazil. The analysis revealed that, economically, investment in water and sanitation was the most relevant factor, peaking in 2012 due to the Growth Acceleration Program, but subsequently declining and reducing sustainability. Socially, population growth emerged as a critical factor, as social dynamics are closely linked to consumption needs and environmental pressures. Lastly, from an institutional perspective, the country's political instability appeared as a key obstacle to sustainable action. Overall, by integrating these subsystems, EWM allowed for a comprehensive understanding of their impact on sustainability outcomes and guided policy priorities. Similarly, Wang et al. (2020) applied the EWM to assess the sustainability performance of the Fujian Province in China. Using 59 indicators derived from the Sustainable Development Goals, grouped into social, economic, and environmental dimensions, they calculated entropy-based weights to objectively capture the variability and significance of each indicator. While Fujian's overall development index improved, their analysis highlighted that low performance in certain social indicators—related to health and governance—significantly hindered sustainable development. Additionally, greater variability in environmental indicators resulted in higher entropy weights, highlighting imbalanced progress.

Beyond its use in sustainability assessment, entropy has also been applied to microeconomic modelling. Tsirlin and Gagarina (2020) developed a model exploring parallels between thermodynamics and economic behaviour. In thermodynamics, energy transfer occurs through heat and work; in economics, resources are exchanged through trade, production, and consumption. The authors introduce an economic indicator of irreversibility, demonstrating its maximum for a loan system in equilibrium. Their analysis defines economic agents as entities that engage in resource exchange and consumption, establishing wealth and capital dissipation functions. This reflects the principle that it is impossible to indefinitely generate profits from a transaction with an agent, akin to entropy constraints in physics. They argue that the Second Law of Thermodynamics translates into economics as follows: without external adjustments, resource flows do not move from agents with higher valuation to those with lower valuation, and profit generation is ultimately limited. Equilibrium in economic systems, like in thermodynamics, corresponds to maximum entropy, or in economic terms, to maximum net capitalization of agents. At this point, profitability declines to zero. The highest level of capitalization matches the highest invested capital, since total capital remains constant in an isolated system. Accordingly, thermodynamic balance equations find analogies in economics through capital, resource, and welfare balance equations, where non-negative welfare growth must be maintained across subsystems within systemic limits.

At the macroeconomic level, entropy has inspired the Maximum Entropy Production (MEP) hypothesis. According to Jenkins (2005), economic and political behaviours do not necessarily aim to maximize individual utility but rather tend to optimize entropy production systemically. This implies that political power depends not only on financial resources but also on control over energy and material resources, which produce entropy. Thus, companies controlling energy sources and governments managing their distribution hold greater economic and political influence. However, maximising entropy production does not always yield positive outcomes. Its impacts depend on natural and economic constraints. Under abundant fossil fuel availability, the tendency towards maximum entropy production becomes evident.

Policy interventions, however, can shape this tendency in different ways. A carbon tax tends to be less effective at curbing emissions than research-and-development incentives, which act as "catalytic" policies that reshape the dynamics of industrial processes rather than the equilibrium they settle into; rigid planning, in turn, may unintentionally slow growth by constraining entropy production, so that economic systems tend to expand more efficiently when subjected to as little disturbance as possible (Jenkins, 2005, pp. 14, 16).

Governments can promote systemic sustainability by crafting regulations that prevent excessive concentration and maintain diversity and resilience within economic systems. According to Goerner et al. (2009), sustainable economic systems require a careful balance between efficiency and resilience. Overemphasizing efficiency and concentration can increase systemic fragility and threaten long-term economic vitality. Recognising entropy and assimilative capacity enables new frameworks for factor use, which has major implications for policy design—especially regarding trade-offs between income growth and ecosystem vulnerability. In this context, policy measures to reduce environmental capital degradation become essential. Examples include the promotion of creative closed-loop production systems that recycle waste and emissions, as well as the development of renewable and low-GHG emission technologies as alternatives to continued reliance on fossil fuels (Haddad & Solomon, 2024; Gu & Chen, 2021; Jenkins, 2005)**.**The pursuit of technologies focused on natural capital would also be encouraged by a deeper conceptualization (Thampapillai, 2014).

The MEP principle is also relevant in global environmental agreements. An MEP-driven agreement can be found in the Montreal Protocol (Murdoch & Sandler, 1997), which successfully limited the production of chlorofluorocarbons (CFC) and other compounds that deplete the stratospheric ozone layer. The success was made possible by the potential decline in economic activity (entropy production) in certain industries (Jenkins, 2005). However, as a result of the decline in global entropy production, the suggested reduction in CO2 emissions envisioned in the Kyoto Protocol (Babiker et al., 2002) can be considered much more challenging to achieve. Modeling studies have examined the effects of various carbon-reduction incentives on industrial processes, showing that different types of policies affect sectors in different ways. Environmental impacts arising from the exhaustion of natural resources not only represent a risk but also amplify other vulnerabilities. Environmental risk is increasingly acting as a trigger for other forms of harm—economic, social, geopolitical—which mutually reinforce one another, contributing to greater systemic disorder. Therefore, entropy, disorder and irreversibility, combined with rising complexity, are contributing to a polycrisis situation (The Global Risks Report, 2023).[5] In the coming years, as ongoing, parallel crises deepen fundamental changes in the economic and geopolitical environment, the various threats we face are expected to intensify.

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[5] Concurrent shocks, profoundly interrelated risks, and deteriorating resilience are raising the prospect of polycrises. Over the medium term, deteriorating geopolitical cooperation will have repercussions throughout the global risk landscape, including contributing to a potential polycrisis of interconnected environmental, geopolitical, and socioeconomic risks pertaining to the availability and demand for natural resources. There are four possible futures centered on food, water, metals and minerals scarcity, all of which could spark a humanitarian as well as an ecological crisis, ranging from water wars and famines to continued overexploitation of natural resources and a slowdown in climate mitigation and adaptation. Given the unpredictability of global risk interactions, comparable foresight exercises might assist in identifying future links, guiding preparatory steps toward reducing the scale and scope of polycrisis before they arise (The Global Risks Report, 2023).

Adopting an entropy approach requires accounting for ecological limits and resource scarcity. Accordingly, it proves particularly useful also when dealing with policy evaluations. A prominent example of how entropic and ecological constraints are being addressed at the institutional level is the adoption of the Sustainable Development Goals, or SDG, established by the United Nations — a set of 17 objectives aimed at promoting a more sustainable global economic model (United Nations, 2015). At the heart of this agenda lies a recognition of physical and biological limits to growth. Within this context, the concept of entropy becomes particularly relevant — not as a mere metaphor, but as a physical constraint: it defines the limits to energy efficiency, resource renewability, and waste absorption that economies must face in the long run (McMahon & Mrozek, 1997). We provide two examples of applications of a bioeconomic approach to policy evaluation, referring to the works of Jin et al (2020) and Stanujkic et al (2020). Both studies apply entropy to assess sustainable development performance, ensuring that policies are based on data-driven insights rather than arbitrary weighting.

Stanujkic et al. (2020) employ entropy to evaluate the progress of EU countries toward SDGs, while Jin et al (2020) refine the National Sustainable Development Index (NSDI) by incorporating economic, social, and environmental dimensions. By applying entropy-based approaches that emphasize biological constraints, policymakers can prioritize investments in high-impact areas, such as renewable energy adoption, social welfare programs, and circular economy initiatives, instead of relying solely on economic growth as a measure of progress. Furthermore, entropy-based assessments uncover hidden imbalances by identifying countries that may appear economically strong yet perform poorly in terms of environmental and social sustainability. As stressed in both studies, this methodology provides a systematic framework for decision-making, thereby guiding governments toward more holistic and effective sustainability strategies that balance economic development with social and environmental responsibility.

From a policy perspective, acknowledging entropic constraints requires a shift from traditional growth centric paradigms toward models that explicitly incorporate biophysical limits (Georgescu-Roegen, 1971; Daly, 1991; Romeiro & Sa Earp, 2013). This entails promoting circular economy frameworks that prioritize resource efficiency and waste minimization (Haddad & Solomon, 2024), as well as ecological fiscal reforms that internalize environmental externalities (Thampapillai, 2014). It also involves targeted public investments in technologies that enhance the resilience and productivity of natural capital while reducing systemic vulnerabilities (Kamiński & Okólski, 1980 ; McMahon & Mrozek, 1997). Incorporating entropy into macroeconomic modeling also allows for a more integrated assessment of long-term systemic risks, capturing the complex feedback loops between economic activity, resource depletion, and environmental degradation (Jakimowicz, 2020; Ruth, 2007). This is particularly relevant in the context of mounting global challenges, where climate change, biodiversity loss, social inequality, and geopolitical instability increasingly interact and reinforce one another (World Economic Forum, 2023). Moreover, the entropic perspective highlights the importance of accounting for energy flows, material throughput, and ecosystem services as fundamental inputs into production and welfare models, offering a richer framework for evaluating trade-offs between short-term economic gains and long-term ecological sustainability (Georgescu-Roegen, 1971; Daly, 1991; Jenkins, 2005). As such, entropy-based frameworks provide not only a diagnostic tool for assessing current trajectories but also a normative foundation for designing transition pathways that align economic systems with the carrying capacity of the biosphere (Haddad & Solomon, 2024; McMahon & Mrozek, 1997).

5. Conclusion

In this paper, we traced the adaptation of the concept of entropy into economic thought, with a particular focus on ecological economics. The growing applications of entropy in economics suggest that this field of study will further expand in the coming years. The ever-growing attention to the finiteness of resources, increasing awareness of planetary limits, and the study of alternative development and growth models—including degrowth, post-growth and a-growth—make the application of the Second Law of Thermodynamics in economic models both interesting and useful, as Georgescu-Roegen argued. The Law of Entropy is indeed essential in this context, as the harsh conditions of life-supporting structures arise from their absolute dependence on available energy, coupled with continuous and irreversible entropic degradation. While this is not the first study to explore this intersection, we believe the originality of our contribution lies in adopting a bioeconomic approach. Considering this, we reviewed the application of entropy to various economic theories, highlighting differences in methodologies and implications. Since our goal is to deepen the understanding of entropy as a resource constraint on economic processes, our contribution builds upon the concept as strictly defined in thermodynamics. Nonetheless, future work should explore in greater detail other applications, such as in finance or income distribution theory.

We distinguished classical theories, which apply classical mechanical concepts, from more innovative approaches that incorporate the Second Law of Thermodynamics and focus on ecological scarcity and resource finiteness. Specifically, our discussion is grounded in the contributions of Georgescu-Roegen (1971), the father of bioeconomics. The adoption of a bioeconomic approach was suitable to select some of the numerous applications of entropy economics, shifting our focus to micro and macroeconomic applications that take ecological constraints into account. We also discussed the policy implications of this approach, as it is highly useful for both policy making and evaluation. From an ecological economics perspective, governments can implement tools such as quotas or capital taxes to stabilize output and reduce entropy. These measures help shift incentives from capital accumulation toward technologies that enhance natural capital efficiency. The MEP hypothesis offers an alternative view of economic behavior, suggesting that systems may evolve to maximize entropy production rather than utility. However, this tendency is not always compatible with sustainability and is constrained by ecological and systemic limits (Jenkins, 2005). Introducing an entropic constraint in economic modelling, even if it provides a more representative picture of reality, comes with some limitations. In fact, it overlooks the fact that economic systems, while subject to thermodynamic laws, cannot be treated as purely physical systems. Given the fact that they also involve social interactions and human activities, entropy alone is not sufficient to provide a complete framework. Moreover, entropy-based models tend to overlook the role of technological progress which—although insufficient on its own to counteract long-term resource depletion—remains a key and unavoidable component of economic evolution (Romeiro, Sa Earp, 2013). Furthermore, while entropy represents a necessary constraint, it must be acknowledged that it presents computational challenges, as its measurement in economics is more abstract than in physics and quite complex to integrate into economic modelling (Herbert et al, 2023). Issues such as the complexity of required data, the need for standardized indicators, and the integration of these tools into existing institutional frameworks remain significant barriers to widespread adoption. This approach could, in fact, provide an effective framework for analyzing the challenges faced by implementing economic programs in addressing economic inequality among social classes and nations. Indeed, the human species is the only one in the biological world to exhibit, alongside biological differences, social inequalities, which can cause major upheavals in history, as emphasized by early social philosophers such as Plato and Aristotle. However, we emphasize that our intention is not to apply the physical laws of thermodynamics mechanically to social realities. Rather, we adopt entropy as a guiding metaphor and analytical framework to explore how resource depletion, energy dissipation, and systemic constraints manifest in economic systems. As with any interdisciplinary borrowing, this transfer entails epistemological trade-offs: while it opens promising paths for integrated analysis, it also requires critical awareness to avoid oversimplification. Recognizing these boundaries, our approach aligns with a bioeconomic tradition that values both scientific rigor and conceptual flexibility. This alignment enables a richer understanding of sustainability challenges, grounded not only in material flows but also in broader structures—social, institutional, and ecological—that shape them. As noted by Romeiro and Sà Earp (2013), modelling and quantifying ecosystem resilience thresholds is extremely challenging, which complicates accurate forecasting due to the behaviour of ecosystems. This set of inputs represents a new research trajectory that could be further explored in future studies. A more in-depth analysis of the applicability of entropy to post-growth theoretical models might represent a fruitful avenue. Such an inquiry may help overcome current limitations and foster a more robust and comprehensive theoretical framework within this field.

Declarations

Ethical Approval: this article does not contain any studies with human participants performed by the author.

Consent to Participate: Not applicable as this study did not involve human participants. Consent to Publish: Not applicable as this study did not involve human participants.

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Appendix

Key Terms and Concepts

This glossary provides a conceptual reference to enhance accessibility and clarity for readers from different disciplinary backgrounds.

1. Thermodynamics and physical foundation of entropy

- **Entropy:** A thermodynamic measure of the dispersion of energy within a system. In isolated systems, entropy tends to increase, driving the system toward equilibrium.
- **First Law of Thermodynamics (Energy Conservation):** Energy cannot be created or destroyed, but only transformed or transferred between forms, so that the total amount of energy remains constant in a closed system.
- **Second Law of Thermodynamics (Entropy Increase):** In closed systems, entropy tends to increase over time, reflecting the irreversible dispersion of energy as systems evolve toward thermodynamic equilibrium.

- **Thermodynamic Equilibrium:** The state at which entropy is maximized, and no further spontaneous macroscopic energy transformations occur.
- **Heat Death:** A hypothetical final state in which no useful work can be performed because no energy gradients remain. In classical thermodynamics, this corresponds to maximum entropy and uniform temperature.
- **Isolated system:** A system that cannot exchange energy or matter with its surroundings. In such systems, maximum entropy is achieved at the thermodynamic equilibrium of the system.

2. Entropy in Economic Thought

- **Bioeconomics:** An economic approach that incorporates biophysical constraints, recognizing that economic processes are embedded in ecological systems governed by the laws of thermodynamics (Georgescu-Roegen, 1971).
- **Ecological Economics:** An interdisciplinary field emphasizing sustainable economic development within the carrying capacity of ecosystems, integrating ecological and economic principles.
- **Neoclassical Economics:** A school of economic thought based on rational agents, market equilibrium, and closed-system assumptions that largely disregard physical and ecological constraints.
- **Technological Abundance:** The belief that ongoing technological innovation will indefinitely substitute for resource shortages, enabling continuous economic growth.
- **Axiom of Material Value:** The notion that natural resources have no intrinsic value unless assigned a price through market exchange.
- **Axiom of Abundance:** The view that Earth's vast size renders resource depletion irrelevant for long-term economic growth.
- **Degrowth:** An alternative economic paradigm promoting reduced production and consumption to ensure environmental sustainability, social equity, and long-term well-being.
- **Stationary State:** An economic condition where production and consumption stabilize over time, maintaining a steady equilibrium without further growth.
- **Fourth Law of Thermodynamics (Georgescu-Roegen's Formulation):** An extension of thermodynamic principles applied to economics, emphasizing that resource degradation is irreversible, making infinite growth impossible.
- **Open Economic System:** An economic system that constantly exchanges energy and materials with its environment, in contrast to the closed-system models used in much of neoclassical economics.
- **Maximum Entropy Production (MEP) Hypothesis:** The tendency for complex systems to evolve toward states that maximize entropy production, within the constraints imposed by their environments.
- **Sustainable Scale:** The maximum physical volume of economic activity that can be maintained over time without compromising essential ecological functions.
- **Resource Scarcity:** The limited availability of natural resources required for production and consumption, which imposes physical limits on economic activity.
- **Energy Quality (Low vs. High Entropy):** Low-entropy energy is highly concentrated and capable of performing work; high-entropy energy is dispersed and no longer useful for economic processes.
- **Ecosystem Resilience Thresholds:** Critical tipping points beyond which ecosystems may undergo irreversible change or collapse, often unpredictably.

- **Technological Progress (in Entropic Context):** Advancements that may improve resource efficiency and delay resource depletion but cannot eliminate the fundamental thermodynamic constraints on economic activity.
- **Co-evolutionary Dynamics:** The mutual and interdependent evolution of economic systems and ecosystems, characterized by feedback loops and non-linear interactions.
- **Throughput:** The flow of energy and materials extracted from nature, processed by the economy, and returned to the environment as waste.

3. Applications of Entropy in Economics Models and Policy

- **Econophysics:** An interdisciplinary field where physicists apply statistical physics and thermodynamic principles to analyze complex economic systems, using methods such as probability distributions, scaling laws, and stochastic models.
- **Complexity Economics:** An approach that studies economies as complex adaptive systems characterized by nonlinear dynamics, feedback loops, and emergent behavior, incorporating tools from physics, biology, and information theory.
- **Self-Referential Economic Systems:** A feature of economic models where theories and expectations influence the behavior of economic agents, making economic systems reflexive and socially constructed, unlike purely deterministic physical systems (Castoriadis, 1975).
- **Entropy Weight Method (EWM):** A multi-criteria decision-making tool that applies entropy to determine the relative importance of sustainability indicators based on their variability across regions or time, enhancing the objectivity of sustainability assessments (Cunha-Zeri et al., 2022).
- **Microeconomic Entropy Models:** Approaches that apply thermodynamic principles to individual agents’ behavior, where resource exchanges, capital dissipation, and profit generation mimic energy transfer and irreversibility found in physics (Tsirlin & Gagarina, 2020).
- **Irreversibility (Economic Context):** A principle emphasizing that once resources are transformed or consumed, they cannot be fully recovered or restored to their original state, echoing the Second Law of Thermodynamics.
- **Wealth Dissipation Function:** A microeconomic analogy to entropy, describing how the capacity to generate additional wealth diminishes over time as systems approach resource or profit equilibrium (Tsirlin & Gagarina, 2020).
- **Catalytic Policies:** Policy interventions that indirectly influence the systemic dynamics of entropy production, such as promoting research and development, circular economy models, or innovation rather than directly targeting static growth goals (Jenkins, 2005).
- **Assimilative Capacity:** The ability of natural ecosystems to absorb and neutralize waste outputs from economic activities without suffering degradation or loss of functionality.
- **Polycrisis:** A situation in which multiple interconnected global risks (economic, environmental, geopolitical, social) reinforce each other, leading to amplified instability and systemic disorder (The Global Risks Report, 2023).
- **A-Growth:** An emerging alternative to growth and degrowth paradigms, suggesting a pragmatic focus on improving well-being and reducing environmental impact without rigidly opposing GDP growth, especially in developing economies (Haddad & Solomon, 2024).
- **Natural Capital:** The stock of renewable and non-renewable natural resources—such as air, water, soil, and biodiversity—that provide essential ecosystem services and serve as a foundation for economic activity (Thampapillai, 2014).

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