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The Role of Energy and Entropy in Economic Thought: From Georgescu-Roegen to Daly

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EN **Abstract.** This article reappraises Georgescu-Roegen's bioeconomics, grounded in the entropy law, alongside Herman Daly's steady-state program. Conceiving the economic process as irreversible matter–energy transformations (throughput) makes the limits of substitution assumptions visible and foregrounds the determining role of "useful work (exergy)" alongside the energy quantity in production. At the measurement level, the System of Environmental–Economic Accounting (SEEA) and Material Flow Accounting (MFA) enable an asset-based tracking of welfare. On the normative plane, Daly's sequencing of scale–distribution–allocation is institutionalized through carbon and material budgets, cap–auction–dividend mechanisms, and ecological tax reform. Within Weitzman's "prices versus quantities" framework, the superiority of quantity instruments is examined for domains characterized by high uncertainty. The study argues that this chain—from theory to indicators to rule design—grounds sustainability policy in the principle "rules (scale) first, allocation (prices) second."

Keywords. Bioeconomics; Steady-State Economy; Entropy.

JEL Codes: B10**,** B50, Q57.

ES El papel de la energía y la entropía en el pensamiento económico: de Georgescu-Roegen a Daly

ES **Resumen.** Este artículo reevalúa la bioeconomía de Georgescu-Roegen, basada en la ley de la entropía, junto con el programa de estado estacionario de Herman Daly. Concebir el proceso económico como transformaciones irreversibles de materia y energía (throughput) hace visibles los límites de los supuestos de sustitución y sitúa en primer plano el papel determinante del "trabajo útil (exergía)" junto con la cantidad de energía en la producción. En el plano de la medición, el Sistema de Contabilidad Ambiental-Económica (SEEA) y la Contabilidad de Flujos de Materiales (MFA) permiten un seguimiento del bienestar basado en activos. En el plano normativo, la secuencia de Daly—escala-distribución-asignación—se institucionaliza mediante presupuestos de carbono y materiales, mecanismos de tope-subasta-dividendo y reforma fiscal ecológica. En el marco de "precios versus cantidades" de Weitzman, se examina la superioridad de los instrumentos de cantidad en ámbitos caracterizados por alta incertidumbre. El estudio sostiene que esta cadena—de la teoría a los indicadores y de ahí al diseño de reglas—fundamenta la política de sostenibilidad en el principio de "primero reglas (escala), después asignación (precios)".

Palabras clave. Bioeconomía; Economía de estado estacionario; Entropía.

Códigos JEL: B10**,** B50, Q57.

PT O papel da energia e da entropia no pensamento econômico: de Georgescu-Roegen a Daly

PT **Resumo.** Este artigo reavalia a bioeconomia de Georgescu-Roegen, fundamentada na lei da entropia, em paralelo ao programa de estado estacionário de Herman Daly. Conceber o processo econômico como transformações irreversíveis de matéria e energia (*throughput*) torna visíveis os limites dos pressupostos de substituição e coloca em primeiro plano o papel determinante do "trabalho útil (exergia)" ao lado da quantidade de energia na produção. No plano da mensuração, o Sistema de Contabilidade Econômico-Ambiental (SEEA) e a Contabilidade de Fluxos de Materiais (MFA) viabilizam o acompanhamento do bem-estar com base em ativos. No plano normativo, a sequência de Daly—escala-distribuição-alocação—institucionaliza-se por meio de orçamentos de carbono e de materiais, mecanismos de teto-leilão-dividendo e reforma tributária ecológica. No arcabouço "preços versus quantidades" de Weitzman, examina-se a superioridade dos instrumentos de quantidade em domínios caracterizados por elevada incerteza. O estudo sustenta que essa cadeia—da teoria aos indicadores e destes ao desenho de regras—fundamenta a política de sustentabilidade no princípio “primeiro as regras (escala), depois a alocação (preços)”.

Palavras-chave. Bioeconomia; Economia de estado estacionário; Entropia.

JEL classificação: B10**,** B50, Q57.

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1. Introduction

The mainstream theoretical framework of economic growth assumes broad substitution possibilities among resources. It posits that, thanks to technical progress, the long-run substitutability among nature, capital, and labor is very high. In this approach, energy and material flows are typically relegated to the background as “intermediate inputs,” while growth is explained primarily through aggregate capital accumulation and productivity gains (Solow 1974; Stiglitz 1974; Dasgupta and Heal 1979). The intellectual rupture termed the “entropic turn” enters precisely at this point. Incorporating the Second Law of Thermodynamics (irreversibility and the increase of entropy) into the ontology of economics reconceptualizes the economy as a sequence of material-energetic transformations and defines growth—beyond the “knowledge–technology” logic—as a process constrained by physical throughput (the flow of energy and matter from nature into the economy, and of wastes from the economy into the environment) (Georgescu-Roegen 1971; Daly 1991).

At the core of Georgescu-Roegen’s critique lies the claim that production functions systematically render invisible the historical–physical role of energy and materials. In his view, the economic process is not a “mechanical cycle” but an irreversible chain of transformations that converts low-entropy resources into high-entropy wastes. Capital and labor are organizational carriers of this transformation, yet without the flow of energy and matter production is impossible (Georgescu-Roegen 1971). This insight implies far more than an abstract lesson in physics. If economic growth depends on the continuous drawdown of low-entropy inputs, then long-run substitution arguments and “backstop technology” assumptions (i.e., boundless technological substitution) may engender undue optimism in normative policy design (Solow 1974; Stiglitz 1974).

Herman Daly’s “steady-state economy” program translates this critique into an institutional and policy framework. Positioning the economy as a subsystem of the ecological system, Daly defines sustainability through three principles: (i) the harvest rate of renewable resources should not exceed their natural regeneration rate; (ii) the use rate of nonrenewables should not surpass the pace at which renewable substitutes are developed; and (iii) emissions should not exceed ecosystems’ assimilative capacity (Daly 1991). These principles provide a theoretical basis for instruments that move beyond the logic of classical optimal taxation—physical caps, carbon pricing, material–energy budgets, and carbon/material accounting. In this way, the entropic turn yields a chain that runs from theory to indicators and from indicators to rules. A theoretical move that challenges production functions unfolds toward environmental extensions in national accounts (SEEA, material flow accounts), “genuine savings”/natural capital indicators, and policy rules such as the carbon budget (Weitzman 1976; Hartwick 1977; Ayres and Warr 2009; Kümmel 2011).

The original contribution of this article is situated on three interrelated planes. First, rather than subsuming the Georgescu-Roegen and Daly traditions under a homogeneous label of “ecological economics,” it reconstructs—through the lens of the history of economic thought—the intellectual trajectory that runs from an entropy-based ontological critique to the design of institutional rules, in a deliberately differentiated manner. Within this framework, Daly’s steady-state program is interpreted not as a straightforward continuation of Georgescu-Roegen’s methodological radicalism, but as a purposive institutional synthesis that translates Georgescu-Roegen’s emphasis on entropy and irreversibility into an implementable architecture of scale, distribution, and allocation. Second, the article treats the concepts of entropy, exergy, and throughput not merely as elements of a theoretical repertoire of critique, but as links in an analytical chain that connects measurement systems (e.g., SEEA, material flow accounting, and exergy accounting) to policy rules (e.g., carbon and material budgets, physical caps). Third, it reformulates the central “prices versus quantities” debate in climate and sustainability policy—consistently with the Weitzman framework—as a formal decision problem derived under conditions of uncertainty, threshold risks, and varying degrees of substitutability. In doing so, the article aims to show that entropy-based economic thought is not only a normative critique of growth, but also a guide to institutional design grounded in measurable indicators and binding rules.

There are, of course, powerful counter-arguments to the entropic turn. The neoclassical tradition maintains that substitution and innovation mechanisms can "ameliorate" long-run resource scarcities through the price system; backstop technologies, scale economies in renewables, and process efficiency gains underpin this optimism (Solow 1974; Stiglitz 1974). In addition, the Hartwick rule contends that intergenerational welfare can be maintained if the rents from exhaustible resources are invested appropriately (Hartwick 1977). This article situates the distinction between strong and weak sustainability within the history of ideas by making explicit the assumptions under which these claims hold—perfect substitutability, low transaction costs, an unbounded domain for innovation, the externalization of waste-assimilation capacity, and the like (Dasgupta and Heal 1979; Daly 1991).

The claim of the "entropic turn" is therefore two-layered. On the epistemic plane, it anchors the economic process in a physics-based ontology; on the normative–institutional plane, it translates the rule architectures derived from that ontology (physical caps, material–energy accounting, the carbon budget) into the language of policy. The article contributes by (i) bringing to light the internal plurality and methodological divergences along the Georgescu-Roegen–to-Daly continuum without homogenizing them under a single "ecological economics" label; (ii) clarifying, in historical–conceptual terms, the selective conditions under which neoclassical counter-responses succeed; (iii) showing that the construction of indicators can be read as a history of ideas; and (iv) analytically disentangling how the "prices or rules?" divide in contemporary climate and sustainability debates relates to the entropic framework.

2. Conceptual Background: Energy, Exergy, Entropy

At its most basic, economic activity consists of transforming energy and materials drawn from nature within production processes and ultimately returning them to the environment as waste. According to the First Law of Thermodynamics, energy is not destroyed; it changes form. Hence the total quantity of energy may remain constant, but this tells us nothing directly about how useful that energy is for doing work. To take an everyday example: two sources with the same amount of energy differ radically in their work potential—electricity can be converted almost entirely into work, whereas low-temperature warm water cannot produce the same amount of work. This difference indicates that, in evaluating economic processes, we must attend not only to the quantity but also to the quality of energy (Ferm, 1956; Moran et al., 2011).

The Second Law—i.e., the entropy principle—states that transformations are irreversible. In practice, this means that at each step of production energy "dissipates," shifting from ordered, work-ready forms to more dispersed, less useful ones. Even if the amount of energy in a system remains the same, its capacity to be converted into work declines over time. Efficiency gains matter; yet as one approaches physical upper bounds, marginal improvements diminish. For this reason, the view that "technology substitutes for everything" may not hold in the physical world except in particular sectors and under specific conditions (Callen, 1985; Bejan, 2016).

Exergy enters at this point. Exergy denotes the maximum useful work that can be extracted from an energy source under prevailing environmental (reference) conditions. It is the most concrete way to measure the quality of energy. This is why the same amount of energy can yield different amounts of work in different contexts: high-voltage electricity has high exergy, whereas low-temperature heat has low exergy. The unavoidable frictions, heat losses, and mixing encountered in production processes "destroy" part of the exergy. That destruction is, in effect, the economic face of entropy production: the more entropy we generate, the more exergy we lose. In economic terms, "raising efficiency" often means losing less exergy for the same energy input and thereby producing more useful work (Kotas, 2012; Dincer et al., 2013).

The distinction between the quantity and the quality of energy also matters for growth theory. Treating energy merely as an intermediate input with a small cost share can obscure the physical carriers of production. A growing body of work shows that growth responds not simply to energy consumption per se but, in particular, to flows of useful work. In other words, *which* energy carrier is used, *with which* technology, and *with how much* exergy loss can shape output and productivity gains. This perspective underscores that the substitution elasticities observed in production functions are not uniform across contexts; in some sectors, requirements for energy quality can render substitution limited (Ayres et al., 2009; Kümmel, 2011).

On the measurement side, three instruments stand out. Material flow accounts track the flows of materials/mass into and out of the economy, making visible how much primary input each sector draws and how much waste it generates. Environmental–economic accounts (SEEA) integrate energy and material flows with national accounts, incorporating natural-capital depletion and pollution costs into welfare measurement. Exergy accounting, by contrast, centers on the convertibility of energy into work and answers the question, "where and how much exergy did we generate, and where and how much did we lose?" Taken together, these three approaches quantify the physical footprint of growth and help us judge more precisely where price-based instruments (e.g., a carbon tax) are appropriate and where physical limits (e.g., an emissions cap or a material budget) are warranted (Krausmann et al., 2017; UN SEEA, 2012; Serrenho et al., 2016).

In sum, this conceptual background implies the following: we must read the economy not only through monetary and accounting aggregates but also through the lens of energy quality and irreversible transformations. Viewed this way, we see more clearly how far efficiency improvements can realistically go, in which sectors substitution is genuinely feasible, and in which policy domains price signals alone will prove insufficient. This, in turn, grounds debates on growth, sustainability, and the measurement of welfare on a firmer physical footing.

2.1. Georgescu-Roegen's Bioeconomics

Georgescu-Roegen's bioeconomic approach conceives the economic process not as the reversible cycles of mechanics but as a thermodynamic flow in which low-entropy matter and energy are irreversibly transformed into high-entropy wastes. Growth is therefore constrained not by an abstract function of capital–labor–technology combinations but by the material–energetic throughput that enters the economy from nature and exits to the environment. Technological change alters outcomes only insofar as it reorganizes this flow (Georgescu-Roegen 1971). Incorporating the Second Law—entropy increase—into the ontology of economics renders visible the issue of "energy quality" that remains implicit in production functions. While energy is conserved in quantity, its capacity to be converted into useful work declines; production and consumption are thus historical and irreversible processes (Callen 1985; Bejan 2016).

Within this framework, Georgescu-Roegen proposes conceiving production as a relationship between funds and flows. Funds—such as labor, equipment, and land—provide services over time and furnish capacity; yet the physical nature of production rests on the consumption, within the process, of low-entropy flows—energy carriers and ordered matter. Expanding funds—enlarging the stock of machinery, upgrading labor quality—does not abolish the qualitative and quantitative constraints on flows, because output emerges through the unavoidable entropic transformation of these flows as organized by the funds (Georgescu-Roegen 1971, 1976). From this vantage point, substitution elasticity holds only under specific local conditions and within limits. In certain sectors, requirements for high-quality energy/matter drive substitution with capital or labor up against a physical ceiling (Kümmel 2011).

What distinguishes bioeconomic readings is the centrality they accord, in economic analysis, to the difference between the quantity of energy and its convertibility into work—that is, to exergy. The fact that the same number of joules offers different work potential across carriers (high for electricity, low for low-temperature heat) sets the real limits of production technologies. Friction, mixing, and heat losses within processes destroy exergy, and this destruction is directly tied to the entropy produced (Moran et al. 2011; Dincer and Rosen 2013). Hence, efficiency improvement often means producing less exergy loss—and thus more useful work—for the same energy input. In growth accounting, the causal role concealed behind the appearance of energy as a "small-share intermediate input" becomes salient once one examines useful-work flows. Indeed, the results of Ayres and Warr indicate that a substantial portion of what is treated as the "black box" of total factor productivity can be explained by improvements in energy quality (exergy) (Ayres & Warr 2009).

One of the most debated contributions in the literature is the thesis that complete, closed-loop recycling of matter is, in principle, impossible; often referred to as a "fourth law," this claim points to the entropic costs of purification and separation themselves (Ayres 1999; Mayumi 2001; Mirowski 1989). Georgescu-Roegen contends that this does not trivialize recycling, but rather counsels caution against the myth of full circularity and calls for process-design prudence (Georgescu-Roegen 1975, 1976). Critiques typically turn on the distinction between "practical impossibility" and "principled impossibility"; nonetheless, the debate has yielded, in policy discourse, a precautionary norm that strengthens the waste hierarchy and preferences for product life-extension and repair/maintenance (Mayumi 2001; Mirowski 1989).

The translation of the bioeconomic framework into the domains of policy and measurement can be traced along three lines. First, environmental extensions are added to national accounts; material flow accounts and SEEA-type systems make it possible to read output growth together with resource extraction and waste generation (UN 2012; Krausmann et al. 2017). Second, through "natural capital" and "genuine savings" indicators, the measurement of welfare is rewritten by valuing exhaustible resources and internalizing environmental degradation (Weitzman 1976; Hartwick 1977; Dasgupta and Heal 1979). Third, exergy accounting disaggregates economy-wide useful-work flows and exergy destruction by sector; this serves as a technical compass in choosing between price instruments (tax/ETS) and physical caps (emissions and material budgets) in policy design (Serrenho, Warr, and Ayres 2016; Dincer and Rosen 2013).

Neoclassical counter-arguments respond to bioeconomics along two channels. The first, via the Hartwick rule, claims that intergenerational welfare can be sustained provided resource rents are invested appropriately, thereby offsetting the depletion of natural capital with substitutionary investment (Hartwick 1977; Dasgupta and Heal 1979). The second argues that substitution and innovation mechanisms—especially backstop technologies—will alleviate scarcity (Solow 1974; Stiglitz 1974). From a bioeconomic perspective, the task is to make explicit the conditions under which these claims hold: physical constraints such as energy-carrier quality, exergy requirements, and ecosystems' assimilative capacity may narrow the scope for substitution in particular sectors; rebound effects can convert simple efficiency gains into dynamics that raise aggregate demand (Sorrell 2009). The useful-work–based findings of Ayres and Warr and of Kümmel indicate quantitative upper bounds that are sensitive to energy quality, without categorically rejecting the possibility of substitution (Ayres and Warr 2009; Kümmel 2011).

In the end, Georgescu-Roegen's bioeconomics moves debates on growth and welfare beyond the "price-signal–substitution" dialectic, refocusing attention on how physical laws are translated into institutional designs. This focus is institutionalized through Daly's steady-state principles and, in practice, opens the door to instruments such as carbon budgets, product life-cycle material targets, and exergy-sensitive process design (Daly 1991). In this way, bioeconomics becomes an intellectual program in which economic thought is anchored in a physical ontology and, along the theory–indicator–rule chain, policy architectures are derived from that ontology.

2.2. Daly's Steady-State Program

Daly's steady-state program positions the economy as a subsystem of the ecological system and normatively reorders the "scale–distribution–allocation" triad: first, keeping the economic scale within biophysical limits (physical constraints on throughput); second, the distribution of income/wealth (equity); and only then market allocation (efficiency). In Daly's view, unless the prevailing theoretical sequencing—allocation first, then distribution, with scale last—is reversed, price signals will obscure the ecological costs of growth (Daly 1991; Daly 1996). A steady state is not "stagnation without growth"; it is a dynamic equilibrium in which population and the stock of man-made capital remain relatively stable, the use of renewable resources does not exceed ecosystems' regenerative rates, and waste/emission flows are kept below assimilative capacity (Daly 1991; Daly & Farley 2011).

The program is distilled into three simple rules. First, for renewables, harvest must not exceed natural regeneration: in stocks such as fisheries, forests, and surface waters, annual withdrawals should remain below natural growth/net increment. Second, for nonrenewables, use must not outpace the development of renewable substitutes: as fossil fuels and ores are depleted, renewable infrastructure capable of delivering the same services (e.g., electrification, heat pumps, storage, recyclable materials) must be built up at least as rapidly to create replacement capacity. Third, emissions must be kept below ecosystems' assimilative capacity: flows such as CO_2, NOx, particulates, and nutrients should be capped at levels that do not strain the carrying limits of receiving environments (Daly 1991; Daly & Farley 2011). Taken together, this triad displaces the assumption that "pricing solves everything," prioritizing physical caps and, under those caps, price and incentive instruments.

The policy architecture centers on the cap–auction–trade principle: (i) a cap is set at a societally accepted, scientifically grounded limit; (ii) usage/emission rights are allocated via auction so that scarcity rents are socialized; and (iii) trading (a secondary market) is permitted to allow for efficiency. Daly's distinctive move is to replace regimes that freely allocate permits with a system that socializes scarcity rents and channels the revenue either back to citizens as a per-capita dividend or toward ecosystem restoration and infrastructure transition (Daly 1996; Daly & Farley 2011). Complementary instruments include ecological tax reform (taxing resource extraction and pollution rather than labor/capital), deposit–refund schemes, and performance standards; border carbon/circularity adjustments are used to mitigate leakage risks (Daly 1996; Daly & Farley 2011).

Daly's program deliberately departs from the neoclassical thesis of "weak sustainability." The Hartwick rule and the subsequent literature posit that intergenerational welfare can be maintained by appropriately investing rents from exhaustible resources; they assume that natural capital is substitutable by man-made capital (Hartwick 1977; Dasgupta & Heal 1979). Daly, by contrast, argues that certain ecological functions (climate regulation, biodiversity, soil formation) are critical and nonsubstitutable; accordingly, a strong sustainability approach—i.e., quantity/cap constraints for natural capital—should be paramount (Daly 1991; Daly 1996). From here he turns to measurement: GDP alone does not capture welfare; extensions such as natural-capital indicators, the SEEA, and material flow accounts bring the biophysical reality of scale into accounting frameworks (Weitzman 1976; UN 2012). So long as the empirical case for absolute and persistent decoupling on which "green growth" claims rest remains limited, the Daly line insists first on the principle of scale (Jackson 2009; Kallis 2019).

In steady-state macroeconomics, a distinct set of regulations is proposed for employment, innovation, and stability. On employment, the main thrust is to shift the tax burden from labor to resource extraction, to support work-sharing (shorter hours, repair/maintenance, and local services), and to condition public procurement on designs compatible with durability and repair (Daly 1996; Daly & Farley 2011). Innovation is steered not toward "more," but toward longer-lived and repairable products, processes that reduce exergy loss, and designs that close material cycles—in other words, directed innovation is paramount. For financial stability, the emphasis falls on instruments that temper growth-dependent debt dynamics (e.g., "narrow banking" proposals that raise full-reserve/coverage ratios), on resource auctions that socialize rents, and on capital-flow management measures that limit speculative pressures (Daly 1996). In foreign trade, border adjustments and common standards are advocated for carbon-intensive imports that circum vent scale constraints; for global justice, distributional mechanisms such as a per-capita carbon dividend are proposed (Daly & Farley 2011).

Common critiques cluster under three headings. "Unemployment." How is employment to be sustained in a non-growing economy? Daly's response is to reduce taxes on labor and tax throughput instead, shorten working hours, promote repair–maintenance and local services, and preserve the demand base by returning scarcity rents as dividends (Daly 1996). "Innovation slows." The program shifts R&D from quantity to quality; innovation focused on product longevity and exergy efficiency can increase overall welfare (Daly & Farley 2011). "Measurement and efficiency loss." A GDP-centered understanding of efficiency is misleading because it neglects externalities; under a dashboard of indicators (SEEA, GPI/ISEW, natural-capital balance sheets), efficiency is redefined (Weitzman 1976; Jackson 2009). The useful-work/exergy-based growth findings of Ayres–Warr and Kümmel support the view that price signals alone may be insufficient and that a mix of physical caps and pricing instruments may be required (Ayres & Warr 2009; Kümmel 2011).

In the final analysis, Daly's steady-state vision is a proposal to move from welfare economics premised on "infinite substitutability" to an institutionally grounded design that is biophysically coherent. The theory begins with caps that define scientific limits; scarcity rents are socialized and returned for fair distribution; allocation then proceeds via relative prices within those limits. Thus the policy debate shifts from the "prices or rules?" dichotomy to the sequencing "rules (scale) first, prices (allocation) second." When the choice of scale is correct, the design of distribution is just, and allocation operates efficiently, the steady state appears not merely as a normative ideal but as an institutionally implementable framework (Daly 1991; Daly 1996; Daly & Farley 2011).

2.3. From Bioeconomics to Institutional Design: Continuity and Rupture

The relationship between Nicholas Georgescu-Roegen and Herman Daly is often portrayed in the ecological economics literature as a linear transmission of an intellectual legacy. Yet this lineage, while marked by strong theoretical continuity, also entails a pronounced methodological and normative reorientation. Georgescu-Roegen's contribution is shaped by a radical critique that interrogates the ontological status of the economic process, whereas Daly's steady-state program seeks to translate that ontological critique into a normative framework that is institutionally and politically implementable (Georgescu-Roegen, 1971; Daly, 1991). Accordingly, the connection between the two approaches should be understood not as a simple continuation, but as a process of critical translation and reconstruction.

Georgescu-Roegen's bioeconomic approach conceives economic activity as a material–energetic process grounded in irreversible entropic transformations. Within this framework, the second law of thermodynamics is not merely a technical constraint, but an ontological objection to economics' mechanical assumptions of equilibrium and circularity (Georgescu-Roegen, 1971). The production process necessarily entails the conversion of low-entropy energy and matter into high-entropy wastes; neither capital accumulation nor technological progress can eliminate this irreversibility (Georgescu-Roegen, 1975). Bioeconomics therefore adopts a cautious stance toward technology: innovation may expand possibilities for substitution, yet such expansion is, in principle, not unbounded given entropic limits (Georgescu-Roegen, 1976; Ayres, 1999). In this respect, Georgescu-Roegen's approach is analytically radical, deliberately suspending any premature leap from critique to prescriptive policy blueprints.

Daly's steady-state economics likewise begins from the acceptance of entropy and irreversibility, yet it shifts the analytical emphasis from ontological critique to institutional and normative design. For Daly, the central issue is not the existence of entropic limits per se, but how such limits are to be translated into economic decision-making processes (Daly, 1991). Accordingly, in Daly's framework the entropy law functions not as a direct claim about the impossibility of growth, but as a normative principle requiring that economic scale be constrained by biophysical ceilings. The concept of throughput is then linked to concrete institutional instruments such as carbon budgets, renewable resource harvest rules, and emissions caps (Daly, 1996; Daly & Farley, 2011).

This divergence is also evident in their respective conceptions of technology. Whereas Georgescu-Roegen adopts a cautious and often skeptical stance toward technological change, Daly embraces the idea of directed technological progress. Within the steady-state framework, the problem is not technology as such but its orientation: innovation should be incentivized not to generate greater throughput, but to reduce exergy losses, extend product lifetimes, and constrain material flows (Daly, 1996; Daly & Farley, 2011). In this way, technology becomes not a means of transcending entropic limits, but an institutional component that enables the maintenance of welfare within those limits.

At this point, the fundamental distinction between the two approaches becomes clear. Georgescu-Roegen's analytical radicalism compels economics to confront the laws of physics, while maintaining a deliberate distance at the level of policy prescription. Daly, by contrast, tempers this radical ontological critique and translates it into a politically and institutionally implementable program. The relationship can be summarized as follows: Daly shares Georgescu-Roegen's entropy-based ontological critique, yet he deliberately moderates Georgescu-Roegen's methodological radicalism by converting it into an actionable institutional framework (Georgescu-Roegen, 1971; Daly, 1991).

Therefore, the intellectual trajectory from Georgescu-Roegen to Daly represents not a rupture, but a reorientation carried out within a critical continuity. While the ontological claim of irreversibility in the economic process is preserved, in Daly's work this acceptance is anchored in a normative ordering of priorities—first scale, then distribution, and only lastly allocation—and in concrete policy instruments (Daly, 1991; Daly, 1996). In this sense, Daly's steady-state program can be understood as an interface that translates bioeconomics' critical legacy within the history of economic thought into the institutional language of contemporary sustainability and climate policy (Jackson, 2009; Kallis, 2019).

3. An Entropy-Based Decision Framework for Choosing Between Prices and Quantities

In environmental policy design, the choice between price-based instruments (taxes, feebate schemes) and quantity-based instruments (budgets, caps, quotas) is conventionally framed in classical welfare economics as a comparison of marginal abatement cost and marginal damage curves. This approach was given a systematic formal articulation in Weitzman's Prices vs. Quantities analysis (Weitzman, 1974). Yet in domains such as climate change, biodiversity loss, and material resource use, this choice is not merely a matter of imperfect information or measurement error; it is shaped directly by irreversible physical processes and entropic constraints (Georgescu-Roegen, 1971; Daly, 1991).

In this context, the proposed entropy-based decision framework derives the choice of policy instrument along two core dimensions: (i) threshold risk and uncertainty, and (ii) substitutability and exergy dependence. When these dimensions are assessed jointly, the conditions under which price- or quantity-based instruments are welfare-superior can be formally distinguished.

(i) Threshold Risk, Uncertainty, and Irreversibility

The first dimension concerns the structure of the marginal damage function associated with environmental harm. In the context of the climate system, ecosystem services, and natural stocks, damage functions are typically non-linear: once certain thresholds are crossed, damages escalate rapidly and may become irreversible. From the standpoint of entropy-based economics, this implies not merely probabilistic uncertainty, but a physical one-way directionality grounded in the laws of thermodynamics (Georgescu-Roegen, 1971). In such systems, the costs of error are asymmetric: exceeding environmental limits is not a deviation that can later be corrected through price signals, but one that generates a permanent loss of welfare.

In Weitzman's (1974) analysis, quantity-based instruments can be welfare-superior when the marginal damage curve is steep and subject to substantial uncertainty. The entropy-based framework generalizes this result: in systems characterized by irreversible threshold risks, specifying physical limits ex ante becomes not merely a normative preference but an analytical necessity, rather than relying on ex post price adjustments (Daly, 1991).

(ii) Substitutability, Exergy Requirements, and Technological Limits

The second dimension concerns the substitutability of environmental inputs within production processes and the quality of energy used—namely, exergy. In neoclassical models, the effectiveness of price signals rests on the assumption of high elasticities of substitution. Yet many production processes—especially in sectors requiring high temperatures, high energy density, or continuous energy throughput—are structurally dependent on high-quality energy. This implies that, in the short to medium run, price increases tend to induce only limited substitution responses (Ayres & Warr, 2009; Kümmel, 2011).

From an entropy and exergy perspective, the problem is not merely one of costs but of physical fitness. Low-exergy energy forms, regardless of how inexpensive they become, cannot perform certain productive functions. Hence, even if substitution possibilities can be expanded through technological change and capital accumulation, they are not unbounded in principle (Georgescu-Roegen, 1976). Under these conditions, the effectiveness of price-based instruments diminishes, and defining policy objectives directly through quantity constraints yields more coherent outcomes.

(iii) A Formal Decision Rule and Policy Matrix

When these two dimensions are considered jointly, the following decision rule can be derived:

High threshold risk and low substitutability:

- Quantity-based instruments should be prioritized.
  Carbon and material budgets, emissions caps, and absolute use constraints are necessary to keep the economic scale within biophysical limits.

Low threshold risk and high substitutability:

- Price-based instruments are relatively more effective.

Taxes and market signals can encourage technological directionality and efficiency improvements.

This decision rule embeds Daly's principle of "first scale, then distribution, and only lastly allocation" within a formal framework. Where scale cannot be set through the price mechanism but must instead be determined by physical limits, market allocation becomes meaningful only within those limits (Daly, 1991; Daly & Farley, 2011). In this way, policy design moves beyond the binary "prices versus quantities" dilemma and systematically clarifies which instrument should take priority under which conditions.

4. Counter-Arguments and Internal Debates

The core neoclassical counter-argument is that scarce natural inputs can, in the long run, be offset through mechanisms of substitution and innovation. In the resource–growth literature, Solow (1974) and Stiglitz (1974) show that even in the presence of exhaustible resources, per-capita consumption can be sustained—and may even rise—under assumptions of suitable substitution elasticities and sufficient technical progress. In this approach, "backstop" technologies—an abundant or renewable energy source together with its associated capital set—place an upper bound on the long-run marginal cost; consequently, the "entropic limit" debate is reduced, within the price system, to an R&D problem oriented toward technology. The Hartwick rule yields the institutional corollary of this view: converting exhaustible resource rents into investment goods in the right way can maintain intergenerational welfare, a conclusion consistent with the thesis of weak sustainability (Hartwick 1977; Dasgupta & Heal 1979).

Bioeconomic critiques of this framework emphasize that substitution results are conditional: in sectors that require high-quality energy/matter, substitution elasticities may be low; moreover, when waste-assimilation capacity and pollution-stock dynamics (e.g., the long-lived effects of CO_2) are left outside the model, welfare paths appear overly optimistic. On the neoclassical side, by contrast, the directed technical change literature argues that carbon prices can shift innovation toward low-carbon technologies, thereby increasing substitutability over time. The "price signal plus R&D support" pairing in climate policy rests on this argument (Acemoglu et al. 2012). The bioeconomic line, however, stresses that while price signals are necessary, they may be insufficient in some domains; owing to entropic limits and exergy requirements, priority should be given to physical caps (Daly 1991; Daly & Farley 2011).

The debate around energy efficiency juxtaposes the two approaches on an empirical plane. The neoclassical expectation is that efficiency gains will reduce resource demand; by contrast, the bioeconomics and industrial-ecology literatures show that the Jevons/rebound effect—especially at the system level—can offset part or even all of those gains through induced increases in demand. Meta-analyses and sectoral studies find that the magnitude of rebound varies widely by context. Although macro-level "backfire" is not always confirmed, rebound effects support pairing simple efficiency targets with quantity constraints in policy design (Sorrell 2009; Cullen & Allwood 2010). Studies on the other side argue that, with appropriately set pricing and elasticity parameters, efficiency policy can reduce net resource use; the divergence often stems from short- versus long-run horizons and from partial- versus general-equilibrium assumptions (Dasgupta & Heal 1979).

Critiques have also been directed at the measurement proposals of the bioeconomic approach. It is argued that conceptual mismatches and data limitations arise when the notion of "entropy" is transferred directly to macroeconomic aggregates, and that exergy accounting can be coarse without detailed maps of technologies and processes. While Ayres and Warr's useful-work–based growth accounting links a large share of total factor productivity to improvements in energy quality, opponents caution that these results may be sensitive to functional-form choices and data selection (Ayres & Warr 2009; Kümmel 2011; Stern 2011). The neoclassical measurement line, for its part, advances green net national income and asset-based indicators for dynamic welfare measurement, advocating the internalization of natural-capital depreciation via shadow prices rather than by direct recourse to entropy (Weitzman 1976; Arrow et al. 2012). Bioeconomics counters that shadow prices themselves may be unreliable in the face of critical thresholds and non-substitutable functions, and therefore calls for prioritizing quantity-based thresholds (e.g., carbon budgets) (Daly 1996).

The internal debate between "green growth" and "steady-state/decoupling skepticism" turns on contemporary evidence. The green-growth claim holds that absolute and sustained decoupling (i.e., declining aggregate environmental pressure alongside expanding economic activity) is achievable through renewables, circularity, and servicization. System-level studies, however, have shown that historical evidence for large-scale, enduring absolute decoupling is limited—an assessment that becomes even more challenging when material flows and global carbon are measured on a consumption-embedded basis (Haberl et al. 2020; Hickel & Kallis 2020). The opposing view points to instances of decoupling in particular regions and indicators and contends that, with an appropriate policy mix, these patterns can be generalized; disagreements typically hinge on metric choice (production- vs. consumption-based), time horizon, and spillover effects (OECD 2011; UNEP 2019).

At the level of policy instruments, the prices-versus-quantities debate is revisited through Weitzman's classic framework: in domains such as climate, where the marginal damage curve is uncertain and steep, quantity instruments may be welfare-superior; by contrast, when technological and cost deviations dominate, price instruments (taxation) may be preferable. The bioeconomic line advocates a budget-based approach for climate, whereas the neoclassical line places greater weight on pricing combined with R&D; in practice, most policy mixes gravitate toward hybrid solutions (Weitzman 1974; Acemoglu et al. 2012; Daly & Farley 2011).

Finally, debates also persist within the bioeconomics tradition itself. Georgescu-Roegen's thesis on the *in-principle* impossibility of complete material recycling is accepted by some as a normative caution, while others criticize it as an overgeneralization from physics; Mayumi (2001) and Mirowski (1989) layer this discussion through the lenses of intellectual trajectory and conceptual history. Within the Daly line, the practical instantiation of the "scale–distribution–allocation" sequencing concentrates on how carbon budgets should be apportioned and how scarcity rents should be socialized; proposals such as cap–auction–dividend seek to address efficiency and equity simultaneously, yet face tests of political feasibility and global coordination (Daly 1996; Daly & Farley 2011).

In the sustainability literature, the claim that the relationship between economic growth and environmental pressures can be managed through "decoupling" is commonly examined through the distinction between relative and absolute decoupling. Relative decoupling refers to environmental pressures increasing more slowly than economic output, whereas absolute decoupling requires total resource use or emissions to decline in absolute terms even as economic activity continues to expand (OECD, 2011; UNEP, 2019). However, empirical findings suggest that—especially over the long run and at the global scale—evidence for persistent and widespread absolute decoupling remains limited (Haberl et al., 2020; Hickel & Kallis, 2020). This assessment is highly sensitive to the measurement approach: while production-based indicators may suggest emissions declines in certain countries, consumption-based accounting reveals that, once global supply chains and import content are taken into account, environmental burdens have largely been displaced to other regions (Peters et al., 2011; Wiedmann et al., 2015). From an entropy-based economics perspective, the decoupling narrative is approached with structural skepticism, since the problem is not only the spatial redistribution of environmental pressure, but the irreversible consumption of low-entropy matter and energy. Efficiency gains and technological substitution may reduce exergy losses; yet, given physical irreversibility and rebound effects, there is no guarantee that total throughput will decline in absolute terms over the long run (Georgescu-Roegen, 1971; Sorrell, 2009; Ayres & Warr, 2009). Accordingly, within an entropic framework the central question is not whether growth can be decoupled from environmental impacts, but how welfare can be maintained within biophysical limits even if decoupling fails to materialize. It is precisely here that the steady-state approach offers an institutional solution: rather than relying on the empirical success of decoupling, it constrains economic scale through physical ceilings and reorganizes distribution and allocation within those limits (Daly, 1991; Daly & Farley, 2011).

5. From Measurement to Rules: A Policy Skeleton

This section examines how the analytical framework grounded in entropy and material–energetic throughput is transferred into the policy domain via measurable indicators and binding rules. The aim is to anchor economic decision-making not only in price signals but also within an institutional architecture that reflects biophysical constraints. The theoretical point of departure is Daly's sequencing of "scale–distribution–allocation": first, the economic scale is fixed within biophysical limits; next, distributional mechanisms are specified in accordance with principles of justice; finally, allocation proceeds—within those limits—through prices and incentives (Daly 1991; Daly & Farley 2011).

First, the measurement and accounting layer must be established. Environmental–economic accounting systems (SEEA) integrate energy and material flows into national accounts, thereby rendering resource extraction, emission streams, and natural-capital depreciation trackable within a coherent accounting language (UN 2012). In parallel, material flow accounts (MFA) disaggregate the mass entering and leaving the economy by product/process categories (Krausmann et al. 2017). Where feasible, exergy accounting is incorporated to make visible, at the sectoral level, both the capacity of consumed energy to be converted into useful work and the exergy destroyed within processes; this shifts efficiency and substitution debates onto a terrain attentive to the quality of energy (Serrenho, Warr & Ayres 2016).

Second, the biophysical limits derived from the measurement infrastructure are translated into clear, binding rules. Three core rules stand out: (i) in renewable stocks, the harvest rate must not exceed the natural regeneration rate; that is, annual withdrawals are kept below the stock's annual net increment; (ii) for nonrenewable resources, an attenuating extraction path is followed; the rate of use is progressively reduced in line with the pace at which renewable infrastructure capable of providing the same services is installed and scaled; (iii) for stock pollutants, flows are constrained so as not to exceed assimilative capacity; in particular, for CO_2, annual emissions caps are defined within the framework of scientifically grounded carbon budgets (Daly 1991; Daly & Farley 2011). These rules institutionally guarantee an "upper bound," regardless of the direction in which prices may signal.

Third, the architecture of allocation and incentives is designed within these limits. For stock pollutants, an effective and equitable solution is a cap–auction–trade regime: rights are allocated by auction under a cap derived from the scientific budget (thereby socializing scarcity rents), and trading in a secondary market is permitted to enhance efficiency; the proceeds are returned to society via per-capita dividends or transition investments (Daly 1996; Daly & Farley 2011). When damage curves are steep and uncertain, the welfare superiority of quantity instruments over price instruments can be justified within Weitzman's (1974) framework. That said, price instruments such as a carbon tax and feebates serve complementary functions; when combined with directed technical-change policies (R&D support, standards, public procurement), they accelerate the diffusion of low-carbon technologies (Acemoglu et al. 2012).

In renewable-stock management, stock assessment and the total allowable catch (TAC) are set annually on the basis of scientific evidence; in adverse cycles, control rules that automatically ratchet quotas downward are applied; and basin-based "safe yield" principles govern water allocation. The objective is to manage within a precautionary range that secures long-run yield rather than targeting the risky levels around MSY (Daly 1991; Daly & Farley 2011). For nonrenewable resources, tying the resource (Hotelling) rent to an investment rule—i.e., allocating the rent to reproducible capital—offers a transition path consistent with asset-based sustainability accounting (Hartwick 1977; Dasgupta & Heal 1979). In this way, Daly's physical-cap approach is institutionally articulated with the asset-valuation strand of welfare theory (Arrow et al. 2012).

On the product and materials policy front, design and market instruments are deployed in tandem. Design standards (durability, repairability, disassemblability, recovery rates), extended producer responsibility, and deposit–refund schemes aim to close material loops and reduce exergy losses; green public procurement coordinates demand in this direction. These instruments are targeted using MFA/SEEA indicators and are monitored through regular MRV (measurement–reporting–verification) processes (UN 2012; Krausmann et al. 2017; Daly & Farley 2011).

Finally, the governance and equity dimension is an integral component of the architecture. Cap–auction–dividend designs socialize carbon and resource rents, generating a net positive flow for lower-income groups; ecological tax reform lightens the burden on labor/capital while pricing throughput. Polycentric governance arrangements enhance compliance and implementation capacity by coupling national caps with local knowledge and monitoring institutions (Ostrom 1990; Daly 1996). The welfare linkage is accounted for through regularly reported green NNP, genuine savings, and natural-capital balance sheets, thereby giving practical expression to the dynamic welfare-measurement connection in the Weitzman (1976) tradition (Weitzman 1976; Arrow et al. 2012; UN 2012).

5.1. From Accounting to Rules: Applied Illustrations

This article primarily traces—through the lens of the history of economic thought—the theoretical role of the concepts of entropy and exergy along the intellectual trajectory from Georgescu-Roegen to Daly. Nevertheless, to make the policy counterpart of the argument explicit and to concretize the "measurement/accounting → rule → institution" chain—particularly by placing in an applied context the conditions under which price-based instruments (taxation) versus quantity-based instruments become salient—the following sub-section is added. Focusing chiefly on the EU ETS and California's cap-and-trade program, the sub-section synthesizes selected findings from the empirical evaluation literature to render key design lessons visible; it does not seek to provide an extensive methodological discussion or to produce new empirical estimates.

Within a carbon-budget logic, the core of designing a "quantity instrument" is that a declining cap effectively locks the aggregate emissions trajectory onto a path consistent with the budget. The trading mechanism delivers cost-effective compliance by reallocating abatement toward units with lower marginal abatement costs. The empirical evaluation literature indicates that the effectiveness of this approach depends not merely on the "spot price level," but on institutional credibility, the stringency of the cap, the allocation/auction architecture, and the broader mix of complementary policies.

EU ETS emissions and economic performance: A sectoral evaluation based on a counterfactual emissions dataset finds that, even during low-price phases, the EU ETS abated roughly 1.2 billion tons of CO_2 (about 3.8%) over 2008–2016; it suggests that the operative mechanism may run through an expectations/credibility channel, whereby the prospect of future tightening shapes current behavior (Bayer & Aklin, 2020). A large-scale study using firm-/installation-level matching and difference-in-differences (DiD) estimates reports around a 10% reduction in emissions among regulated installations over 2005–2012, while finding no statistically significant adverse effects on profitability or employment; if anything, the results are consistent with increases in revenues and fixed assets (Dechezleprêtre, Nachtigall, & Venmans, 2023).

EU ETS – innovation (directed technological change): With respect to the EU ETS's "dynamic efficiency," there is strong micro-level evidence that regulated firms increased low-carbon patenting and innovation. For instance, one study shows that low-carbon patenting rose by roughly 10% among regulated firms, and that this increase did not occur by fully displacing other types of innovation (i.e., there is no evidence of crowding out) (Calel & Dechezleprêtre, 2016). At the same time, the same study emphasizes that only a small share of the overall increase in low-carbon patents in Europe can be attributed to the ETS, suggesting that the ETS should be viewed not as the sole determinant of innovation dynamics, but as part of a broader package of complementary R&D policies, standards, and incentives (Calel & Dechezleprêtre, 2016).

California cap-and-trade – cross-sectoral heterogeneity and the policy mix: A study evaluating California's cap-and-trade program using a synthetic control approach reports that the broader policy package produced a pronounced decline in the electricity sector (emissions 48% lower than the counterfactual), while yielding a pattern consistent with 6% higher emissions in the industrial sector relative to the counterfactual. This finding indicates that cap-and-trade does not generate a uniform effect across the economy; rather, differences in coverage, the strength of the price signal, the available set of technological options, and complementary regulations can sharply differentiate outcomes across sectors (Lessmann & Kramer, 2024).

California cap-and-trade – leakage and "resource shuffling" risks: Under conditions of regional or incomplete coverage—especially where electricity imports and interconnections with neighboring grids are significant—cap-and-trade design can be vulnerable to emissions leakage and to reallocation behaviors commonly described as "resource shuffling." For California's electricity sector, evidence indicating both a non-trivial *ex ante* leakage potential and *ex post* patterns that are partly consistent with resource shuffling further underscores the importance of border adjustments, allocation rules, and robust MRV (measurement, reporting, and verification) capacity in the architecture of a quantity-based instrument (Lo Prete, Tyagi, & Xu, 2024).

In the United Kingdom, carbon budgets constitute an institutionalized "quantity rule" designed to govern the climate target through pre-specified aggregate emissions limits rather than leaving it to the price signal. The UK Climate Change Committee's (CCC) *Net Zero* report and its carbon budget documents systematically articulate the budget logic—covering the level of the budget, its periodization, and progress monitoring—in the language of policy design and evaluation (UK Climate Change Committee, 2019, 2025). This framework is consistent with Weitzman's (1974) intuition that, where threshold risks and uncertainty are high, quantity-based instruments hold an advantage.

There are also applied academic examples of translating the "carbon budget" idea to the sectoral/meso level. For instance, studies that methodologically develop a sectoral carbon budget approach for the building/construction sector—and that operationalize the "cap–pathway–assessment" logic—show that budgeting can function not only as a national target-setting device but also as an instrument for evaluation and policy targeting (Steininger et al., 2020; Habert et al., 2020). In addition, political–institutional assessments of the performance of UK climate governance discuss—within an empirical and historical framework—the role carbon budgets play in the policy process, including the operation of advisory bodies, monitoring practices, and patterns of political conflict and compromise (Lockwood, 2021).

The acceptability and perceived fairness of carbon policy depend critically on how revenues are used. In this regard, the "dividend/rebate" approach has been examined extensively in both the empirical public-opinion literature and the distributional-impact literature.

In terms of public support: A large-sample, incentivized experimental study showing how alternative revenue-recycling designs (e.g., an equal per-capita "climate dividend") shift support levels makes the political-economy significance of revenue returns concrete (Woerner et al., 2024).

Effects of rebate programs: An empirical study examining how carbon-tax rebate programs shape public support finds that a rebate, on its own, may not automatically generate support—thereby underscoring the importance of policy design (Mildenberger et al., 2022).

Distributional impacts: A classic applied study that analyzes the household burden of carbon pricing using microdata within a general-equilibrium framework shows that revenue recycling can mitigate regressive effects (Rausch et al., 2011).

Broader synthesis: A meta-analysis reviewing the distributional impacts of carbon pricing systematically classifies which types of revenue recycling tend to produce more "compensatory/progressive" outcomes (Ohlendorf et al., 2021).

Sweden: A study that estimates the causal effect of a carbon tax on transport fuels on emissions using a synthetic control approach shows that carbon taxes can generate measurable impacts in the real world (Andersson, 2019).

British Columbia (BC): A comprehensive review of the "revenue-neutral carbon tax" experience synthesizes a wide range of empirical findings on emissions, economic performance, and distributional outcomes (Murray & Rivers, 2015). A study employing a detailed empirical design to examine effects on gasoline consumption shows that the carbon tax significantly reduced fuel use (Lawley & Thivierge, 2018). Using panel-data and synthetic control methods, another study finds that the tax lowered natural gas consumption, thereby making the "price signal plus policy" effect empirically tangible (Xiang & Lawley, 2019). Taken together, this case literature indicates that there are real-world policy implementations that effectively test the entropy-based concern with "scale/throughput" at the level of institutional design, and it also demonstrates—on empirical grounds—why revenue-recycling design (dividend, tax reductions, or other schemes) is critical for both distributional outcomes and political support.

A prerequisite for a policy architecture grounded in the entropy/throughput approach is that biophysical flows be measurable. The *SEEA 2012 Central Framework* links environmental flows and assets to a standardized system consistent with national accounts (United Nations, 2012). *Economy-Wide Material Flow Accounts* (EW-MFA) provide a methodological framework for the regular monitoring of material flows into and out of the economy (resource extraction, trade, and waste) (Eurostat, 2018). Such accounting infrastructures supply the technical basis for tracking quantity rules such as caps and budgets and for establishing corrective mechanisms; the OECD's green growth indicators framework likewise provides policy-oriented support for this linkage (OECD, 2011). Moreover, the MFA-based literature has shown how resource/throughput indicators can be extended through consumption-based measurement approaches (Wiedmann et al., 2015; Krausmann et al., 2017). In this way, "scale" becomes a policy object not only in terms of emissions but also through material flows.

6. Conclusion

This study reads the intellectual line running from Georgescu-Roegen's bioeconomic critique grounded in the entropy law to Daly's steady-state program not by flattening it under a single "ecological economics" label, but as a process of translation and reconstruction that extends from an ontological rupture to the design of institutional rules. The text's central thesis is that the entropy–exergy–throughput framework does not merely generate a critique of economic growth; it also offers an institutional design logic for sustainability policies by establishing a "theory → indicator → rule" chain that operates between measurable metrics and binding rules.

Within this framework, the first core finding is that conceiving the economic process not through mechanical/cyclical equilibrium metaphors but as a physical process defined by the irreversible transformation of low-entropy resources renders visible the problem of "energy quality," which often remains implicit in production functions. Such an ontology strengthens the conditionality of substitution optimism. Low-exergy forms of energy, regardless of their price, may be incapable of performing certain productive functions, thereby structurally narrowing the scope for substitution; accordingly, the economic decision problem is constrained not only by cost levels but also by the "physical suitability" conditions of production.

The second finding is that the transition from Georgescu-Roegen to Daly represents a shift in orientation: from the analytic radicalism of an entropy-based ontological critique—marked by a deliberate "distance" at the level of policy—to the translation of that critique into a politically and institutionally implementable program. Daly's contribution lies in his refusal to reduce entropic constraints to a singular claim such as "the impossibility of growth"; instead, he translates them into an institutional language centered on the principle that economic scale must be determined, in a rule-based manner, within biophysical limits. The ordering "scale first, then distribution, and only lastly allocation" thereby becomes a design principle, enabling the construction of a policy architecture that extends from physical ceilings to cap-auction-trade–type arrangements.

The "enduring traces" of this translation can be traced across three planes. The first lies in the domain of measurement and accounting: the environmental extensions of national accounts (SEEA) and material flow accounts (MFA) make it possible to track welfare not solely through flow variables (GDP), but through an asset-based logic (including natural capital), by aligning resource extraction and waste/emissions flows with national accounting frameworks. Weitzman's dynamic welfare identity further strengthens the theoretical foundations of indicators such as "green NNP" and genuine savings by establishing the equivalence between welfare change and net investment valued at shadow prices. A third trace is most visible in rule-based policy design. Quantity-based instruments—such as carbon budgets, harvest rules, and decline pathways—reinforce their claim to normative superiority in domains characterized by high uncertainty and significant threshold risks; here, Weitzman's "prices versus quantities" framework connects instrument choice to a systematic decision logic.

Accordingly, the third finding is that the question of policy instrument choice (price-based versus quantity-based instruments) can be reformulated under conditions of uncertainty, threshold risk, and substitutability: (i) where threshold risk is high and substitution capacity is low, quantity instruments (budgets/ceilings/quotas) should be prioritized; (ii) where threshold risk is relatively low and substitution capacity is high, price instruments may prove more effective. In this way, the debate moves beyond the binary "prices or quantities?" toward the conditional question "which instrument under which conditions?". The institutional counterpart of this decision logic is to establish the ordering "scale first (rule), then allocation (price)"—without excluding the price mechanism, yet without granting it primacy. First, an accounting and monitoring infrastructure (SEEA, EW-MFA, MRV standards) is put in place; next, scale is bound through quantity rules such as carbon/material budgets; finally, arrangements such as cap–auction–trade or cap–auction–dividend aim both at cost-effective allocation and at the public capture of scarcity rents (the justice dimension).

At this juncture, the reference to the applied evaluation literature underscores that a "rule-based scaling" approach is not an abstract normative proposal; rather, it is one whose success can be tested in the real world, contingent on factors such as the stringency of the cap, institutional credibility, the architecture of allocation and auctions, and the broader mix of complementary policies. That empirical assessments of cap-and-trade regimes demonstrate heterogeneous effects and the decisive role of fine-grained design features, in turn, reinforces the entropy-based approach's emphasis on institutional design.

In recent years, the evidentiary basis of claims about absolute and sustained decoupling has also become the subject of intense debate, owing to issues of indicator choice (production-based versus consumption-based), time horizon, and geographical spillovers. Systematic reviews suggest that the evidence for a persistent decoupling of resource use and emissions from GDP at the global scale is limited, and that some regional "successes" can be weakened by externalization dynamics and imported-content effects (Haberl et al., 2020; Hickel & Kallis, 2020). These findings support the entropic framework's insistence on the triad of physical ceilings, directed innovation, and equitable allocation, while also rendering it imperative that policy design remain context-sensitive and explicitly experimental.

Nevertheless, the study's own limitations are explicit. While the text develops a theoretical and institutional synthesis within the axis of the history of economic thought, it deliberately restricts any claim to producing a new empirical estimation or constructing a full-fledged formal model—as reflected, for instance, in the positioning of applied examples largely at the level of a "summary of the evaluation literature."

This limitation renders the future research agenda more salient and calls for progress on at least three levels:

1. **Theoretical and measurement integration:** Through systematic comparisons of macroeconomic models that represent energy not merely as a "quantity" but as exergy/useful work, substitution elasticities should be decomposed into sector-specific components and made sensitive to carrier- and quality-differentiation. In parallel, welfare metrics consistent with carbon–material budgets (green NNP, genuine savings, inclusive wealth) should be integrated within a common valuation backbone. In this context, developing exergy-accounting panels—disaggregated by country and sector and consistent with SEEA and MFA series—should be a priority.
2. **Limits of dynamic substitution and directed innovation:** It is necessary to disentangle—both formally and empirically—under what conditions policies for directed technical change (pricing + R&D + standards) can genuinely raise long-run substitution elasticities, and in which sectors substitution remains structurally constrained due to entropic ceilings. Findings such as the "efficiency paradox" should be calibrated with respect to general-equilibrium effects and time-horizon distinctions, thereby recasting the question from "price or rule?" into the triad "which rule + which price + which mission?".

Governance and just transition: The distributional effects of cap-auction-dividend arrangements, their interaction with labor displacement dynamics, and their implications for regional inequalities should be measured using micro-data and causal methods. In addition, field-based research in the Ostrom tradition should deepen our understanding of how polycentric governance architectures mobilize local knowledge and monitoring, and to what extent community-based rules can operate complementarily with national ceilings (Ostrom, 1990). Finally, this agenda should also examine how carbon budgets and material targets can be embedded fairly and effectively into the global trade regime through border adjustment mechanisms (e.g., CBAM).

The practical backbone of this research agenda is the institutionalization of a "measure → cap → allocate → monitor and correct" cycle. Its core components include: the regular reporting of SEEA/MFA/exergy accounts under MRV standards; the multi-year announcement and legal enforceability of carbon and material budgets; automatic adjustment rules triggered in cases of budget overshoot; and the transparent earmarking of resulting scarcity rents toward dividends and/or transition investments.

In conclusion, the entropy-based lineage running from Georgescu-Roegen to Daly yields two enduring contributions to the history of economic thought: (1) an ontological correction that reconstructs the economy as a material–energetic process beyond mere "monetary magnitudes"; and (2) a rule-design approach derived from this ontology and subject to oversight through measurement systems. The article's final proposition is that, in the age of sustainability, an effective and just policy architecture requires thinking jointly about quantity rules that institutionalize biophysical limits and market allocation operating within those limits, rather than relying on substitution optimism driven primarily by price signals. Looking ahead, the integration of (i) exergy-based macro representations, (ii) asset-based welfare measurement, and (iii) rule-based governance will be decisive for both the academic literature and policy practice.

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