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Thermoeconomics under the Zaragoza and Berlin Schools: A Comparative Analysis

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Abstract:

Thermoeconomics has evolved through different methodological traditions, among which the Berlin and Zaragoza approaches are particularly influential. Both are grounded in the second law of thermodynamics but offer complementary perspectives. The Berlin tradition focuses on the analysis and optimization of industrial systems, emphasizing exergy destruction, exergy losses and exergoeconomic cost calculations that integrate physical and economic information. In contrast, the Zaragoza tradition extends second-law analysis to long-term sustainability and resource availability, building on the idea of entropic degradation of natural capital. It introduces concepts such as exergy replacement costs, thermodynamic rarity, loss of resource accessibility, and resource depletion due to dispersion and irreversible damage.

Within the thermoeconomic community, different views exist regarding reference environments, irreversibility, the purpose of exergy indicators, and the relationship between physical and economic costs. These differences should be seen as complementary rather than contradictory, reflecting the need to address challenges at multiple scales—from industrial optimization to long-term sustainability assessment.

This work provides a systematic comparison of the Berlin and Zaragoza schools, analyzing their conceptual foundations, methodologies and objectives. Particular attention is given to their points of convergence and methodological differences across scales, including the treatment of exergy destruction, resource scarcity, environmental degradation, and cost allocation, with the aim of identifying synergies that bridge industrial optimization and global sustainability assessment.

Keywords:

Thermoeconomis; Exergoeconomis; Exergoenvironmental analysis; Advanced Exergy-based Methods; Symbolic Thermoeconomics; Thanatia; Pristinia; Exergoecology

1. Introduction

Thermoeconomics is a specialized branch of engineering that integrates exergy analysis with economic principles to provide system designers and operators with information crucial to the creation of cost-effective plants. Frequently described as exergy-aided cost minimization, it is founded on the principle that exergy, rather than energy or mass, is the only rational basis for assigning monetary values to energy carriers and thermodynamic inefficiencies, such as exergy destruction and losses. The conceptual roots of this discipline were first suggested by J.H. Keenan in 1932 [1]. Formal modern development took place in the 1960s mainly through the work of Tribus, Elsayed and Evans [2], [3], who introduced the term "thermoeconomics," as well as Edward Obert and Richard Gaggioli [4]. During the 1980s and 1990s, the field was further consolidated through the contributions of key researchers such as Szargut, Tsatsaronis, von Spakovsky, Frangopoulos, Sciubba and Valero, among others, establishing a solid methodological framework for the analysis and optimization of thermal systems.

Over time, it became evident that thermoeconomics goes beyond the optimization of energy systems, addressing more fundamental questions related to the process of cost formation. In this sense, the discipline has evolved toward a deeper interpretation of economic value grounded in physical principles, linking thermodynamic irreversibilities with resource consumption and cost generation. This perspective has opened the way to broader applications, including sustainability assessment and resource accounting, reinforcing the role of the Second Law of Thermodynamics as a unifying framework for analyzing both engineered systems and the use of natural resources.

Thermoeconomics has established itself as a fundamental discipline for understanding energy and material systems, largely through two influential methodological traditions: the Berlin and Zaragoza schools. While both share a common foundation in the Second Law of Thermodynamics, they have developed distinct perspectives that address the challenges of efficiency and resource management at different scales. These traditions represent complementary ways of addressing challenges, ranging from the specific optimization of industrial plants to the global assessment of long-term resource use and environmental transformations.

This article provides a systematic and constructive comparison of these two thermoeconomic approaches. By analyzing their conceptual foundations and methodological formulations, we aim to highlight areas of convergence, while identifying opportunities for integration. The ultimate goal is to propose a roadmap that leverages the strengths of both traditions to advance a comprehensive, Second-Law-based sustainability science.

2. The Berlin Perspective: A Comprehensive Framework for Energy System Evaluation

The Berlin School[1] of energy engineering, centered at the Technical University of Berlin (TU Berlin) and led by George Tsatsaronis (GT), has significantly contributed to shaping the field. This school of thought is characterized by the integration of thermodynamics with economics and environmental science, using exergy as the sole rational basis for assigning costs and environmental impacts to energy streams.

2.1. Foundational Work and the Birth of Exergoeconomics

In his first publication on the subject [5], GT coined the term exergoeconomics (to describe a specific rational combination of exergetic and economic analyses at the component level), generalized the terms fuel and product (the latter according to the purpose of a component) as well as the formulations of the exergy balances and cost balances, introduced the variables cost per unit of exergy for fuel and product, cost difference (which later was replaced by the relative cost difference) and exergoeconomic factor. These variables are used for consistent evaluation purposes in all of the following developments by the Berlin Group. The foundational methodology was established in a seminal 1984 EPRI report [6], providing a general procedure for evaluating energy systems and applied to coal-fired power plants. This early work proved that thermodynamic inefficiencies (exergy destruction) are directly linked to economic performance [7], [8]. These principles were further consolidated in the widely cited textbook "Thermal Design and Optimization" 9].

2.2. Standardizing Cost Assignment: SPECO and Cogeneration

Early refinements in exergy costing demonstrated that thermodynamic values are essential for understanding the cost formation process in thermal systems [10]. To address ambiguities in cost assignment, the school in collaboration with Lazzaretto [11] developed the Specific Exergy Costing (SPECO) methodology. SPECO applies principles from business administration through its fundamental F and P principles, ensuring that thermodynamic definitions of fuel and product are consistently translated into costing equations. This rigorous approach was previously applied to various systems, including the thermoeconomic design of complex IGCC power plants [12]. In some cases, the cost and environmental-impact allocation process is improved by splitting the total exergy of a stream into physical and chemical exergy and further splitting the physical exergy into thermal and mechanical exergy and the chemical exergy into reactive and non-reactive exergy [9]. In [13] a complex and costly but fairer than the others allocation process is presented and applied to a cogeneration system.

2.3. Advanced Exergy-Based Methods

Over the last almost three decades, the Institute for Energy Engineering at TU Berlin has pioneered the Advanced Exergy-Based Methods [14]–[16] to overcome the limitations of conventional analyses. These methods split variables such as exergy destruction, costs and environmental impacts into more detailed parts [17]–[19]:

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[1] The terms “Berlin School” or "Berlin Group” include the contributions of the research groups formed and led by G. Tsatsaronis at Desert Research Institute (1982-1986), Tennessee Tech University (1986-1994) and Technical University of Berlin (1994-2024).

- Avoidable vs. Unavoidable: Identifies the portion of inefficiencies, costs, and environmental impacts that can realistically be reduced through technological improvement, and distinguishes them from the unavoidable values.
- Endogenous vs. Exogenous: Quantifies how much of a component's inefficiency, costs, and environmental impact is caused by itself versus through the interactions with other components.

These advanced tools have been applied to optimize refrigeration systems [20], chemical processes [21], [22], and large-scale power plants [23], [24]. Other efforts include 3-D exergy-based methods that offer a spatial understanding of where system improvements are most effective [25]. Finally, the recent work by R. Castillo demonstrates the importance of streams recirculating within the overall system to the thermodynamic, economic, and environmental performance of the system [26], [27].

2.4. Exergoenvironmental Analysis and Sustainability

The framework was expanded to include ecology through exergoenvironmental analysis [28], [29]. By combining exergy analysis with Life Cycle Assessment (LCA), researchers assign environmental impacts to exergy streams using indicators like the Eco-indicator 99. A feature of this analysis is the tracking of pollutant formation within components. This specifically tracks chemical species generated during reactions, including CO, CO2, CH4, N2O, NOx, and SOx [30]. The total environmental impact of a component is thus the sum of its construction-related impacts, its pollutant formation, and the impact associated with its exergy destruction. This approach has guided the improvement of steam methane reforming for hydrogen production and SOFC systems [31] or power plants with CO2 capture [32]. Recent developments explore the relationship between monetary costs and environmental impacts, revealing critical trade-offs for power plant designers [32].

3. The Zaragoza School: A Thermodynamic Theory of Cost and Natural Resources Assessment

The Zaragoza school of thermoeconomics, led by Antonio Valero at the University of Zaragoza, is founded on the principle that thermodynamics is fundamentally a physics for the value of natural resources [33]. While other traditions prioritize the optimization of human-engineered systems through economic feasibility, the Zaragoza school seeks to bridge the gap between physics and economics by quantifying the physical sacrifice of resources required to achieve a productive purpose. This perspective asserts that because every exergy loss is a physical indicator of irreversibility, the Second Law provides the only objective basis for a theory of cost [34].

3.1. Foundational work: The exergy cost theory

The school's cornerstone, the Exergy Cost Theory (ECT), was established in 1986 to measure the cumulative amount of exergy resources consumed to manufacture a product within defined boundaries [35]. In this framework, the exergy cost (expressed in kWh or GJ) represents the total amount of resource consumption required to generate a given flow within a productive structure. Its evaluation is based on the definition of the exergy efficiency of each component within the system, linking local performance to the overall resource consumption. To standardize cost allocation, the school developed the F-P-R rules (Fuel-Product-Residue), which distribute costs based on the thermodynamic purpose of each component [36], [37]. To provide rigorous mathematical foundations, Antonio Valero and César Torres [38] integrated these principles with Leontief's Input-Output analysis, creating a matrix-based approach where the physical structure of energy interrelationships is the "primal" model and the cost structure is its mathematical "dual".

However, the set of costs depended on the definitions assigned to each component. To develop a physical theory of cost that is independent of these definitions, a set of linearized characteristic equations was proposed that relate the exergies of the input flows to those of the output of each piece of equipment, based on its physical behaviour. This transformation constitutes "Structural Theory" and does not represent a simple reformulation of thermoeconomics, but rather an extension of thermodynamics to any system composed of components interconnected via exergy flows. In this sense, the "exergy cost' becomes a new thermodynamic function, which rigorously measures the amount of irreversibilities that have been generated to reach the current state of a given flow, whether it be a product or a waste stream.

Thermoeconomic diagnosis builds upon this framework, and consists of a perturbation theory that identifies malfunctions (intrinsic failures) and dysfunctions (induced irreversibilities), enabling operators to quantify the additional resource consumption attributable to specific component failures. This approach has been successfully applied, for example, to the diagnosis of a thermal power station[39]. To advance the diagnosis of complex systems, the school introduced the Relative Free Energy function and the deterioration temperature parameter. These tools allow efficiency to be defined by a component's intrinsic physical behaviour and its specific deterioration path rather than external, arbitrary environmental conditions [40].

3.2. Thanatia and mineral resource assessment

In parallel, the Zaragoza school introduced Exergoecology in 1998 as a rigorous thermodynamic framework for the assessment of natural resources [41]. This methodology extended the principles of thermoeconomics to the evaluation of natural fluxes and geological endowment, providing a physical basis for resource accounting [42], [43]. A major milestone in resource accounting was reached through the work of Thanatia [44], [45]. Thanatia is a conceptual model of a "commercially exhausted" Earth where all fossil fuels are burned and all mineral deposits are dispersed in the crust [46], [47]. This baseline allowed the school to overcome a significant limitation: the fact that chemical exergy often fails to align with social value or practical scarcity of non-energy resources. They proposed the concept of Exergy Replacement Cost (ERC), which identifies concentration exergy and not chemical exergy as the key factor to assess the physical value of mineral resources. ERC is assessed as the exergy effort required to reconcentrate minerals from Thanatia back to their original mine conditions (with prevailing technologies), effectively quantifying the "natural bonus" or geological heritage lost through extraction, i.e., the shadow cost of resource depletion. It also allows for a more rational allocation of costs among material flows. In turn, the concept of Thermodynamic Rarity combines the hidden natural bonus (ERC) with the real mining and refining costs, providing a stable indicator of absolute scarcity independent of market price fluctuations [48]–[50]. The concept of thermodynamic rarity can be generalized to any object. It is additive, and its opposite would be abundance. It is measured in kWh. This concept was applied to analyse the mineral capital degradation of several regions in the world [51], [52] and to several industries such as the automotive [53] or renewable technologies [54], [55].

3.3. Pristinia and topsoil fertility assessment

Additionally, The Zaragoza School has extended exergy analysis to ecological systems through the concepts of Pristinia and topsoil exergy. As opposed to Thanatia, Pristinia defines a reference state representing undisturbed natural conditions, enabling the assessment of ecosystem degradation [56]. The exergy of topsoil quantifies soil as a form of natural capital, capturing its formation and functional value in terms of fertility. This is characterized through three key components: nutrients (OPTNUT), organic matter (OPTSOM), and optimum biota (OPTMIC). Together, these concepts provide a thermodynamic basis to evaluate land use impacts and resource depletion [57].

3.4. Circular Thermoeconomics

Recent developments have formulated Circular Thermoeconomics [58], [59], which enables the assessment of the cost associated with waste generated alongside products, recognizing that all residues possess exergy—thermal, mechanical, and chemical (both in concentration and composition)—just like the final products. By applying the irreversibility–cost relationship, the school tracks the footprint of exergy destruction from natural resources to final products, identifying the "irreversibility backpack" of objects [60]. Within this framework, waste is treated as an "external irreversibility" that should be internalized: before being released into the environment, its exergy can be partially recovered, or additional resources must be expended to mitigate it up to a "pinch point of recovery," where further recycling becomes thermodynamically counterproductive. This approach extends thermoeconomic analysis far beyond conventional energy systems, encompassing extractive, industrial, and recycling chains, and enabling the evaluation of impacts throughout the full life cycle of any product. When waste ultimately enters the ecosphere, its irreversibility footprint is quantified based on the natural rarity of all resources consumed in its formation, as well as its impact on the biosphere, framed in terms of the nine planetary boundaries identified by Rockström et al [61]: climate change, ocean acidification, stratospheric ozone depletion, nitrogen and phosphorus cycles, global freshwater use, deforestation and topsoil degradation, biodiversity loss, chemical pollution, and atmospheric aerosol loading. By expressing the total resource load in objective physical units (e.g., kWh or GJ), this methodology provides a rigorous, physically grounded basis for assessing intergenerational justice and the true ecological cost of human activity [62].

4. Bridging Industrial Optimization and Global Sustainability: A Constructive Comparison of the Berlin and Zaragoza Schools of Thermoeconomics

Thermoeconomics has evolved through two primary methodological traditions that, while sharing a foundation in the Second Law of Thermodynamics, offer complementary perspectives on the functioning of energy systems and the transformation of natural resources. The Berlin tradition, led by George Tsatsaronis and Tatiana Morosuk, focuses on the evaluation and optimization of industrial systems. In contrast, the Zaragoza tradition, led by Antonio Valero, César Torres, and Alicia Valero, extends these principles to long-term sustainability and the assessment of natural resource availability.

4.1. Conceptual Convergences

Both schools agree that thermodynamics provides the essential scientific basis for resource conservation and that exergy is the most appropriate numeraire, as it captures both the quantity and quality of energy and matter. This common foundation enables a rational distribution of production costs and the identification of the "hidden" costs associated with irreversibility. In this context, both traditions have addressed the challenge of cost allocation in co-products through exergy-based methodologies—such as the Berlin School's SPECO approach and the Zaragoza School's F-P-R rules—thus overcoming the limitations of conventional mass- or energy-based criteria. However, structural theory overlay a relationship between cost and physical performance, rather than a relationship between cost and efficiency.

Furthermore, the Zaragoza School extends this framework to non-energy systems by introducing the concept of Exergy Replacement Cost, which enables a more consistent allocation of costs in material systems. This approach addresses the limitations of chemical exergy, which does not adequately reflect the social value or scarcity of raw materials, and provides a more meaningful basis for analysing resource use and depletion in non-energetic production systems.

A central point of convergence also lies in the interpretation of irreversibility. While industrial applications often rely on precise technical concepts such as internal exergy destruction and external exergy losses, both schools recognize these as specific expressions of the broader principle of irreversibility governed by the Second Law (Gouy-Stodola theorem). This shared understanding facilitates communication across disciplines: exergy-based variables support rigorous technical analysis, while more general concepts such as degradation and irreversibility help convey the long-term physical impacts of human activity on the ecosphere to a wider audience.

Finally, both traditions intersect in their treatment of the relationship between physical and economic costs, based on exergy criteria. The Second Law is used as a universal framework to quantify degradation, although with different emphases depending on the analytical objective.

4.2. Methodological Differences: Industrial vs. Ecological Scale

The primary distinction between the two schools lies in their analytical scope and purpose. The Berlin perspective focuses on the optimization of human-engineered energy industrial systems in the short and medium term. It provides analytical tools for evaluating and improving system performance by quantifying exergy destruction and losses, and by distinguishing between avoidable and unavoidable as well as endogenous and exogenous inefficiencies. A key strength of this approach is its integration of physical behavior with economic reality through exergoeconomic cost procedures, enabling engineers to identify practical improvement options. From this perspective, incorporating monetary values is essential, as real-world decisions related to energy are very often driven by economic feasibility.

In contrast, the Zaragoza tradition extends the analysis to long-term sustainability and the depletion of natural resources at the planetary scale. It focuses on the "physical sacrifice" of resources by tracing the footprint of exergy destruction from the Earth's crust to final products. Building on the concept of the entropic degradation of natural capital, this approach introduces metrics such as exergy replacement costs and thermodynamic rarity to quantify resource depletion and the loss of accessibility. A central element is the development of a Physical Costing framework, which expresses costs in thermodynamic terms and remains independent of market prices, thereby capturing environmental damage and resource scarcity that are often overlooked in conventional economic assessments.

4.3. The Role of Money and the "Physics of Value"

A constructive debate exists regarding the integration of economic information:

Exergoeconomics asserts that while nature follows physical laws, engineering decisions are driven by economic feasibility. Therefore, it prioritizes integrating monetary costs (investment, maintenance) with thermodynamic performance. By incorporating monetary values (costs), this method provides essential guidelines for policymakers and individuals, acknowledging that most real-world decisions are fundamentally guided by economic feasibility. In this framework, the objective is to satisfy societal needs in the most sustainable yet acceptable and realistic way possible.

The Zaragoza tradition extends the Second Law to long-term sustainability and resource availability. Building on the concept of the entropic degradation of natural capital, it introduces metrics such as exergy replacement costs (ERC) and thermodynamic rarity to quantify the depletion of natural stocks and the loss of resource accessibility. This approach moves beyond market-based valuation, which often fails to capture environmental damage or true geological scarcity, and instead proposes a Physical Costing framework grounded in exergy. By expressing costs in universal energy units (e.g., kWh or GJ), it captures the "physical debt" that current generations impose on the future through the irreversible dispersion and degradation of resources. This perspective responds to a key limitation of conventional economic systems, which tend to treat nature as external and rely on price signals that do not reflect physical reality. In contrast, because natural processes are governed by energy and not monetary values, the Second Law provides a consistent and objective basis to assess degradation. As such, expressing sustainability in energy terms offers a more robust and scientifically grounded metric, independent of subjective economic or social criteria.

4.4. Reference Environments

Defining the "dead state" or reference environment (RE) is a key area of divergence:

Berlin prefers a standardized reference environment to ensure that results are comparable across different studies and analysts.

Zaragoza rather advocates for ad-hoc reference states tailored to specific problems, and introduces Thanatia as a baseline for assessing the exergy replacement costs of mineral resources or Pristinia as the reference state representing undisturbed natural conditions, enabling the assessment of topsoil degradation. For local issues—such as the scarcity of fresh water in a specific territory—ad hoc reference states or complementary agreements may be necessary to reflect local physical realities accurately

4.5. Circular Thermoeconomics and Waste Internalization

In the realm of environmental impact, the Berlin School extends its framework through exergoenvironmental analysis, combining exergy analysis with Life Cycle Assessment (LCA) to assign environmental impacts to exergy streams using indicators such as the Eco-indicator 99. This approach includes the tracking of pollutant formation within system components, integrating construction, operational emissions, and exergy destruction into a unified assessment, enabling the evaluation of trade-offs between thermodynamic efficiency, environmental impact, and economic performance.

The Zaragoza School, in turn, formulates Circular Thermoeconomics, which treats waste as “external irreversibilities” and provides a methodology to evaluate their physical cost throughout the production process. This framework analyzes the opportunities to internalize residual exergy before it leaves the system, recognizing that waste valorization itself generates new irreversibilities and additional residual streams. By doing so, it identifies “pinch points” beyond which further recycling becomes thermodynamically counterproductive. When waste is ultimately released into the ecosphere, its impact is no longer limited to its remaining exergy, but must be evaluated through the natural rarity of all resources involved in its formation, as well as its effects on the biosphere, linking thermodynamic analysis with global environmental limits.

Table 1 shows a comparison of both influential traditions.

Table 1. *Comparison of Influential Traditions*

Feature	The Berlin School (Tsatsaronis)	The Zaragoza School (Valero)
Primary Goal	Optimization of industrial energy systems	Assessment of global sustainability and resources
Analytical Scope	Technosphere (Society-to-Society)	Nature-Society-Nature (Ecosphere-to-Ecosphere)
Core Metric	Exergoeconomic costs (Monetary units/kWh)	Exergy costs / Physical costs (kWh/kWh or GJ)
Baseline / RE	Unique Standard Reference Environment	Ad hoc. For minerals, Thanatia (Commercial end of the planet); For topsoil, Pristinia
Scarcity Indicator	Market prices / LCA indicators	For minerals: Thermodynamic Rarity (ERC + Embodied Exergy)
Waste Treatment	Exergoenvironmental externalities (LCA units)	Internalized "Irreversibility Backpack" (Physical units)
Advanced Tools	Avoidable/Unavoidable/ Endogenous/Exogenous Exergy Destruction	Relative Free Energy (RFE) / Structural Theory

5. Conclusions

The Berlin and Zaragoza Schools represent two of the most influential and complementary traditions in thermoeconomics, both grounded in the Second Law of Thermodynamics but oriented toward different analytical scales and objectives. The Berlin School, centered at the Technical University of Berlin, focuses primarily on the analysis and optimization of engineered energy systems. Its methodology is built on rigorous exergy balances and the integration of thermodynamics with economic and environmental assessments through exergoeconomics and exergoenvironmental analysis. Key contributions include the development of standardized cost allocation procedures (e.g., SPECO) and advanced exergy-based methods that decompose inefficiencies into avoidable/unavoidable and endogenous/exogenous components. This approach provides powerful tools for improving the performance, cost-efficiency, and environmental impact of industrial processes.

In contrast, the Zaragoza School extends thermoeconomic principles beyond engineered systems to encompass natural resources, ecological systems, and long-term sustainability. Through the Exergy Cost Theory and Structural Theory, it provides a physically grounded interpretation of cost as cumulative exergy consumption. Its contributions include the concepts of Exergy Replacement Cost, Thermodynamic Rarity, Thanatia, and Pristinia, which enable the assessment of resource depletion, loss of natural capital, and ecosystem degradation. This framework is particularly suited for evaluating resource use across the full "Nature → Society → Nature" cycle.

While the Berlin approach emphasizes local optimization and system performance, the Zaragoza approach focuses on global resource accounting and intergenerational sustainability. Rather than conflicting, these perspectives are complementary: the former enhances the efficiency of technospheric processes, while the latter provides a broader context for assessing their long-term implications. Integrating both approaches offers a pathway toward a more comprehensive, second-law-based sustainability framework.

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