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Rules of the Spiral Economy: Thermodynamic Principles for Resource Use in a Finite World

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Abstract:

This contribution presents the Rules of the Spiral Economy, a framework grounded in the second law of thermodynamics that connects circular economy ambitions with physical reality. It combines thermodynamics, ecological economics, and industrial ecology into practical principles for designing, using, and recovering materials. Key ideas include avoiding unnecessary mixing, designing for disassembly, prioritizing reuse and repair over recycling, and recognizing unavoidable losses in material cycles. Unlike the circular economy, which often implies closed loops, the spiral economy acknowledges degradation, dispersion, and non-recoverable fractions. Its goal is not perfect circularity but the progressive reduction of losses across successive recovery loops. The framework offers a thermodynamically sound basis for resource assessment, engineering design, and policies consistent with finite resources and long-term sustainability.

Keywords:

Spiral economy; thermodynamics; recycling; exergy

1. Introduction: The Concept of Waste after the Second Law

Production and consumption systems are commonly evaluated in economic or environmental terms, yet all of them are ultimately governed by physical laws. Among these, the second law of thermodynamics is especially relevant because it establishes unavoidable limits to efficiency, recovery, and circularity. Any transformation of matter or energy generates irreversibilities and therefore some degree of waste. For this reason, a thermodynamic perspective provides a rigorous basis for understanding why residues arise and how they may be reduced. The second law of thermodynamics states that the input exergy of a process will always be greater than the output exergy:

Input exergy – Output exergy = Irreversibilities > 0

However, it does not specify whether these irreversibilities are internal or external to the process. Moreover, if we classify the purpose of the flows crossing the boundaries, we can identify the flows, measured in exergetic terms, into resources, products and waste [1], so that the above equation becomes:

Resources (F) – Products (P) = Internal irreversibilities (I) + Waste (R) > 0

One observes that there are two types of irreversibility: exergy destruction within a process, and exergy loss from flows across a boundary.

In the ecosphere, a residue is a residue if it has exergy, whether thermal (heat), mechanical (noise) or chemical (reactivity). Chemical residues can contaminate an environment due to concentrations and compositions. Their exergy eventually dissipates into the environment, resulting in external irreversibilities.

From a thermodynamic point of view, exergy can always be used. This is why the distinction between 'residues' as leftover flows and 'waste' as discarded flows is only practical, not conceptual. Similarly, waste can be energy waves or material flows, whether gaseous, liquid, solid or any multiphase or multicomponent mixture.

The second law amplifies the concept of residue to any exergy loss. Also “waste” which is commonly used for solid residues; however, waste is referred to here to any material either solid, liquid, gas or any mixture.

Waste production is universal and bothersome. We produce waste every time we make something, and maintaining its life also creates more waste. At the end of its life, every product becomes waste, meaning all resources become waste. The total amount of waste produced from the cradle to the grave of any product is its "irreversibility backpack".

Despite the second law, there are opportunities to significantly reduce the 'irreversibility backpack' of products. Based on this perspective, we propose the following rules, which are developed in the next sections.

2. The Rules of the Spiral Economy

Rule 1: Understand Entropy

Energy and material systems obey the Second Law of Thermodynamics: every transformation increases entropy, making perfect circularity impossible. Recycling can slow degradation, but mixing materials accelerates it and makes separation more difficult and costly [2], [3]. Separating materials at the source, such as mono-material packaging, lowers entropy and improves recoverability. By contrast, purification and demixing of complex products are among the most irreversible processes, requiring major energy and material inputs [4]. This explains why repair, reuse, and product longevity often preserve resources better than recycling, as they maintain products in a useful low-entropy state for longer. The objective is not to defeat entropy, but to delay it intelligently by minimizing dispersion and unnecessary mixing. In essence: do not mix things unnecessarily, because separation is costly. This perspective replaces the ideal of a circular economy into a more physically consistent “spiral” model, where every cycle retains less usable energy and materials progressively degrade.

Rule 2: Spiral Economy

The idea of a perfectly closed Circular Economy ignores a basic physical reality: every transformation degrades exergy through friction, heat losses, wear, dispersion, and contamination. Energy quality cannot be recycled, and materials progressively lose quantity and quality in each cycle, making perfect recyclability impossible. This limitation was already emphasized by Georgescu-Roegen [2], who proposed an unnecessary fourth law of thermodynamics stating that matter, like energy, undergoes irreversible qualitative degradation, implying fundamental limits to perpetual recycling and continuous economic growth. For this reason, what is often promoted as a Circular Economy is better understood as a marketing coup, since it suggests a level of physical closure that is not achievable under thermodynamic constraints. A Spiral Economy is a more accurate representation: materials can circulate, but each loop retains less usable value than the previous one. Current recycling systems recover only a fraction of processed materials, often through downcycling, while repeated recovery processes involve additional energy and resource costs. Recognizing these thermodynamic limits does not weaken sustainability—it strengthens it. The real objective is not perfect circularity, but slowing degradation through longer product lifetimes, reuse, repair, efficient recovery, and better design. Thermodynamics, particularly exergy analysis, offers the most rigorous basis for measuring genuine progress toward circularity.

Rule 3: Learn from Nature (Biomimicry)

Biomimicry (bios + mimesis) draws inspiration from 3.8 billion years of evolution, where natural systems optimise resource efficiency, cycling, and resilience. In nature there is no waste in the industrial sense: materials are continuously transformed through cycles driven by solar exergy, where life and decomposition form spiral, not circular, dynamics. Within the Spiral Economy, biomimicry translates into designing industrial systems where the output of one process becomes the input of another, reducing entropy and improving adaptability [5]. This idea is closely linked to circular economy principles, cradle-to-cradle design [6], performance-based models [7], and bio-inspired materials and structures that enhance durability and efficiency [8], [9]. It also includes emotional durability [10] and interdisciplinary approaches that integrate biology, engineering, and design [11], [12]. However, full biomimicry remains an idealisation: natural systems are decentralised, self-repairing, and powered by continuous solar input, whereas industrial systems rely on finite energy sources and centralised infrastructures. Therefore, the Spiral Economy shifts the focus from static circularity to dynamic regeneration, where systems evolve continuously to maintain balance, rather than attempting perfect closure [13].

Rule 4: Eco-design

Eco-design, or design for sustainability and circularity, integrates environmental considerations across the full life cycle of products, from conception to end-of-life and regeneration. Within the “Spiral Economy”, its scope extends beyond waste management to the restoration of the natural systems that supply materials and energy, addressing the thermodynamic challenge of minimising entropy generation and preserving exergy across cycles [14]. Most environmental impacts are determined at the design stage, making strategies such as design for reuse, disassembly, and recycling essential to improve recoverability and reduce waste [15], [16]. Regenerative frameworks like Cradle-to-Cradle and biomimetic design aim to align industrial systems with ecological cycles, where outputs become inputs rather than pollutants [6]. Life cycle assessment combined with exergy analysis further supports design decisions by identifying irreversible losses and prioritising higher-quality recovery pathways. Applications across sectors—including appliances, automotive systems, and electronics—show that modularity, remanufacturing, material substitution, and improved recyclability can significantly reduce resource use and emissions. However, many products are still designed for short lifetimes and low recoverability due to economic optimisation rather than thermodynamic efficiency. Eco-design therefore becomes a central pillar of the Spiral Economy, combining engineering, ecology, and ethics to reduce irreversible losses and support regenerative production systems.assessments.

Rule 5: Systems degrade unevenly

The end of life (EoL) of a product rarely corresponds to the end of life of its components. From a thermodynamic perspective, equipment degrades heterogeneously, meaning that functional modules, subassemblies, and materials often retain usable exergy beyond the failure of the whole system. This enables resource cascading through selective recovery, extending utility and reducing entropy growth [17]. Within the Spiral Economy, this heterogeneity is key: different components have different lifetimes, allowing disassembly and reuse strategies that can achieve significant exergy savings compared with full recycling [18]. Modular design, already used in sectors such as aerospace and electronics, shows that component-level recovery is feasible when systems are designed for disassembly, traceability, and remanufacturing [19]. However, implementation is limited by regulatory, economic, and safety constraints, particularly in contaminated or critical applications. Emerging tools such as design for disassembly, material passports, and digital twins help overcome these barriers by enabling safer and more efficient component reuse [20]. Distinguishing between product failure and component persistence reveals a more granular view of sustainability, where entropy increases unevenly. Exploiting this heterogeneity enables slower degradation loops and more efficient resource use, consistent with the thermodynamic realism of the Spiral Economy.

Rule 6: Recover and Extend the Life of Equipment

The deliberate shortening of product lifespans through planned obsolescence contradicts both sustainability and thermodynamic efficiency, as it accelerates material entropy and increases embodied energy losses [21]. Extending product life through repair and reuse is therefore a central strategy within the Spiral Economy, with both economic and ethical relevance [3]. The right to repair, now supported by policies such as the European Union’s Circular Economy Action Plan, facilitates access to spare parts, tools, and repair information [22]. Evidence shows that repair strategies can extend product lifetimes by 20–50% and significantly reduce waste and material demand [23]. From a systems perspective, repair, reuse, and remanufacturing preserve the high exergy embedded in products, reducing the need for new resource extraction. Life cycle studies confirm substantial environmental benefits compared to full replacement, although exceptions arise when older technologies are significantly less efficient in operation. Overall, rejecting planned obsolescence shifts industrial systems from linear throughput to a more efficient spiral of maintenance and regeneration, where progress is measured by durability and recoverability rather than constant replacement.

Rule 7: Beware of Comminution

The most difficult wastes to recover are those at the smallest scales. As materials are reduced in size, energy requirements increase sharply while particles disperse into air, soil, and water, generating irreversible entropic losses and environmental risks. This fragmentation transforms useful materials into pollutants that are increasingly difficult to re-concentrate or reuse. Sources include industrial dust from mining and cement production, combustion-derived particulate matter (PM10, PM2.5, ultrafine particles), and emissions rich in carbon, metals, and toxic compounds. In addition, microplastics and persistent organic pollutants spread across ecosystems, persisting for decades and accumulating in living organisms [24]. From a thermodynamic perspective, the dispersion of synthetic compounds represents a strong increase in entropy, while their recovery requires high exergy inputs, especially in chemical recycling processes. Unlike natural polymers, which degrade through biological cycles at low energetic cost, anthropogenic materials often follow irreversible and highly dissipative pathways. Within the Spiral Economy, prevention becomes more important than recovery. Priority actions include avoiding hazardous substances, reducing unnecessary grinding, improving combustion efficiency, capturing emissions at source, and recovering valuable fractions from dust and residues. At system level, cleaner production, extended producer responsibility, and continuous monitoring support the reduction of dispersed losses. In this context, there is a fundamental contrast between natural and industrial systems: ecosystems operate through closed, regenerative nutrient cycles, while industrial fragmentation tends to generate open-ended dispersal and persistent environmental accumulation.

Rule 8: First Disassembly

Within the Spiral Economy, physical disassembly is the preferred route for low-entropy material recovery. It consists of mechanically separating products into reusable components or homogeneous material streams through actions such as unscrewing, detaching, or dismantling, instead of using chemical dissolution, melting, or depolymerisation. Thermodynamically, mechanical separation preserves more exergy because it avoids irreversible transformations and reduces entropy generation [3], [4], [25]. Evidence shows that mechanical disassembly often requires less energy and generates fewer emissions than chemical recovery methods, particularly in electronics, vehicles, and household appliances. Pre-dismantling components before metallurgical treatment can substantially reduce processing energy while enabling direct reuse of motors, casings, or circuit boards. Automation through robotic disassembly further increases this potential. Chemical or thermal processes may still be necessary when products contain inseparable composites, thermoset polymers, or complex alloys, although usually at higher exergy cost [26]. This reinforces a key design principle: products should favour screws, clips, rivets, and modular joints over adhesives, welds, or irreversible coatings. Aircraft structures provide a notable example: riveted assemblies combine durability, reparability, inspectability, and easy replacement, demonstrating how reversible joining systems can deliver both mechanical reliability and long-term recoverability.

Rule 9: Entropic backfire

Although metals are often considered infinitely recyclable, the Second Law of Thermodynamics imposes practical limits. Every separation process requires energy, reagents, and treatment steps that increase entropy. Recovering one valuable metal from complex recyclates often leaves behind residues that are more dispersed, contaminated, and difficult to process. This is the essence of Entropic Backfire: each additional recovery step can make subsequent recoveries harder and less economical. This phenomenon is linked to the metal wheel, which describes the industrial interdependence of metals [27]. Many elements are recovered only because they accompany key “carrier metals” such as copper, zinc, lead, or nickel through established metallurgical routes. If the flow of these carrier metals declines, or if products combine metals in incompatible ways, the recovery of associated co-elements is reduced or blocked. Recycling one metal in isolation may therefore hinder the recovery of others. The metal wheel also shows that recycled products often contain artificial combinations of elements not found together in natural ores, complicating separation processes. As residues become increasingly degraded, a point of unrecoverability can be reached where further recycling is less efficient than primary extraction. To reduce entropic backfire, products should be designed with simpler and compatible material combinations, while pre-sorting and separation technologies must improve. Recycling is therefore not limitless closure, but a balancing point between recovery costs, entropy generation, and resource value—one of the clearest expressions of the Spiral Economy.

Rule 10: Urban mining

Landfilling represents one of the most entropic endpoints of industrial metabolism, as it disperses the exergy embodied in materials and makes recovery increasingly difficult. The Spiral Economy reframes landfills not as final sinks but as anthropogenic mines, where metals, plastics, glass, and critical elements remain stored within urban infrastructures and waste deposits [28]. This perspective is supported by evidence showing that urban stocks contain significant quantities of valuable materials, often exceeding those in natural ores. Since these materials are already partially concentrated through industrial processes, their recovery can require far less energy than primary extraction; for instance, recycled aluminum uses only about 5% of the energy of virgin production. Urban mining technologies such as advanced sorting, bioleaching, and metallurgical recovery are improving extraction efficiencies, although heterogeneity and contamination remain key challenges. Despite these barriers, integrated circular systems combining logistics, data, and recovery infrastructure are increasingly viable and environmentally beneficial. Minimizing landfill disposal and promoting urban mining transforms waste into a strategic secondary resource, aligning with the Spiral Economy principle that entropy should be slowed by systematically reintegrating stored materials into production cycles.

Rule 11: The Need of Hepato-industries

Just as living beings have a liver that processes their waste, industrial society also requires specialized systems capable of detoxifying, separating, and reintegrating residues into productive cycles. This metaphor of “hepato-industries” presents recycling and recovery infrastructures as the “liver” of the industrial ecosystem, essential for maintaining balance between production, consumption, and environmental limits [29]. Within the “Spiral Economy”, cities can be understood as metabolic subsystems where industries manufacture goods, households and businesses consume them, and recycling sectors process the resulting waste into secondary raw materials [30]. These liver-industries include urban mining centres, waste valorisation plants, biorefineries, and industrial symbiosis hubs, all acting as entropy-reduction nodes that recover value from complex or contaminated flows [31]. Their effectiveness depends not only on infrastructure but also on coordination. Manufacturing sectors need recovered materials, cities need environmental quality, and recovery industries need stable waste streams and markets. This creates the need for a fourth “organ”: a “brain-manager”, responsible for planning, logistics, and communication across the wider system. Examples such as Japan’s Sound Material-Cycle Society and the Flanders Materials Program show that prioritising these infrastructures improves circularity, employment, and resilience [32]. Yet waste activities are still often seen as marginal rather than vital, limiting investment and innovation. In this sense, many environmental crises—resource scarcity, pollution, climate stress—can be interpreted as symptoms of an underdeveloped industrial liver. Strengthening hepato-industries and their coordination systems transforms waste from a burden into a strategic opportunity for long-term sustainability. limits.

Rule 12: The Broken Link in Value Chains

The Principle of Continuity can be summarized simply: if one link breaks, the chain breaks and the waste is lost. Circular or spiral systems depend on uninterrupted connections between design, production, consumption, collection, reuse, recycling, and reintegration. When one stage fails, materials fall out of circulation, entropy increases, and flows revert to the linear take–make–dispose model [1], [17]. In practice, weak points often arise at interfaces: poor collection systems, inefficient sorting, lack of treatment capacity, or missing markets for secondary materials. In sectors such as electronic waste, disruption at any step destroys previously embedded exergy and generates both economic and environmental losses [33]. Within the Spiral Economy, this resembles industrial metabolism, where continuity depends on diversity, cooperation, and redundancy. Industrial symbiosis networks such as Kalundborg or Ulsan show how waste from one activity can become a resource for another, strengthening resilience through connected loops [34], [35]. These systems often evolve not as perfect circles but as branching networks. The more interconnected they become, the greater the consequences when one link fails. Maintaining continuity through coordination, traceability, and adaptive capacity is therefore essential to prevent waste leakage and premature dissipation of resources.

Rule 13: Soil regeneration

Soil degradation is advancing faster than mineral depletion and has become a major global challenge. UNESCO warned in 2024[1] that up to 90% of land could be degraded by 2050, while food demand continues to rise. Unlike minerals, however, soils can be regenerated if managed properly. Fertile soil is a complex living system composed of minerals, organic matter, water, air, microorganisms, and essential nutrients. Modern agriculture has increased yields through fertilizers, pesticides, fossil fuels, and irrigation, but often at the cost of erosion, biodiversity loss, and greenhouse gas emissions. Agriculture already contributes around a quarter of global emissions. From a thermodynamic perspective, soil quality can be evaluated against an ideal fertile state. Using exergy, degradation is measured as the distance from this optimum and restoration as the physical cost of returning nutrients, organic matter, structure, and water-holding capacity. This provides a more objective framework than purely economic valuation.**[3]** Within the Spiral Economy, sustainable agriculture requires shifting from extractive systems toward regenerative cycles that mimic nature. Practices such as agroecology, conservation farming, composting, and agroforestry rebuild fertility, retain water, sequester carbon, and strengthen resilience to droughts and floods. Soil regeneration is one of the most circular processes available, yet large amounts of organic waste are still burned or discarded instead of being returned to land. Reintegrating biomass through composting, digestate, or biorefineries preserves nutrients and reduces dependence on virgin inputs. Sustainability therefore means not only reducing damage, but restoring the ecological foundations of food production.

Rule 14: Legislation effect

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[1] https://www.iuss.org/events/20th-international-congress-of-soil-science-icss-2024

Environmental regulation can unintentionally hinder recycling when rigid classifications, permits, or compliance systems restrict material recovery more than they enable it. Within the Spiral Economy, this reflects the need for adaptive governance that evolves with technological and material realities [36]. A key barrier is the strict waste–byproduct distinction, which often prevents recovered materials from re-entering production systems even when technically suitable. In addition, complex End-of-Waste procedures and permitting systems create administrative burdens that particularly affect small and medium enterprises [22]. Some countries, such as Japan and the Netherlands, illustrate more flexible, performance-based regulatory models that better support circular practices. Effective regulation in the Spiral Economy should therefore reduce not only material and energy inefficiencies, but also bureaucratic and temporal barriers, shifting from static control toward enabling material recovery.

Rule 15: Denounce Eco-Washing or Greenwashing

Greenwashing, or eco-washing, occurs when corporations, institutions, or products project a misleading image of environmental responsibility while maintaining unsustainable practices. It is an entropic distortion of information, where truth is dispersed and degraded, weakening society's ability to act rationally toward sustainability [37]. Within the Spiral Economy, greenwashing is the communicative equivalent of waste: it dissipates trust, hides inefficiency, and diverts resources and effort toward illusion rather than regeneration. Studies show that exaggerated or false environmental claims are common. The European Commission [38] reported that over 40% of green claims lacked evidence, while only a minority were independently verified. This creates asymmetry between producers and consumers and undermines collective progress. It also reinforces complacency, as consumers may believe that purchasing "eco-labeled" goods substitutes for reducing, repairing, or reusing [39]. While greenwashing disguises unsustainable behaviour through communication, planned obsolescence embeds it directly into product design. Both strategies accelerate material throughput, increase waste generation, and intensify resource extraction, while presenting consumption as progress. Regulatory responses such as the EU Green Claims Directive seek to impose verifiable metrics, life cycle assessments, and transparent reporting. Thermodynamic accounting, including exergy-based indicators, offers a more robust alternative to vague marketing metrics [40]. Yet smaller firms with genuinely sustainable practices may lack resources for expensive certifications. Combating greenwashing therefore requires both truthful disclosure and fair visibility. Just as material waste pollutes ecosystems, semantic waste pollutes perception. Cleaning this informational contamination is essential for a credible transition to sustainability.

Rule 16: Confessional Effect: Beware of Deceptive Recycling Claims

The "confessional effect" describes a psychological mechanism through which consumers reduce environmental guilt by performing symbolic acts such as separating waste or purchasing "green" products. This creates a sense of moral absolution, even when the underlying system remains inefficient. However, it can also lead to moral licensing, where individuals increase consumption after engaging in supposedly sustainable behaviour [41]. Within the Spiral Economy, this effect becomes a feedback loop that reinforces entropy under the illusion of circularity. In practice, less than 10% of global plastic waste is effectively recycled, despite widespread participation in recycling systems [42]. This gap is driven by contamination, technological limits, and greenwashing strategies that exploit consumer trust through poorly defined labels such as "biodegradable" or "eco-friendly" [37]. This dynamic turns sustainability into a form of symbolic consumption, where moral satisfaction replaces structural change. The Spiral Economy instead calls for transparency and accountability in material flows, including recovery rates, resource reintegration, and embodied energy balances [43]. While community-based initiatives such as repair cafés and deposit-return systems offer partial exceptions by reconnecting users with real material cycles, most systems still operate under a false sense of circular closure. In this sense, the end user does not eliminate waste but delegates it, often feeling "free of sin" after disposal, even though the thermodynamic burden remains within the system.

Rule 17: Rule of Waste Disentangling

Promote Actions Beginning with "Un", "De", or "Dis" as Positive Recovery Verbs highlights the power of reversal as a core sustainability strategy. Verbs such as undo, decompose, detach, and dismantle represent not only linguistic choices but operational actions that transform waste from an entropic endpoint into a starting point for reordering. Within the Spiral Economy, these actions align with thermodynamic logic by slowing entropy accumulation through the controlled reversal of material and energy flows [44]. In engineering terms, these verbs correspond to design for reversibility, where components are intentionally created to be separable without loss of function. Research on design for disassembly and remanufacturing shows that recovery rates can increase substantially—up to around 80%—while reducing energy demand. Complementary processes such as decontamination and dematerialisation further preserve exergy by improving material purity and reducing waste mass. Beyond technical aspects, linguistic framing itself shapes behaviour: “reversal verbs” encourage a culture of repair and regeneration rather than disposal, echoing natural processes such as decomposition and recombination. Although some material systems remain irreversibly mixed or contaminated, limiting full recovery, the “un/de/dis” perspective still drives innovation toward modularity, reversible design, and improved material transparency. The Rule of Waste Disentangling ultimately reframes sustainability as a continuous process of unmaking and reconfiguring existing systems rather than constant replacement.

Rule 18: Promote the Re-Economy

The Principle of Re-Actions captures the practical spirit of the Spiral Economy through repeated restorative actions such as Reduce, Reuse, Repair, Recycle, Recover, Restore, and Reinvent. These “Re-” verbs represent strategies to delay entropy, preserve embodied exergy, and reduce dependence on new resources [45]. At the top of this hierarchy is reduction, the most efficient option because it prevents waste before it exists. Reuse and repair conserve the value already embedded in products, while recycling and recovery manage residual materials. Reinvention adds an adaptive dimension, transforming technologies, institutions, and behaviours to support long-term sustainability [19]. Evidence shows that applying these repeated recovery loops can significantly lower emissions and raw material demand, while remanufacturing sectors generate employment and retain much of the original product value [46]. The Re-Economy also implies a broader cultural shift: to rethink, redesign, regulate, remanufacture, retrofit, reward, research, and take responsibility. In this sense, prosperity comes not from endless expansion, but from intelligent repetition and regeneration sources.

3. Conclusions

Modern waste streams are characterized by an increasing material, chemical, and structural complexity. Residues rarely consist of single substances; instead, they are typically mixtures, alloys, or conglomerates of solids, liquids, and gases. Combustion exhaust gases, end-of-life vehicles, hospital waste, or metallic scraps illustrate this challenge, where multiple components appear highly mixed at different scales. From a thermodynamic perspective, separation, purification, and demixing processes belong to the most irreversible operations known, requiring large amounts of energy and material inputs. Paradoxically, the low perceived value of waste, its social rejection, and the technical difficulty of separation have resulted in a systematic underdevelopment of disaggregation and recovery technologies, despite their growing ecological relevance.

The Rules of the Spiral Economy provide a thermodynamically consistent basis for assessing resource use, guiding engineering design, and supporting policies aligned with the finiteness of natural resources and long-term sustainability. These principles, while not comprehensive, illustrate that, thermodynamics, technology, economics, law, ethics, and, above all, nature are essential to achieving a sustainable planet. The physical value of goods resides not in their exergy content or in the exergy required for their production, but in their impact on the ecosphere [47]. Resource extraction and the generation of waste degrade this system, revealing the ecological costs embedded in material production. As the Ellen MacArthur Foundation observes, waste is a human construct; nature produces none. Learning from nature is therefore imperative for effective waste management. In natural systems, thermodynamic laws are never violated and all waste serves a function. However, entropy ensures that perfect circularity is unattainable. From a physical standpoint, there is no circular economy but rather a spiral economy, in which each process inevitably generates residues. While nature metabolises waste primarily through solar energy, present society remains inefficient both in metabolising residues and in reducing the rate of resource extraction. The main reason for this inefficiency, or for the slow implementation of circularity, often lies in the higher economic cost of closing the loop compared with continuing under the conventional system. This economic gap arises because the current economic system does not assign an adequate value either to the goods extracted from the ecosphere or to the impacts imposed upon it. Addressing this inefficiency requires the integration of thermodynamic and economic analysis across the entire life cycle of materials. This broader perspective, termed circular thermoeconomics [1], extends traditional thermoeconomic frameworks—historically focused on power plants and combustion emissions—to all production systems. Here, waste may assume gaseous, liquid, solid, thermal, or radiative forms, and its assessment must include both environmental impacts and the costs associated with generation, mitigation, and recovery. Within this framework, waste is intrinsic to production, and its management entails additional cost, particularly when residues are complex. Despite this, waste retains exergy that can be recovered to enhance efficiency, lower costs, and reduce both emissions and resource consumption. Achieving this often requires new processes or even new industrial sectors embedded within larger production networks. The quantitative evaluation of waste costs is a crucial instrument for optimizing processes. Exergy serves as a unifying metric, enabling heterogeneous forms of waste to be expressed in comparable units and correlated with indicators such as CO_2 emissions—providing greater analytical rigor than conventional simplified methods.

Nonetheless, total recycling is constrained by physical limits, identified as the “pinch point of recoverability”, beyond which recovery is no longer possible. For this reason, the concept of a spiral economy is proposed: a model that measures the effective degree of recovery in light of exergy losses and acknowledges entropy as an inescapable boundary condition of all material processes.

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