THERSAURUS: A COST Action Building a Pan-European Network for Thermodynamic Resource Assessment—The Second Law for Sustainability

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Abstract:
Humanity faces an unprecedented sustainability crisis characterized by resource depletion and environmental degradation. While thermodynamics provided the foundation for the Industrial Revolution, its potential as a guiding framework for sustainability remains largely untapped. This paper introduces the THERSAURUS initiative, a pan-European network designed to redefine thermodynamics for the 21st century. By focusing on the Second Law, the project aims to harmonize definitions, metrics, and standards for exergy and irreversibility to quantify the physical cost of economic activities. Through four pillars—Harmonize, Educate, Consolidate, and Advocate—THERSAURUS seeks to transform thermodynamic insights into actionable knowledge, ultimately bridging the gap between physical reality and societal action.

Keywords:
Thermodynamics, sustainability, resources, COST Action

1. Introduction: the sustainability challenge

The The current global environmental and socio-economic crisis is deeply linked to unsustainable patterns of energy and material consumption. Climate change, biodiversity loss, soil degradation, pollution, and increasing geopolitical tensions over critical raw materials all reflect a common underlying problem: modern economies continue to operate as if natural resources were abundant, endlessly substitutable, and fully recoverable. Yet the physical reality is different. Economic scarcity is ultimately rooted in thermodynamic scarcity: all resources degrade during extraction, transformation, use, and disposal [1], [2].

A fundamental but often overlooked principle is that every productive process consumes not only matter and energy, but also order. High-quality resources—concentrated minerals, fertile soils, fossil fuels, biomass, freshwater, and manufactured goods—are progressively dispersed, mixed, oxidized, contaminated, fragmented, or dissipated. Once degraded, they require additional energy, materials, and effort to restore, and complete recovery is impossible. This is the practical meaning of the Second Law of Thermodynamics. While materials may remain in existence, their usefulness declines as entropy increases and exergy is destroyed. Recycling can therefore slow depletion, but it can never eliminate losses due to dispersion, contamination, wear, and irreversible transformations [3], [4].

This perspective was powerfully anticipated by Nicholas Georgescu-Roegen, who argued in The Entropy Law and the Economic Process [1] that economic activity is inseparable from the physical degradation of low-entropy resources into high-entropy waste. His work challenged the conventional assumption that economic growth could be indefinitely decoupled from material limits, placing thermodynamics at the center of economic reasoning.

Despite their universal relevance, the First and Second Laws of Thermodynamics have historically been applied mainly to isolated engineering systems such as power plants, engines, refrigeration cycles, or chemical reactors. Their implications for wider sustainability challenges—resource depletion, circular economy limits, waste generation, ecological restoration, or industrial resilience—have received far less systematic attention. As a result, many sustainability frameworks remain dominated by economic indicators, mass balances, or emissions accounting, without fully incorporating the physical quality of resources or the irreversible nature of their use.

This gap is increasingly problematic in the context of the green and digital transitions. Technologies such as batteries, photovoltaics, wind turbines, semiconductors, and electrified transport depend on growing quantities of critical materials whose extraction, refinement, and recycling are constrained not only by markets and geopolitics, but also by thermodynamic limits [5]. Likewise, agriculture, water systems, urban metabolism, and waste management cannot be properly understood without considering degradation, recoverability, and the energetic cost of regeneration.

The THERSAURUS COST Action (A Pan-European Network for Thermodynamic Resource Assessment—The Second Law for Sustainability) was conceived to address this challenge. Its central ambition is to transform thermodynamics from a specialized engineering discipline into a foundational science for sustainability assessment and resource policy. By building a pan-European interdisciplinary network, THERSAURUS seeks to connect researchers working in thermodynamics, industrial ecology, life cycle assessment (LCA), ecological economics, materials science, environmental engineering, and policy analysis.

In this sense, the name THERSAURUS evokes a thermodynamic thesaurus: a comprehensive compendium of concepts, methods, and indicators that organizes the vocabulary of thermodynamics for sustainability.

The Action promotes the idea that sustainability cannot be measured solely by monetary cost, mass flows, or carbon emissions. It must also account for resource quality, irreversibility, and the physical effort required to restore degraded systems. Thermodynamic indicators—particularly those based on exergy—offer a rigorous common language to compare heterogeneous resources, identify hidden inefficiencies, evaluate recycling limits, and quantify the real costs of production and consumption systems [6].

2. Core research questions

The initiative is structured around several fundamental questions concerning the disconnect between thermodynamics and sustainability science:

- How can we objectively measure the physical degradation of resources and quantify their regeneration?
- This includes minerals, energy carriers, soils, biomass, water, ecosystems, and manufactured capital.
- What is the real physical cost of economic activities in terms of resource destruction and exergy loss?
- Beyond prices and GDP, what irreversible burdens are created by production and consumption?
- Which common definitions, indicators, and accounting frameworks are needed to integrate irreversibility into extraction, manufacturing, recycling, and waste management systems?
- How can thermodynamics be integrated into Life Cycle Assessment (LCA), Material Flow Analysis (MFA), and circular economy metrics to improve decision-making?
- How can Europe strengthen strategic autonomy and resilience by understanding the thermodynamic limits of critical raw materials, recycling systems, and industrial supply chains?
- What pathways allow the transition from linear, extractive economies toward regenerative systems compatible with planetary boundaries?

THERSAURUS aims not only to advance academic knowledge, but also to provide practical tools for policymakers, industry, and society. By embedding the Second Law into sustainability thinking, it becomes possible to distinguish realistic circularity from rhetorical claims, identify where recovery is physically feasible, and prioritize strategies such as durability, repair, reuse, remanufacturing, and regenerative design before lower-value recycling.

In this sense, THERSAURUS proposes a paradigm shift: from viewing thermodynamics as a narrow technical science of machines, to recognizing it as a universal framework for understanding the metabolism of economies and the long-term stewardship of natural resources.

3. The THERSAURUS Pathway: Four Intertwined Pillars

To address the gap between thermodynamics and sustainability science, THERSAURUS proposes an integrated pathway structured around four mutually reinforcing pillars: Harmonize, Educate, Consolidate, and Advocate (see Fig. 1). Together, these pillars aim to transform thermodynamic resource assessment into a coherent European framework for research, innovation, and policy action.

1. Harmonize

A major barrier to progress is the fragmentation of concepts, methodologies, and terminology across disciplines. Exergy, criticality, resource efficiency, circularity, recoverability, and regeneration potential are often defined differently in engineering, economics, industrial ecology, and environmental policy. This lack of consistency limits comparability between studies and weakens the credibility of indicators used in decision-making.

THERSAURUS therefore seeks to harmonize common definitions, metrics, and standards related to resource quality and degradation. Particular emphasis is placed on:

- Exergy accounting as a universal measure of useful resource potential.
- Irreversibility indicators to quantify destruction, losses, and waste generation.
- Regeneration potential for renewable and partially renewable systems such as soils, forests, biomass, and water.
- Recoverability metrics for minerals, metals, and complex products at end of life.
- Alignment with existing frameworks such as Life Cycle Assessment (LCA), Material Flow Analysis (MFA), and circular economy indicators.
- By building shared methodological foundations, THERSAURUS enables robust comparisons across countries, sectors, and technologies.

2. Educate

The sustainability transition requires not only new tools, but new ways of thinking. Current educational systems often treat economics, engineering, and environmental science separately, while thermodynamics is frequently taught as a narrow technical subject disconnected from broader societal challenges.

THERSAURUS aims to redefine education and training so that future generations understand sustainability through the lens of physical limits, resource quality, and systemic efficiency. This pillar promotes:

- New university modules on thermodynamics for sustainability.
- Interdisciplinary teaching linking engineering, ecology, economics, and policy.
- Training schools, workshops, and summer courses for early-career researchers.
- Practical case studies on energy systems, mining, recycling, food systems, and urban metabolism.
- Communication tools that make entropy, exergy, and circularity accessible beyond technical audiences.

The goal is to inspire a new generation capable of thinking not only in terms of prices and emissions, but also in terms of degradation, limits, and regeneration.

3. Consolidate

Scientific progress is often hindered by the absence of accessible, standardized data. While economic statistics are abundant, information on physical degradation, hidden resource burdens, and irreversibility costs remains scattered or unavailable.

THERSAURUS therefore seeks to consolidate knowledge into shared open-access infrastructures, including datasets, models, and digital tools. Central initiatives include:

- Databases of irreversibility rucksacks (or backpacks): the cumulative hidden exergy losses associated with products, materials, and processes across their life cycles.
- Resource quality maps for minerals, biomass, soils, and industrial residues.
- Open-source tools for exergy-enhanced LCA and circularity analysis.
- Digital platforms linking thermodynamic data with environmental and economic indicators.
- Benchmark case studies for strategic sectors such as batteries, mobility, electronics, water, agriculture, and construction.

This pillar allows researchers, industries, and public institutions to move from abstract principles toward operational assessments and evidence-based strategies.

4. Advocate

Scientific knowledge only creates impact when translated into governance, industrial practice, and public understanding. THERSAURUS therefore includes a strong mission to bridge science and policy, ensuring that thermodynamic insights help shape sustainability strategies at European and national levels.

This advocacy pillar focuses on linking physical exergy costs with conventional economic costs, revealing where markets fail to reflect real resource degradation or waste burdens. It supports:

- Better resource taxation and incentive systems.
- More realistic circular economy policies based on recoverability limits.
- Critical raw material strategies informed by physical scarcity, not only price signals.
- Eco-design regulations that prioritize durability, reparability, and disassembly.
- Public procurement criteria based on life-cycle thermodynamic performance.
- Communication with policymakers, industry leaders, and civil society.

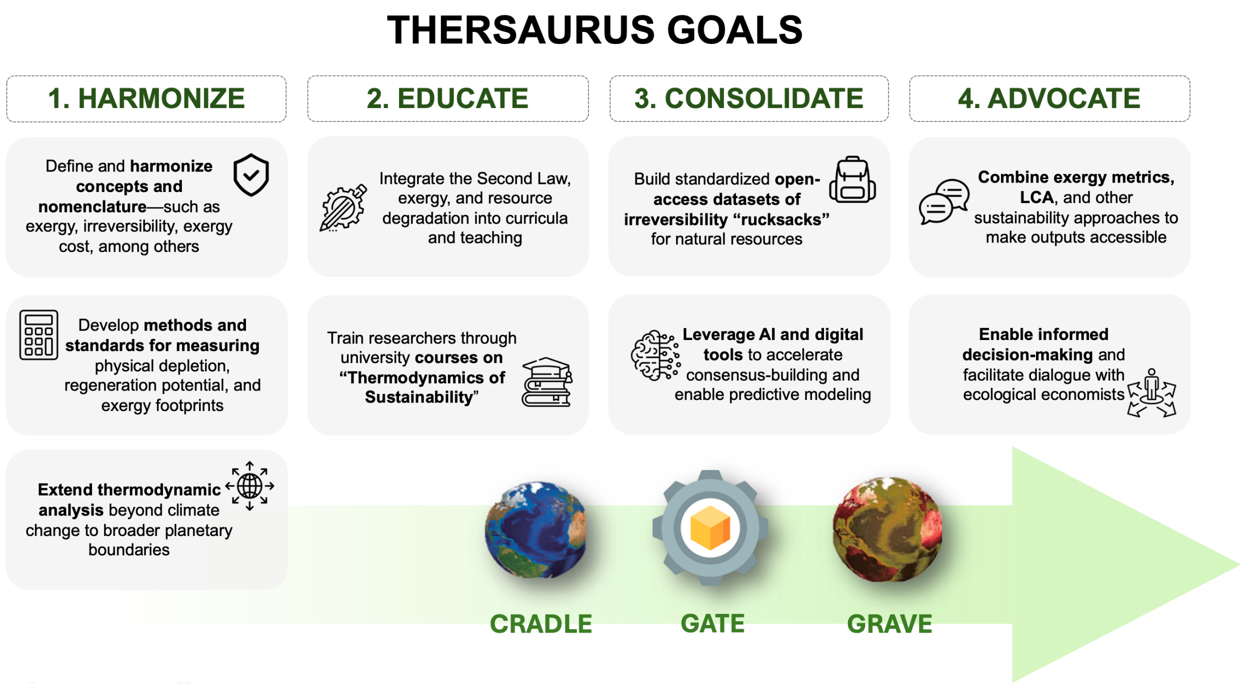

Fig. 1: *Thersaurus goals*

By translating thermodynamic evidence into actionable recommendations, THERSAURUS helps guide Europe toward more resilient and physically coherent sustainability pathways.

These four pillars are deeply interconnected. Harmonized metrics improve education; education strengthens data generation; consolidated data supports advocacy; and policy demand reinforces the need for harmonization. Together, they form a systemic roadmap for embedding the Second Law of Thermodynamics into sustainability science and practice.

In this sense, THERSAURUS is more than a research network. It is a platform for redefining how Europe understands value, waste, efficiency, and long-term prosperity in a finite world.

4. The COST Action Framework: Networking for Change

The scientific and policy challenges addressed by THERSAURUS—fragmented methodologies, inconsistent terminology, dispersed datasets, and the absence of common standards—cannot be solved by isolated research groups working independently. They require coordinated international collaboration capable of integrating expertise from engineering, natural sciences, economics, environmental assessment, and governance. For this reason, THERSAURUS operates as a COST Action, a European networking instrument funded by European Cooperation in Science and Technology.

A COST Action is specifically designed to connect researchers and innovators across Europe and beyond around topics of strategic relevance. It is a bottom-up instrument, meaning that the scientific community itself proposes the topic in response to emerging needs, rather than following a predefined agenda. This flexibility makes COST particularly suitable for THERSAURUS, whose objective is to transform thermodynamics from a specialised engineering discipline into a practical science for sustainability.

Typically lasting four years, a COST Action does not directly fund research itself—such as salaries, laboratory equipment, or infrastructure. Instead, it provides the essential “glue” for coordination, enabling scientists and stakeholders to build communities, share methods, harmonize standards, and generate long-term collaborations. Funding supports activities such as workshops, conferences, working group meetings, training schools, dissemination events, and Short-Term Scientific Missions, through which researchers can visit partner institutions and exchange expertise.

This model is particularly valuable for THERSAURUS because many of the obstacles in thermodynamic sustainability assessment are not purely technical, but conceptual and organizational. Europe already hosts strong expertise in exergy analysis, industrial ecology, life cycle assessment, critical raw materials, ecological economics, and circular economy policy. However, this knowledge is often dispersed across disciplines and countries. The COST framework enables these communities to converge, compare approaches, and develop a common scientific language.

Through this network, THERSAURUS will harmonize methodologies for measuring resource degradation and regeneration, consolidate open-access datasets and digital tools, and redefine educational pathways for future generations. It will also create a bridge between science and policy, helping decision-makers incorporate physical indicators—such as exergy losses, irreversibility costs, and recoverability limits—into sustainability strategies.

Another major strength of the COST framework is its inclusiveness. It encourages participation from early-career researchers, widening countries, neighbouring states, SMEs, industry representatives, and public institutions. This broad participation ensures that thermodynamic resource assessment develops not as a niche academic field, but as a shared European capability with practical relevance for competitiveness, resilience, and environmental stewardship.

Ultimately, THERSAURUS uses the COST Action model not merely as an administrative structure, but as a catalyst for systemic change. By connecting scattered expertise into a coordinated pan-European community, it lays the foundations for a new paradigm in which the Second Law of Thermodynamics becomes central to how Europe understands value, waste, circularity, and long-term prosperity in a finite world.

At the proposal stage, THERSAURUS already gathers over 120 proposers from 34 countries, including COST Full Members, Partner Members, Near Neighbour Countries, and International Partners, some of which are depicted in Fig. 2. The majority come from universities and research-performing institutions, complemented by participants from industry, governmental bodies, and well-known sustainability-oriented organizations. This composition ensures strong cross-sectoral relevance and the practical applicability of the Action’s outputs. A significant share of the proposers is affiliated with departments where thermodynamics plays a central role—such as mechanical, chemical, and environmental engineering—complemented by experts in ecological economics, materials science, and systems modelling, creating a genuinely interdisciplinary environment essential for bridging thermodynamics, sustainability, and policy.

4.1. Funding and coordination activities

As a COST Action, THERSAURUS will dedicate its budget exclusively to networking, coordination, and capacity-building activities, rather than to salaries, laboratory equipment, or direct research costs. This funding model is specifically designed to create the conditions for collaboration, knowledge exchange, and methodological convergence across Europe.

A major component of the budget will support travel and meetings, enabling researchers to attend workshops, annual conferences, Working Group sessions, and Management Committee meetings. These face-to-face interactions are essential for building trust, aligning research agendas, and accelerating interdisciplinary cooperation.

The Action will also finance Short-Term Scientific Missions (STSMs), allowing researchers to spend short periods—typically from a few weeks up to three months—at partner institutions. These visits will be particularly valuable for transferring technical skills, accessing specialized expertise, and developing joint publications or tools. Complementing this, Virtual Mobility Grants (VMGs) will support remote collaboration, data exchange, and online interdisciplinary work when physical mobility is not necessary or feasible.

Another central activity will be the organization of Training Schools, designed especially for students and Young Researchers and Innovators (YRIs). These intensive courses will provide hands-on training in exergy analysis, thermodynamic accounting, sustainability metrics, circular thermoeconomics, and related tools under the broader theme of the Thermodynamics of Sustainability.

Finally, resources will also support dissemination and management activities, including scientific workshops, stakeholder engagement, publications, communication materials, website development, and the administrative coordination required to operate a large international network efficiently.

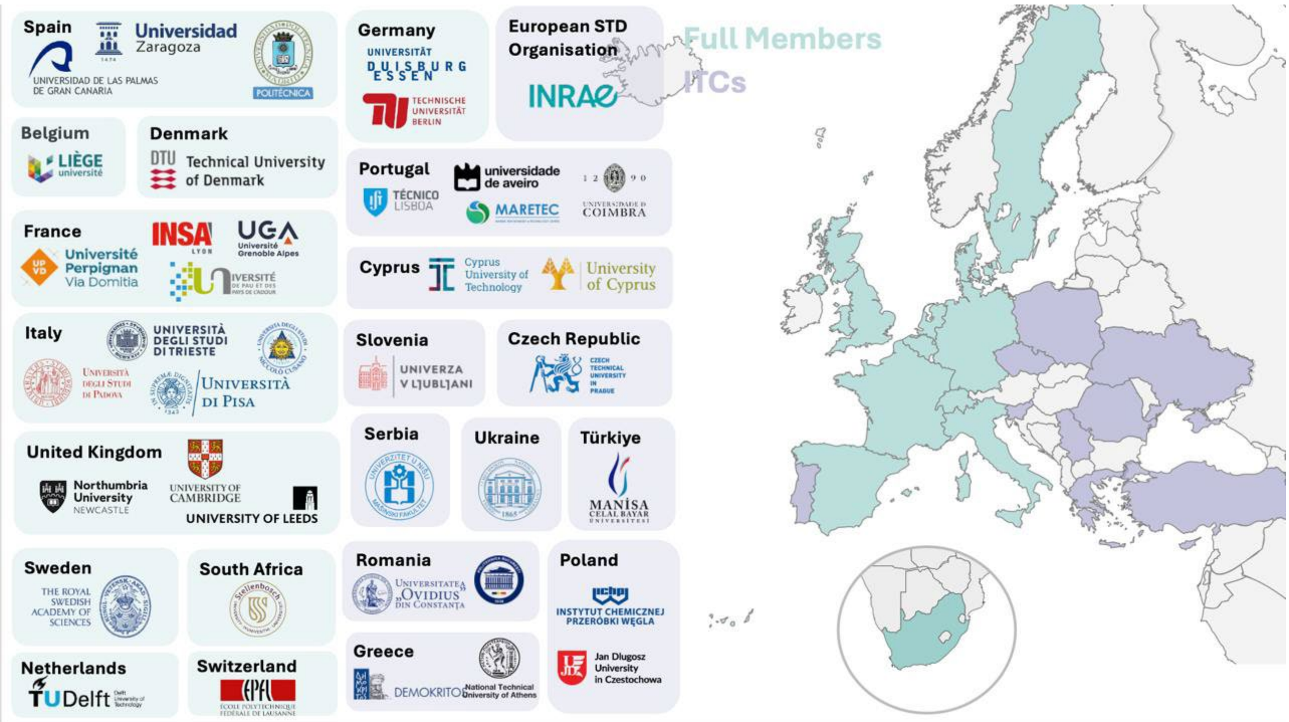

Fig. 2: *Some partners from Thersaurus proposal*

4.2. Key features and inclusiveness

THERSAURUS will be an open and multidisciplinary network, welcoming participants from academia, industry, SMEs, public institutions, and policy organizations. One of the distinctive strengths of the COST framework is its relatively low administrative burden combined with a strong commitment to inclusiveness, diversity, and broad European participation.

A core objective will be geographical balance, with particular attention to researchers from Inclusiveness Target Countries (ITCs), helping strengthen scientific capacity and integration across all parts of Europe. By widening participation, THERSAURUS will ensure that expertise and opportunities are not concentrated in only a few regions.

The Action will also place strong emphasis on early-career support. Young Researchers and Innovators already represent a significant share of the proposing network, and their active participation will be encouraged through mobility grants, leadership roles in Working Groups, training activities, and visibility in conferences and publications. This generational renewal will be essential for consolidating thermodynamic resource assessment as a long-term scientific field.

In parallel, THERSAURUS will commit to gender balance and equitable representation across leadership positions, committees, speakers, and all major activities. Diversity of perspectives is particularly important in a field that aims to bridge engineering, economics, environmental science, and policy.

Through these principles of openness and inclusiveness, THERSAURUS will build not only a scientific network, but also a resilient European community capable of shaping the future of sustainability assessment.

4.3. Implementation and Expected Impact

THERSAURUS will be governed by a Management Committee (MC) composed of representatives from participating countries, ensuring strategic oversight, transparent decision-making, and effective coordination of all network activities. The MC will supervise the implementation of the Action, monitor progress, approve annual work plans, and guarantee alignment with COST principles of excellence, inclusiveness, and interdisciplinarity.

To reinforce the scientific ambition of the initiative, the Action will be supported by a specialized Second Law & Sustainability Committee, bringing together leading experts in thermodynamics, exergy analysis, resource assessment, industrial ecology, and sustainability policy. This body will provide scientific guidance, help harmonize methodologies, identify emerging priorities, and ensure that the Action remains anchored in rigorous physical principles while addressing practical societal challenges.

In the short term, THERSAURUS will focus on building the foundations of a common European framework for thermodynamic resource assessment. This will include the development of standardized terminology, shared methodological protocols, and open-access datasets covering exergy losses, irreversibility indicators, regeneration potentials, and resource “rucksacks” across key sectors and materials. By reducing conceptual fragmentation, these outputs will enable greater comparability and reproducibility across studies.

The Action will also generate practical tools for researchers, industry, and policymakers, including digital platforms, training materials, benchmarking guidelines, and decision-support frameworks that integrate thermodynamic indicators with economic and environmental metrics.

In the longer term, THERSAURUS aims to influence international standards and governance frameworks by contributing scientifically robust concepts and metrics to organizations such as International Organization for Standardization, United Nations Environment Programme, and Intergovernmental Panel on Climate Change. By doing so, the Action will help embed physical reality—through exergy, irreversibility, and material degradation—into global sustainability assessments and reporting systems.

Ultimately, THERSAURUS will provide a science-based compass for transparent, ethical, and efficient resource management. It will strengthen Europe’s leadership in sustainability science, support evidence-based policymaking, and help societies move from abstract circularity narratives toward measurable strategies grounded in the laws of thermodynamics.

5. Conclusions

Just as Sadi Carnot’s insights helped shape the Industrial Revolution by revealing the principles governing energy conversion and efficiency, THERSAURUS seeks to contribute to the foundations of a new sustainability revolution. If the nineteenth century was defined by the mastery of energy for industrial expansion, the twenty-first century must be defined by the intelligent management of matter, energy, and environmental limits. In this transition, thermodynamics is not merely a technical discipline—it is a guide for civilization.

The central message of THERSAURUS is that sustainability cannot rely solely on intentions, narratives, or partial indicators. It must be grounded in the physical reality that all processes consume useful resources, generate irreversibilities, and degrade natural capital. Exergy, as a measure of useful potential, provides a common language capable of linking engineering performance, environmental impacts, economic value, and long-term resilience. By bringing these dimensions together, thermodynamics becomes a practical instrument for policy design, industrial innovation, and responsible consumption.

The network therefore aims to transform the Second Law of Thermodynamics into an operational framework for decision-making. Through common standards, open datasets, training, mobility, and interdisciplinary collaboration, THERSAURUS will help build a European and global community able to assess resource use more rigorously, compare alternatives more honestly, and identify pathways that reduce waste, emissions, and unnecessary extraction. In doing so, it moves beyond simplified visions of circularity toward strategies that acknowledge real limits while still enabling progress.

This effort is also cultural. Modern economies often reward short-term gains while overlooking depletion, pollution, and hidden inefficiencies. THERSAURUS promotes a different perspective: one in which prosperity is measured not only by production volumes, but also by the preservation of options for future generations. A society that understands irreversibility is better equipped to value durability, repairability, regeneration, and intelligent design.

The challenges ahead—critical raw materials, climate change, biodiversity loss, water stress, and growing geopolitical tensions around resources—require stronger scientific foundations than ever before. Thermodynamics offers universal principles that transcend sectors, technologies, and borders. By integrating these principles into sustainability science, THERSAURUS provides a rigorous path forward for present and future generations.

Finally, THERSAURUS is conceived as an open and collaborative initiative. In this spirit, any researcher participating in the ECOS Conference community is warmly welcome to join and contribute to this shared endeavor. Advancing sustainability through thermodynamics will require the collective intelligence of engineers, economists, ecologists, and policymakers working together. The task is ambitious, but so was the industrial transformation inspired by Carnot. The next great transformation can—and must—be one that respects the finite planet on which all economies depend.

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