



Instituto Universitario de Investigación Mixto de la

Energía y Eficiencia de los
Recursos de Aragón

Universidad Zaragoza

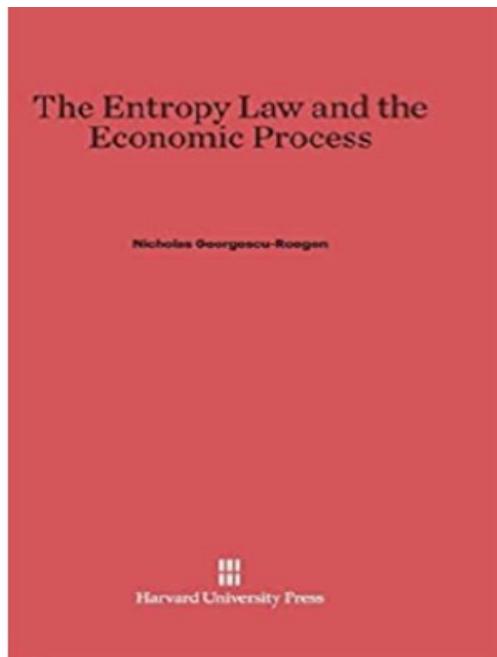
Conceptual Foundations for a Thermodynamics of Sustainability

Antonio Valero

Friede-Gard Prize 2026 · 15 October 2026

Purpose of the presentation

- I present a vision of thermodynamics applied to sustainability that **incorporates the immutable laws of thermodynamics to our economic activities.**
- My aim is to **rethink the way in which society**, policy-makers and industry understand cost and efficiency, not only in monetary terms, but also **in physical terms measured in exergy (kWh).**
- Every human action can be assessed in terms of its **hidden costs: irreversibilities** and the extraction of natural resources that are not reflected in the market price.



Interview by A. Valero with N. Georgescu-Roegen in 1991
<http://habitat.aq.upm.es/boletin/n4/aaval.html>

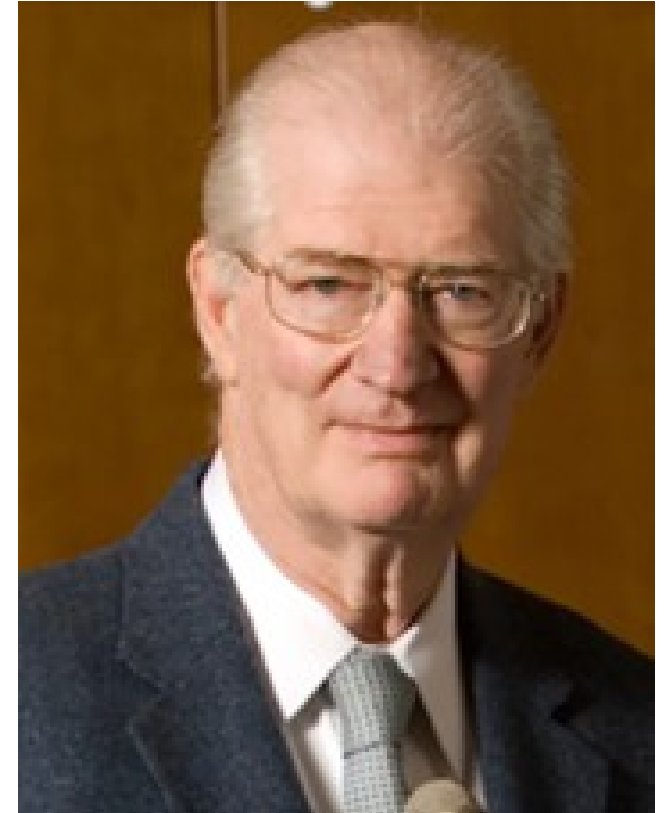
“The Entropy Law itself emerges as the most economic in nature of all natural laws... the economic process and the Entropy Law is only an aspect of a more general fact, namely, that this law is the basis of the economy of life at all levels. . .”

N. Georgescu-Roegen. The Entropy Law and the Economic Process (1971)

- **Nicholas Georgescu-Roegen** proposed that economics should be grounded in the **Second Law of Thermodynamics**, since all economic activity transforms low-entropy resources into high-entropy waste. However, his proposal was never fully operationalised because:
 - **Economists** lacked a measurable indicator of entropy applicable to economic systems.
 - **Thermodynamicists** rarely extended their analyses to economics and sustainability.
- As a result, **no coherent thermodynamic theory of sustainability emerged after 1971.**



- Industrial growth is limited by the stock of terrestrial low entropy, rather than by the stock of solar low entropy which is superabundant but is itself irrelevant because solar energy is flow-limited...
- Georgescu-Roegen and Daly envision the economic system as a materials-processing system in which final products — commodities — are necessarily material in nature.
- As the stock and its maintenance throughput grow, the increasing disorder exported to the ecosystem will at some point interfere with its ability to provide natural services.



Daly, H.E., 1991. Steady-State Economics, Island Press, Washington DC.

What the Second Law means for economics

- All **natural resources are irreversibly degraded** when used in economic activity.
- The **scarcity of mineral resources sets a limit on humanity's survival** on this planet.
- It is practically impossible to fully recover dissipated matter: **recycling can never be complete.**
- Georgescu-Roegen was the first economist of any standing to theorise on the premise that **all the Earth's mineral resources will eventually be exhausted.**
- Georgescu-Roegen argues that **economic scarcity is rooted in physical reality**; that all natural resources are irreversibly degraded when used in economic activity.
- Georgescu-Roegen's work was instrumental in establishing **ecological economics** as an independent academic sub-discipline within economics.
- The Earth's capacity to sustain human populations and levels of consumption is bound to decline at some point in the future as the Earth's finite stocks of mineral resources are extracted and used;
- **Consequently, continued economic growth based on ever-increasing resource extraction and consumption may lead to severe ecological degradation, resource scarcity and growing challenges to the long-term sustainability of human societies**

Robert U. Ayres: exergy and resources

- **Exergy becomes a more natural choice as a common measure of the amount of resources.** It is clearly superior to either net energy or mass in that it incorporates their useful features while surmounting some of their limitations.
- By using exergy as a **common measure of inputs and outputs**, we can immediately **estimate exergetic efficiency**, namely the ratio of exergy outputs to total exergy inputs (including utilities).
- **Natural resources will inevitably become scarcer.**
- **There is a physical limit to dissipation.** In other words, **the highest entropy state of matter on earth is the state in which all chemical elements in the system — say, the earth's crust — are equally dispersed and the matter is homogenized.** In such a homogenous mass, all elements (and chemical species) must be present with finite concentrations. This concentration is the minimum.



Robert U. Ayres, Eco-thermodynamics: economics and the second law. Ecological Economics 26 (1998), 189–209.

Why we need more thermodynamics

- Many of the problems he identified in the current economic system – and for which he proposed a paradigm shift towards the Second Law of Thermodynamics (entropy) – were also due to **a lack of conceptual development within thermodynamics itself.**
- Thermodynamics lacked a more accessible quantity than **entropy**, and so we have utilized exergy and developed new concepts such as **exergetic cost, the Notary's Rule, the exergetic replacement cost, relative free energy, Thanatia, thermodynamic rarity and the concept of Pristinia**, etc
- Every human action can be assessed in terms of its hidden costs: the **irreversibilities and the extraction of natural resources that are not reflected in the market price.**
- I present a vision of thermodynamics applied to sustainability that incorporates the **immutable laws of thermodynamics into our economic activities**

- **The Second Law:** Natural processes increase total entropy and cannot reverse themselves spontaneously.
 - **Entropy:** is an extensive state variable that can be defined for any material substance or any system and which indicates its degree of disorder.
 - Entropy generation = Σ (dissipated heat / T_i)
 - What goes up, comes down
 - What is cold, gets warm
 - What is hot, cools down
 - What is concentrated becomes diluted
 - What is pure, rusts
 - What is alive, dies
- Entropy is generated, $S_g > 0$ = **Irreversibility**
- **But... the units of entropy (kW/K) are unintelligible by non-experts**

Exergy: The maximum amount of work that a subsystem can do on its surroundings as it approaches thermodynamic equilibrium reversibly.

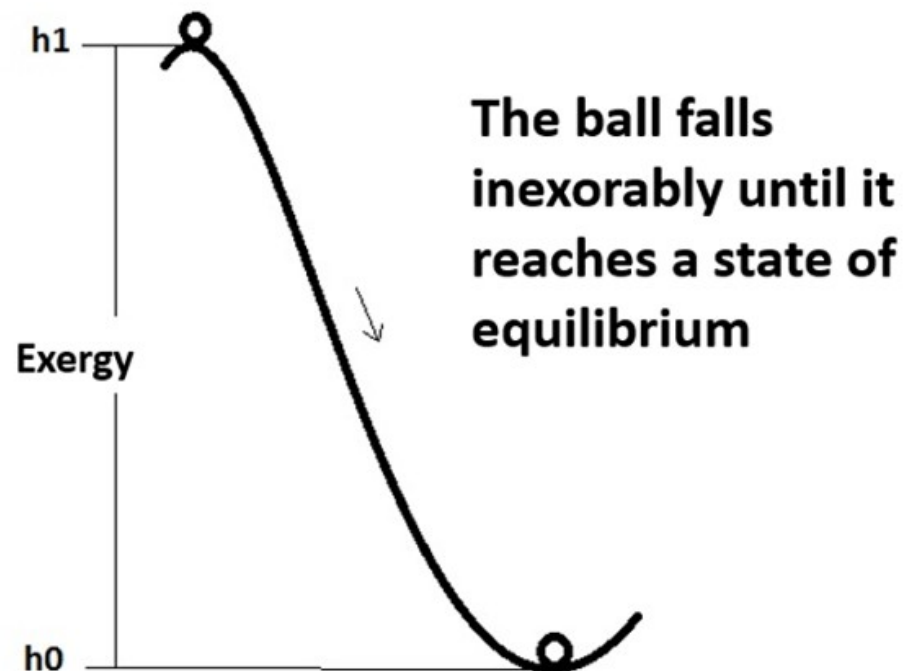
- What goes up, comes down = Destruction of **Mechanical Exergy**
- What is cold, gets warm = Destruction of **Thermal Exergy**
- What is hot, cools down = Destruction of **Thermal Exergy**
- What is concentrated becomes diluted = Destruction of **Chemical Exergy**
- What is pure, rusts = Destruction of **Chemical Exergy**
- What is alive, dies = Destruction of **Chemical Exergy**
- Waste is dispersed = **Destruction of any type of Exergy**

Spontaneous

The Gouy–Stodola theorem: Exergy destruction = $T_0 S_g \equiv$ Irreversibility !!!

The units of exergy (kWh) are understandable, BUT WE NEED a REFERENCE.

Why a reference environment matters



The limit of the system's spontaneous evolution is to reach equilibrium with its environment (dead state)

Jan Szargut and reference states

- Inspired by the geological state of the Planet Earth, he proposed three major environmental media — or ‘sinks’.
- The composition of the atmosphere and that of the ocean are taken to be the reference state.
- For all other elements, mainly metals whose oxides are insoluble solids, are taken to be the reference state.
- In the case of hydrocarbon fuels and carbohydrates, are very closely related to the ‘heat of combustion’.
- **This set of references, one for each chemical element, does not constitute a reasonable geological dead state of the planet.**



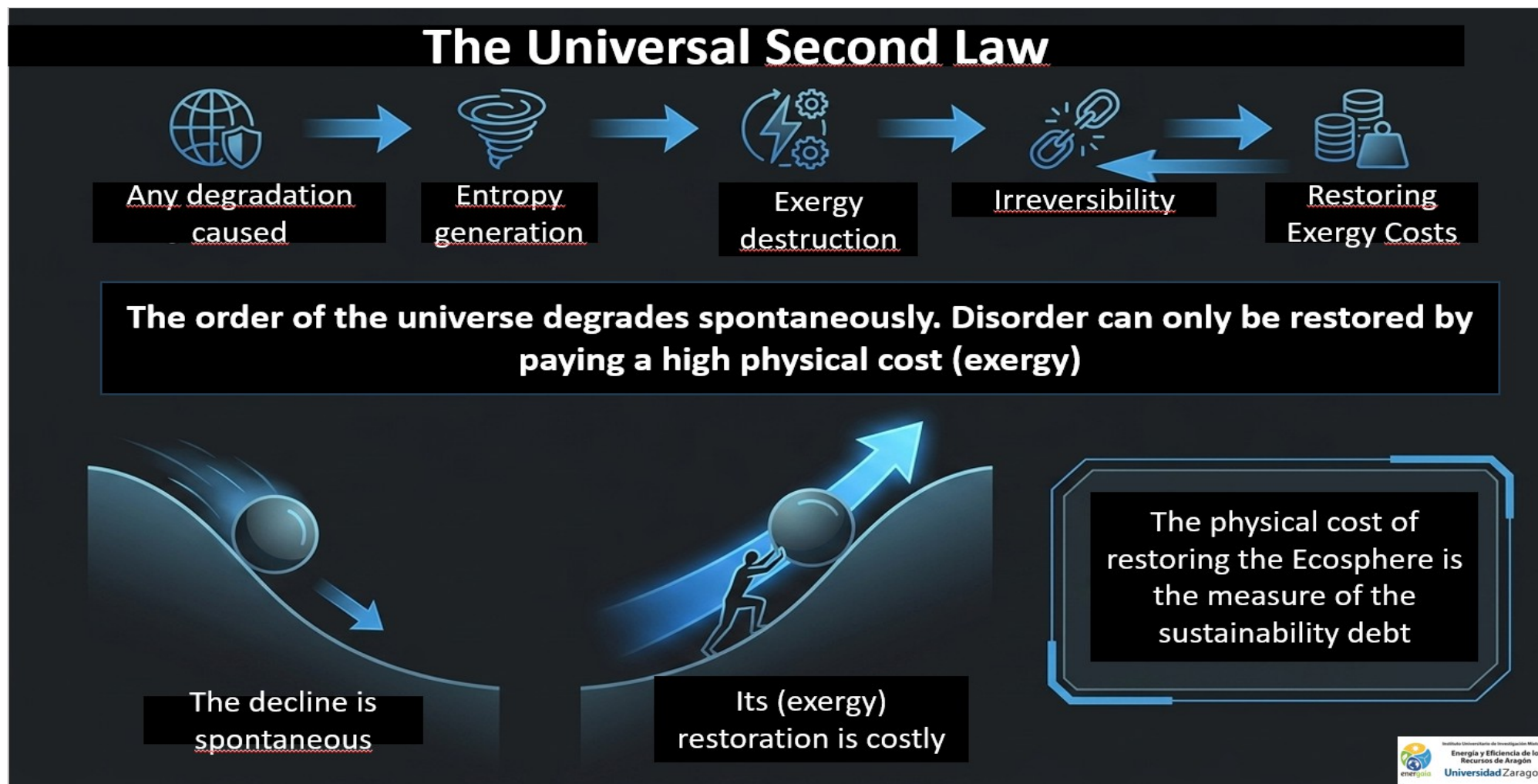
Jan Szargut, Morris, D.R., Steward, F.R., 1988. Exergy Analysis of Thermal, Chemical, and Metallurgical Processes. Hemisphere, NY.

From Szargut's reference to Thanatia

- If our society continues to burn fossil fuels, the composition of the atmosphere will see an increase in CO₂ levels and its temperature will rise as a result of climate change.
- The Earth's crust only changes in composition over geological eras, not human timescales.
- The crust is composed mainly of silicates, which are more stable than oxides. Its composition was unknown, although the approximate concentration of all the chemical elements in the technosphere was known.
- Given that the exergy of metals is generally low, their social value lies in their scarcity, not in their exergy. However, the scarcer and higher the quality of the metal required, the more exergy is needed to extract and refine it.



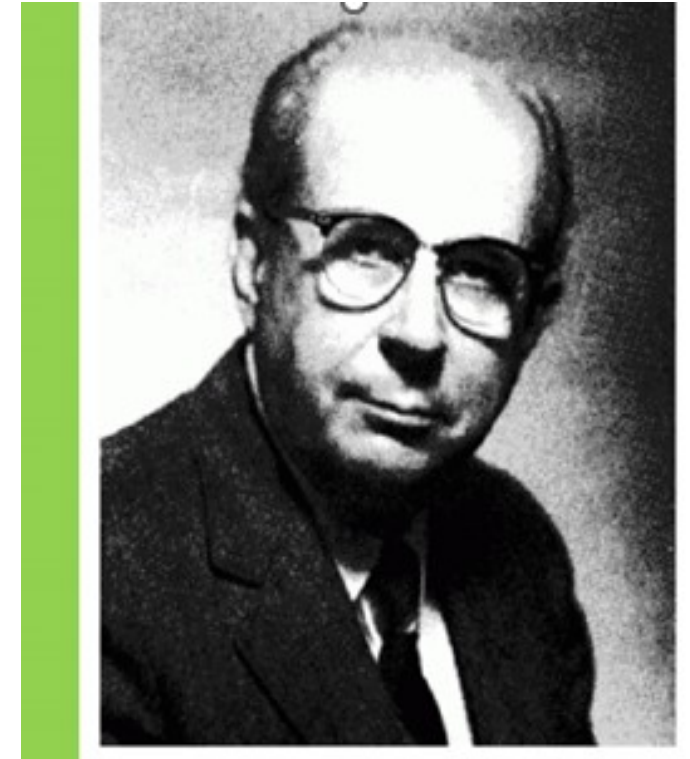
Antonio Valero and Alicia Valero (2014). Thanatia, The Destiny of the Earth's Mineral Resources: A Cradle-to-Cradle Assessment. World Scientific Publishing Co. ISBN 978-981-4273-93-0.



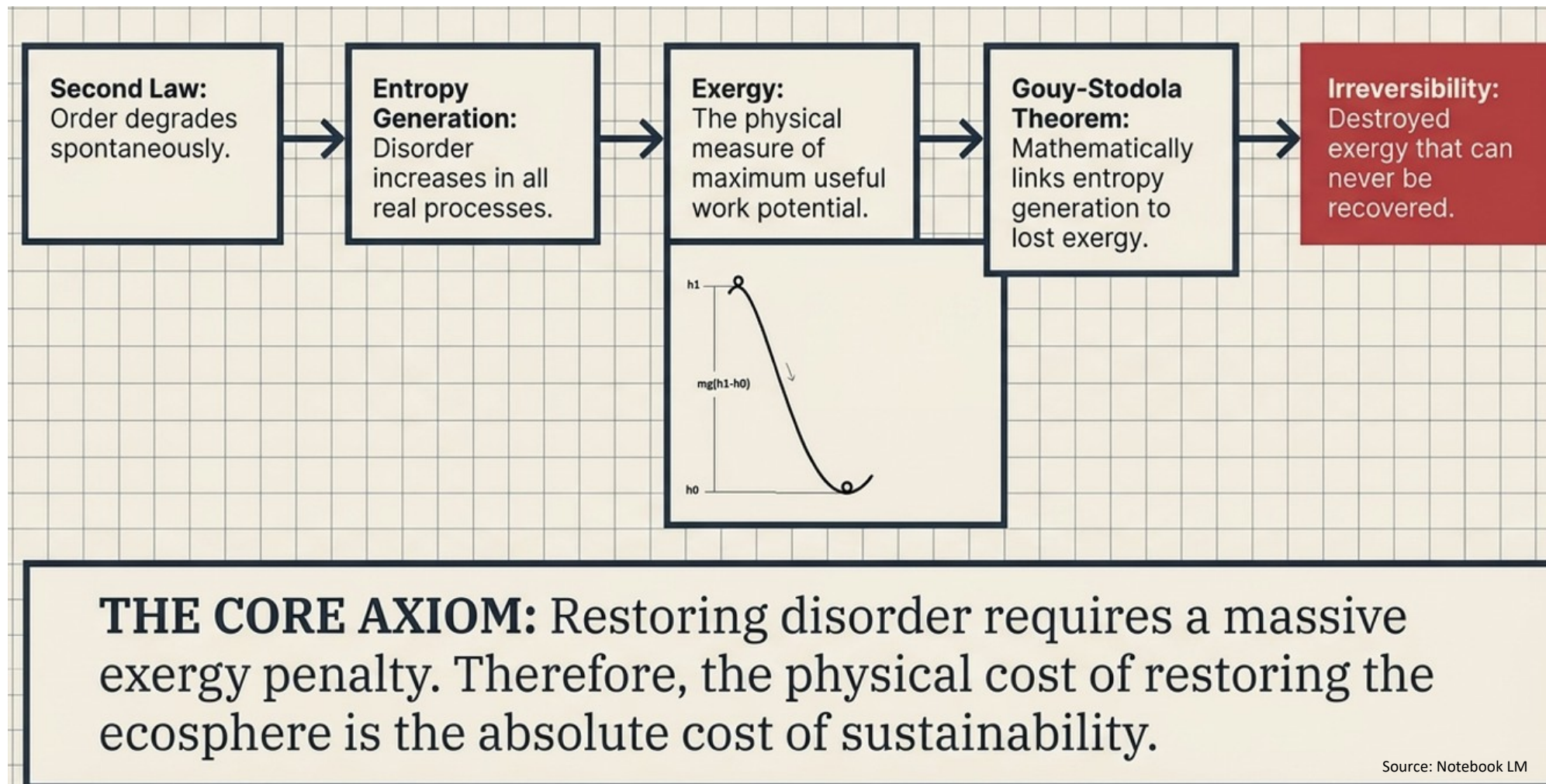
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Georgescu-Roegen and irreversibility

- Nicholas Georgescu-Roegen's concept of irreversibility focuses on the idea that economic processes, like **all natural processes, are fundamentally irreversible due to the second law of thermodynamics.**
- This means that... the inherent tendency towards entropy (increase in disorder) makes true reversibility impossible in reality.
- His work emphasises that **economic activity, especially the extraction and transformation of resources, irreversibly degrades the environment, leading to a qualitative degradation of free energy into bound energy.**

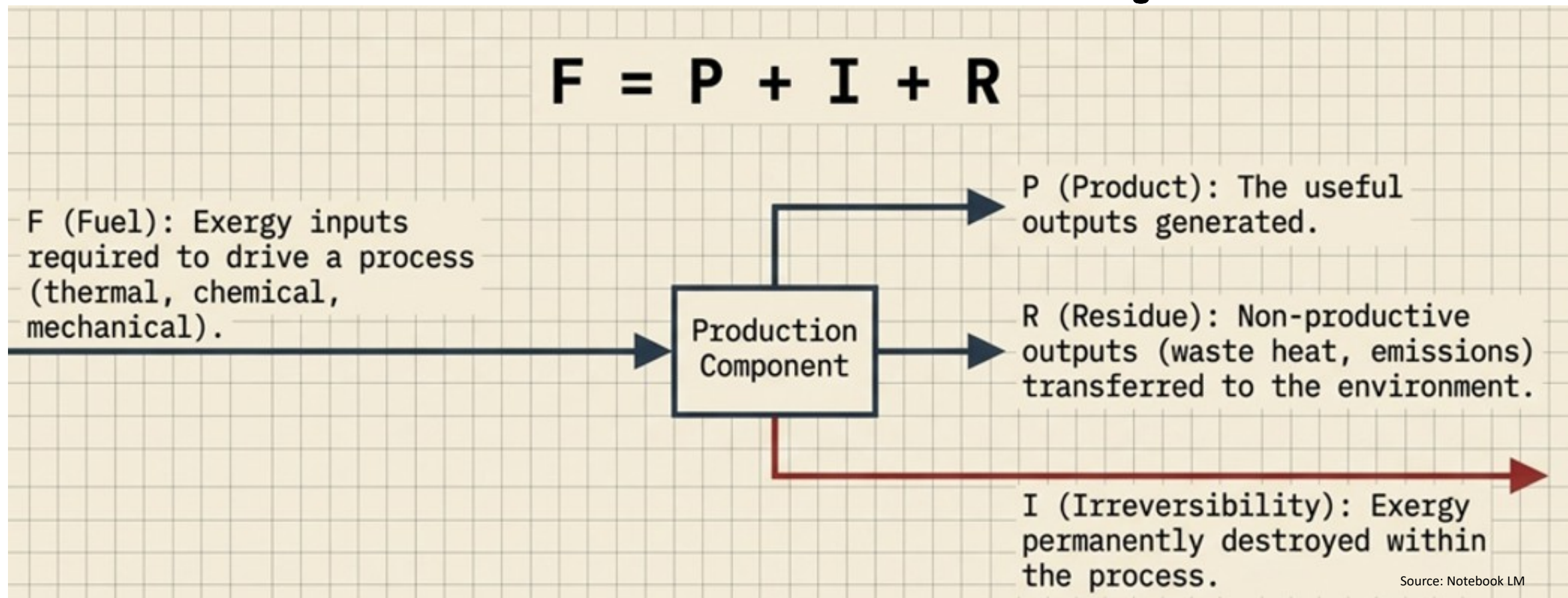


The core axiom: The absolute cost of Sustainability





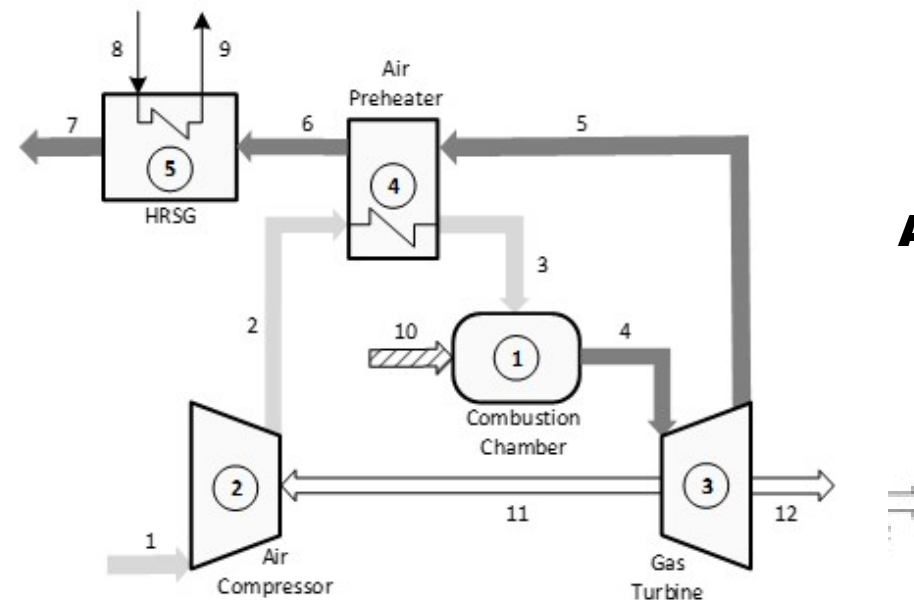
George Tsatsaronis





Antonio Valero

Nr	Process	Fuel	Product	η (%)	k
1	Combustor	$B_{10} + B_3$	B_4	83.49	1.1977
2	Compressor	B_{11}	$B_2 - B_1$	92.11	1.0857
3	Turbine	$B_4 - B_5$	$B_{11} + B_{12}$	95.90	1.0428
4	Air Preheater	$B_5 - B_6$	$B_3 - B_2$	90.27	1.1078
5	HRS	$B_6 - B_7$	$B_9 - B_8$	73.47	1.3611



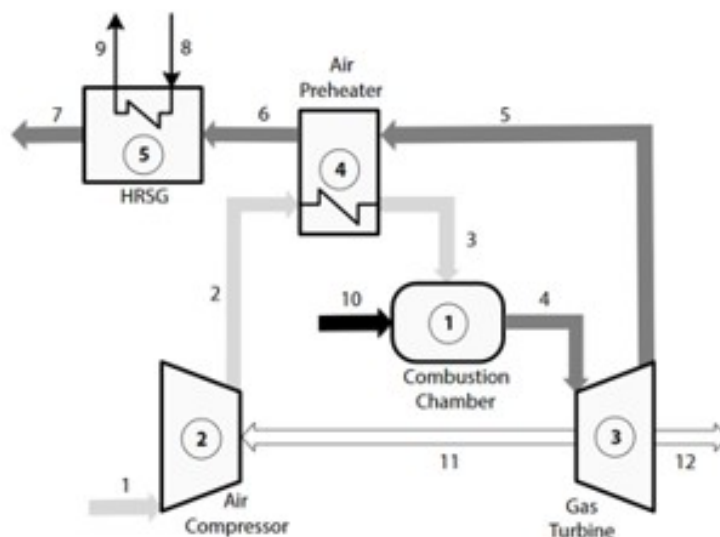
Valero, A., Lozano, M. A., Serra, L., Tsatsaronis, G., Pisa, J., Frangopoulos, C., & von Spakovsky, M. R. (1994). CGAM problem: Definition and conventional solution. [Energy], 19(3), 279–286

$A \times B = I$, where incidence Matrix of the graph ($n \times m$), n is number of components and m the number of exergy flows, B (GJ), contacting the components, whose irreversibility (GJ)



Antonio Valero

CGAM Problem. Cost Equations



External Resources

$$\begin{aligned} B_1^* &= B_1 \\ B_8^* &= B_8 \\ B_{10}^* &= B_{10} \end{aligned}$$

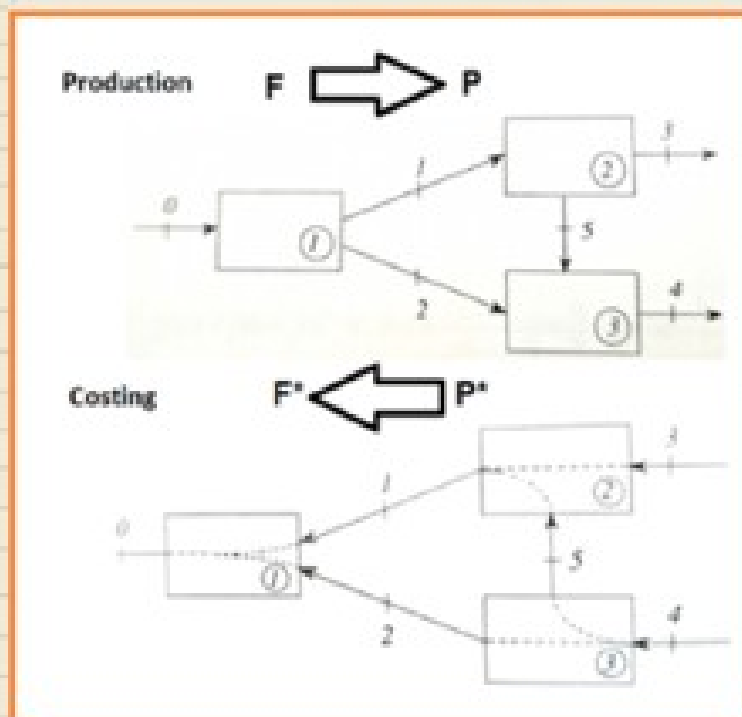
Cost Balances

$$\begin{aligned} B_{10}^* + B_3^* - B_4^* &= 0 \\ B_1^* + B_{11}^* - B_2^* &= 0 \\ B_4^* - B_5^* - B_{11}^* - B_{12}^* &= 0 \\ B_2^* + B_5^* - B_3^* - B_6^* &= 0 \\ B_6^* + B_8^* - B_7^* - B_9^* &= 0 \end{aligned}$$

$A \times B^* = 0$,
where Exergy costs
 B^* (GJ), of the Exergy
flows

Valero, A., Lozano, M. A., Serra, L., Tsatsaronis, G., Pisa, J., Frangopoulos, C., & von Spakovsky, M. R. (1994). CGAM problem: Definition and conventional solution. *Energy*, 19(3), 279–286.

Primal-Dual Mathematical Basis



The Primal System (Leontief)

- The physical exergy flows. Demand-driven.
- Evaluates the exergy required to satisfy production demands through the $\langle FP \rangle$ matrix.

The Dual System (Ghosh)

- The exact exergy costs. Supply-driven.
- Traces the propagation of resource costs through the $\langle PF \rangle$ matrix.

Key Insight: By replacing monetary flows with physical exergy flows, exergy costs propagate rigorously through complex supply chains without relying on arbitrary market prices.

Source: Notebook LM

The Cost–Irreversibility Formula

$$B^* = B + \sum I$$

B^* = Exergy Cost
(Total physical burden).

B = Remaining exergy content
of the product.

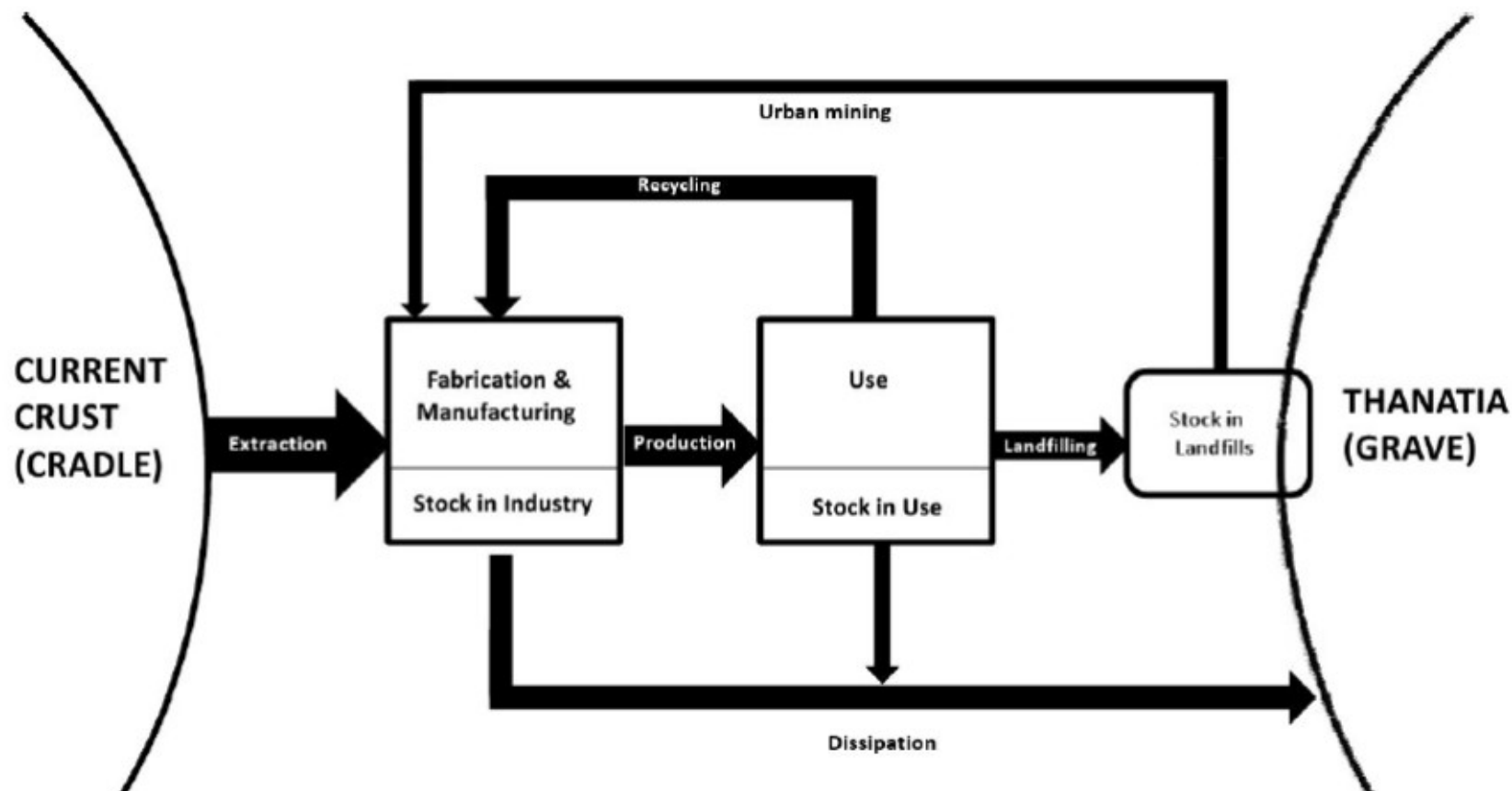
$\sum I$ = Cumulative irreversibilities
generated during production.

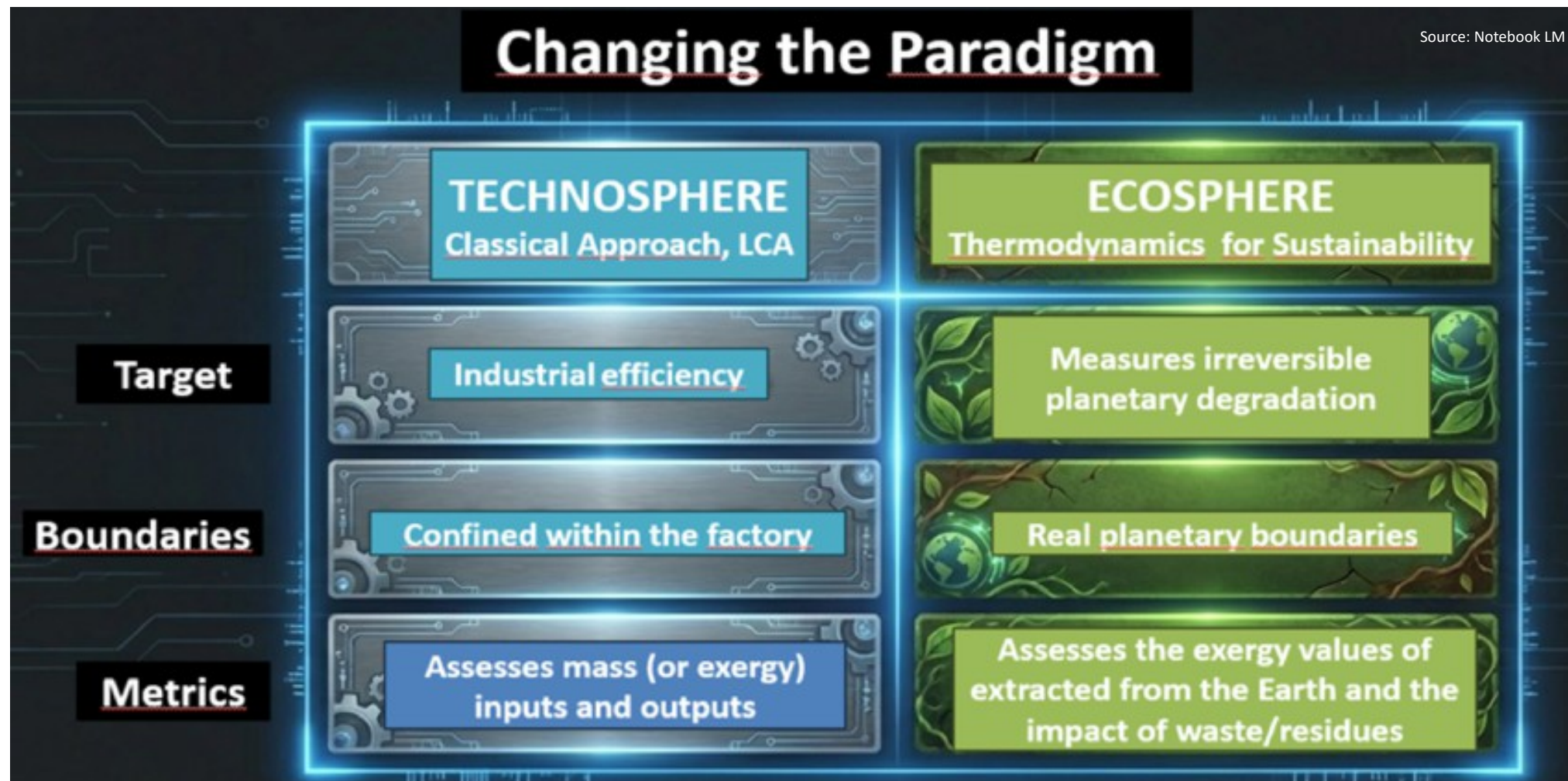
Takeaway: Every product carries an invisible physical burden—the total exergy permanently destroyed during its lifetime.

Source: Notebook LM

If every single object has exergy, it also has an exergy cost, and the difference between the two is the irreversible loss of resources that have been destroyed in order to obtain it.

The evolution of materials towards Thanatia





Classification of Exergy Costs

1. Direct Production Costs

Exergy consumed and irreversibilities generated directly inside industrial processes.

2. Scarcity Costs

Exergy Replacement Cost (ERC) relative to the Thanatia baseline (the thermodynamic cost of natural depletion).

3. Waste Impact Costs

Exergy required to remediate emissions and pollutants back to safe environmental conditions.

4. Indirect Costs

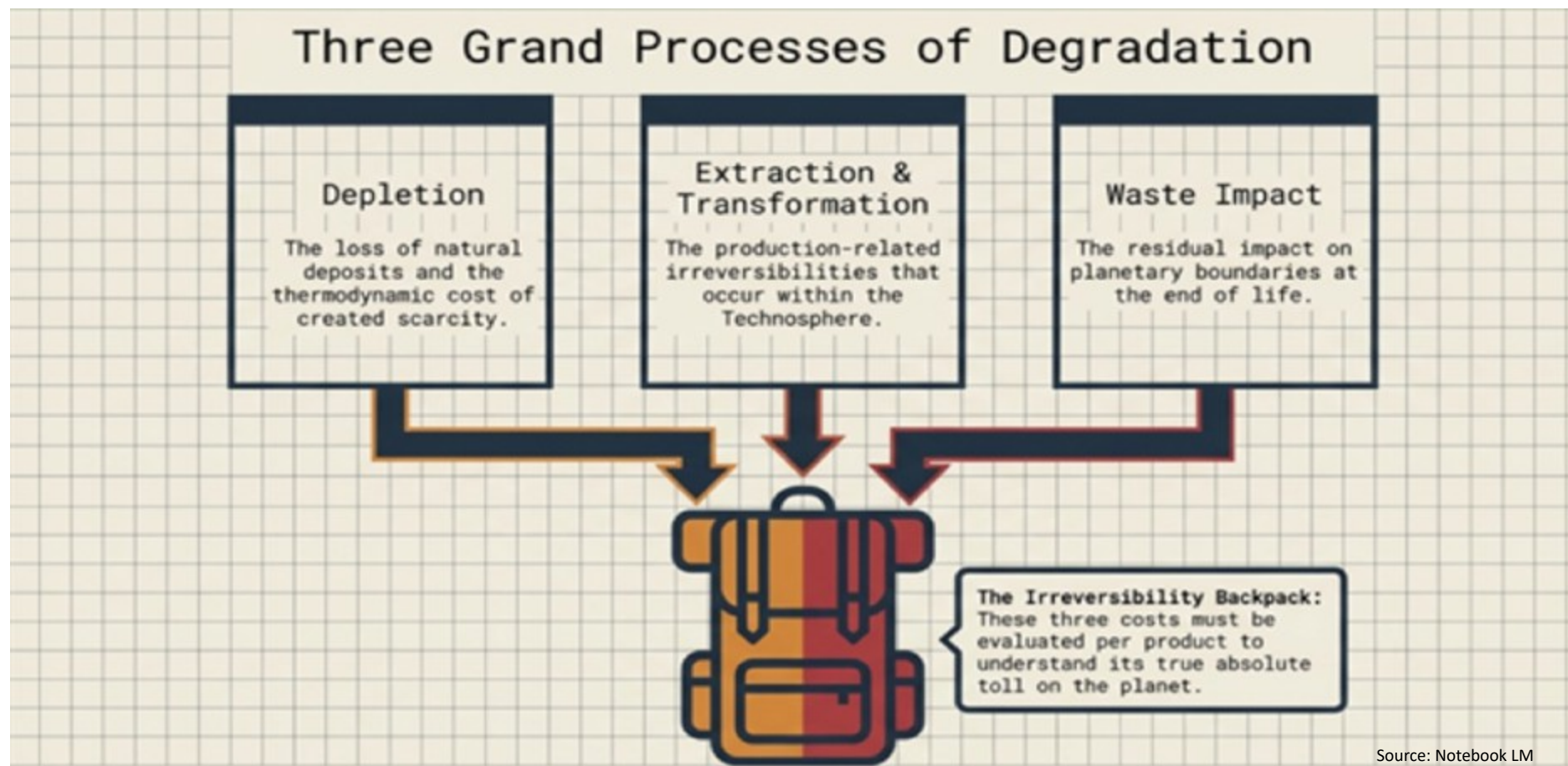
Exergy equivalents associated with labor, ecotoxicology, and broader environmental externalities.

Source: Notebook LM



Enrico Sciubba

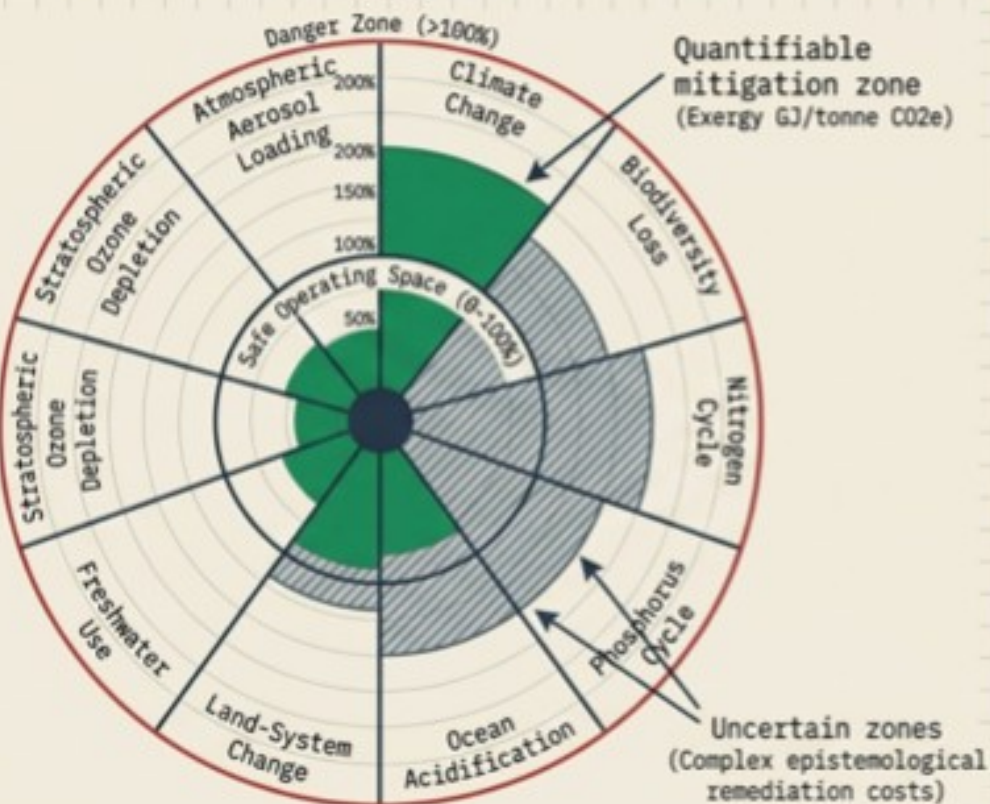
Three major processes of degradation





Johan
Rockström

Planetary Boundaries and Mitigation Costs



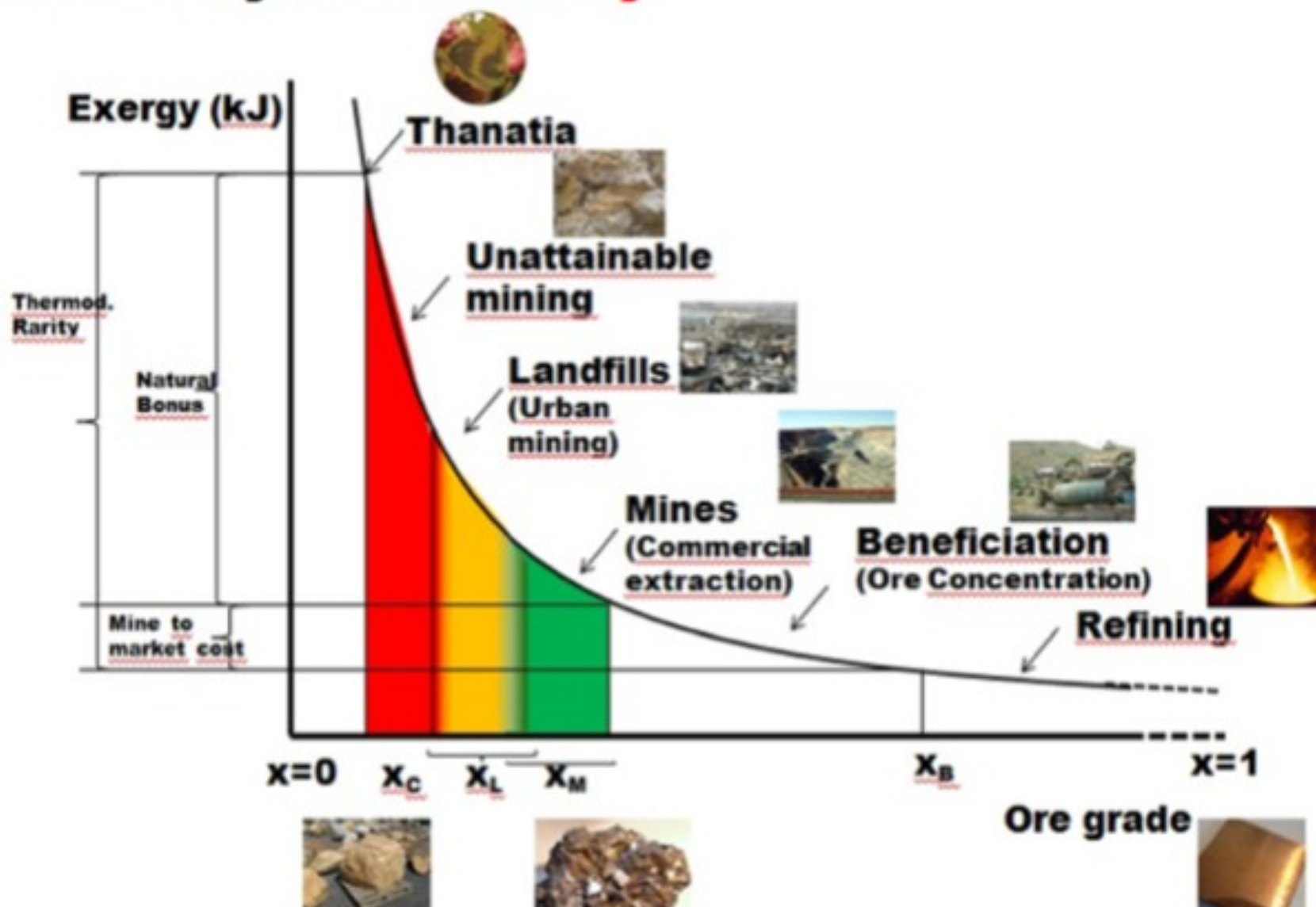
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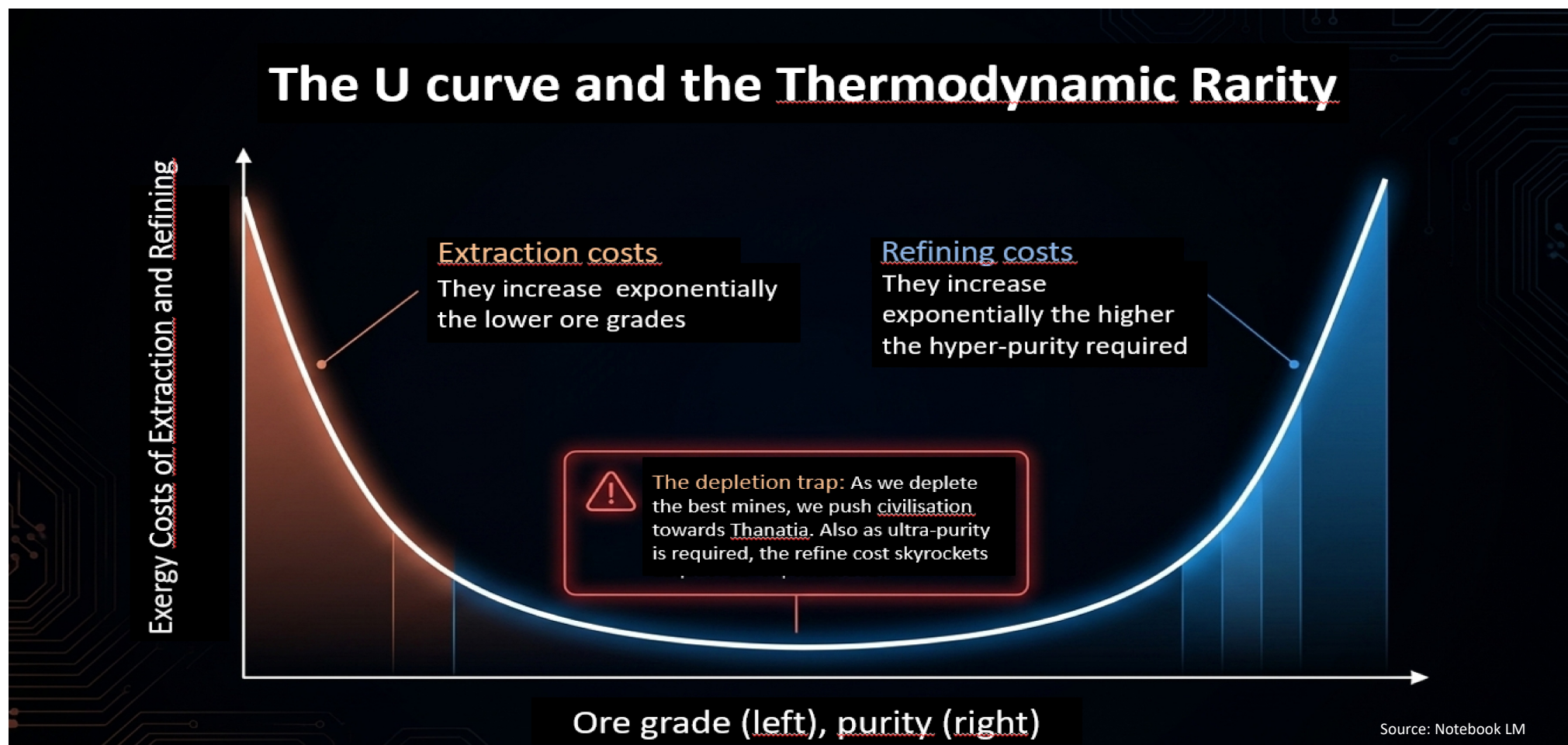
The Goal:
Express environmental impacts as the **thermodynamic work** (exergy) required to remediate them back to safe boundaries.

The Feasible:
Climate Change. Remediation exergy is **quantifiable** (e.g., CO2 capture and geological sequestration measured in GJ per tonne).

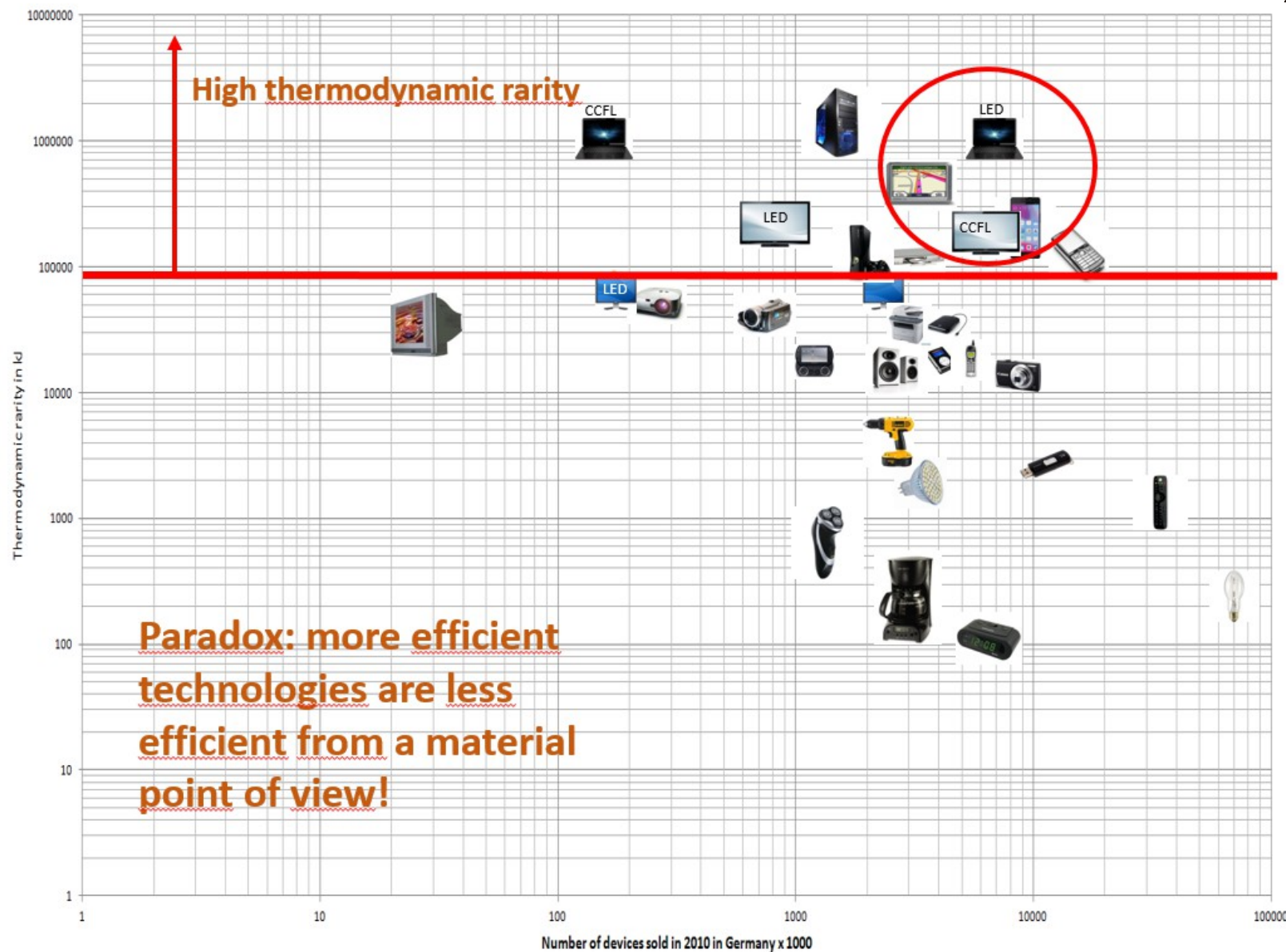
The Challenge:
Biodiversity loss and nitrogen cycle disruption. Assigning precise thermodynamic remediation costs to species extinction remains epistemologically complex. The pragmatic strategy starts with carbon and expands outward.

Thermodynamic rarity





More efficient technologies, greater material rarity?



Source: Own elaboration

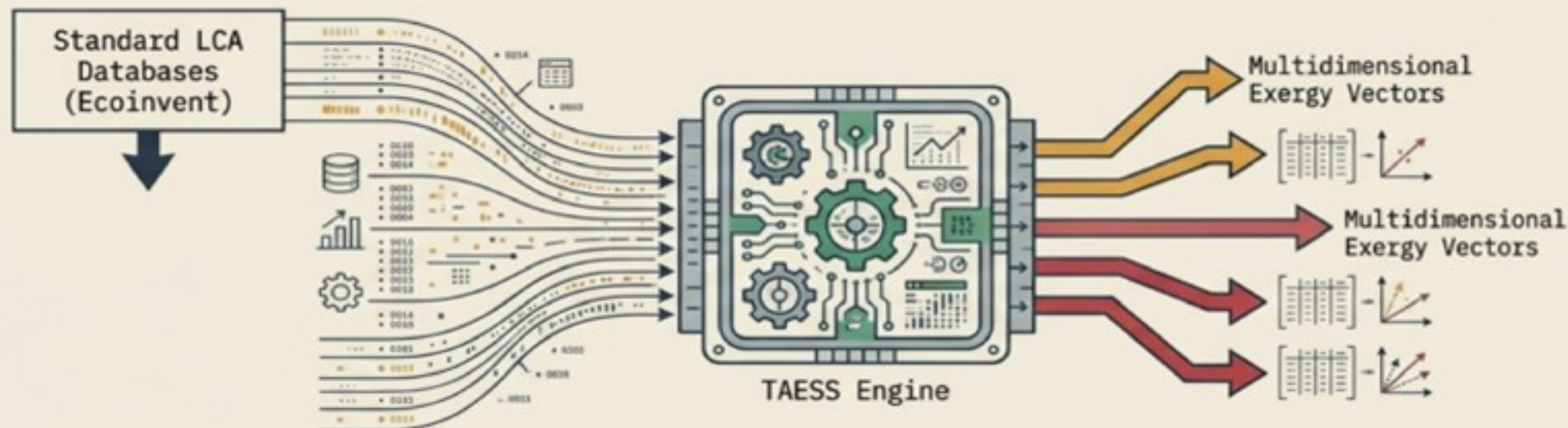
The Thermodynamics of Sustainability should be built on the Second Law of Thermodynamics, using exergy as the universal measure of resource quality, depletion, degradation, and restoration, so that

Sustainability can be understood as the effort to minimise irreversible degradation of the Ecosphere while preserving human well-being on a finite planet.

Order degrades spontaneously. Disorder is only restored with a great exergy cost.

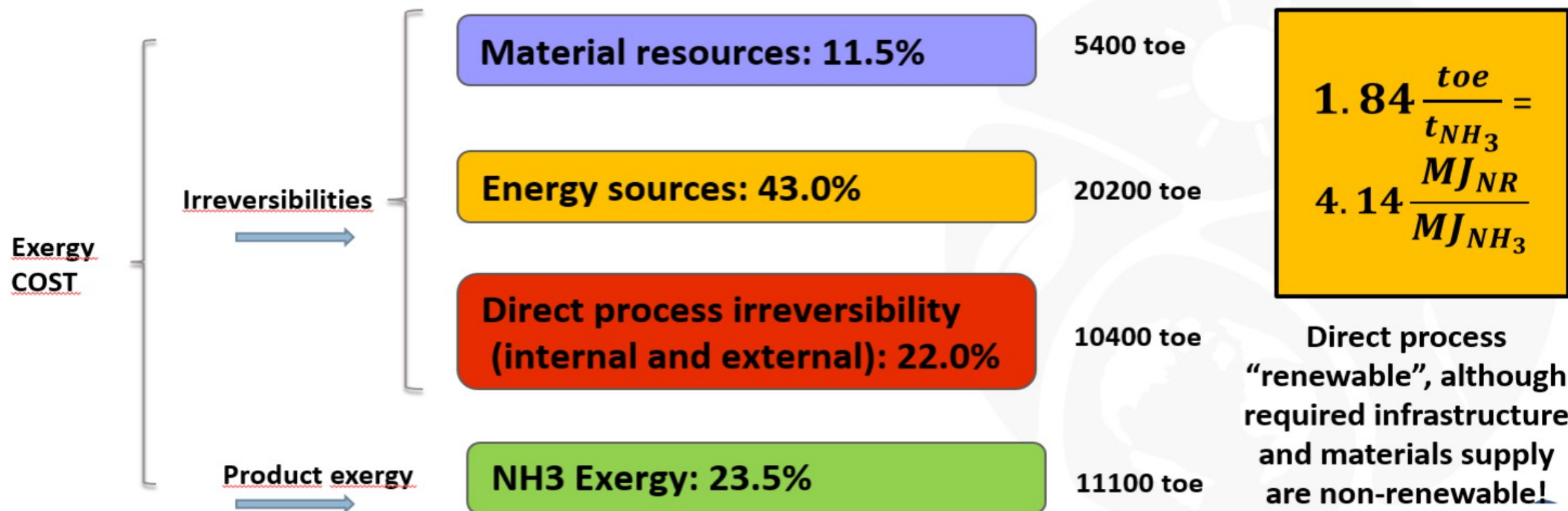
Integration with Databases (TAESS)

Source: Notebook LM



- **Technology:** TAESS (Thermodynamic Assessment of Environmental Sustainability Scenarios).
- **Function:** Connects Exergy Cost Theory directly with global Life Cycle Inventory databases.
- **Scale:** Evaluates 21-dimensional natural resource vectors and 25-dimensional emissions vectors for over 6,000 different products.
- **Impact:** Introduces the missing Second Law perspective into standard industrial accounting.

An irreversibility backpack: green ammonia



1 toe = 41.868 GJ = 11,630 kWh

$$B^* = B + \sum I$$

Source: Notebook LM

From Blueprint to Reality



Diagnosis



Accounting

Nicholas Georgescu-Roegen discovered the thermodynamic disease afflicting classical economics. The Thermodynamics of Sustainability (ToS) built the diagnostic instruments required to measure, track, and treat it.

Source: Notebook LM

The Future of Sustainability Accounting



Irreversibility Footprint
(Absolute kWh)

0.0142 kWh / UNIT (EXERGY COST) ↓ LOSS

1. The Goal: Create an alternative, **universal accounting** system immune to market manipulation.

Establishing a fixed, physical-based ledger using thermodynamics, not monetary valuation.

2. The Vision: Use AI to link every physical object to its exact "**irreversibility footprint**" measured in absolute kWh.

Leveraging machine learning to map product life cycles and quantify real energy costs.

3. The Action: Guide global public sustainability policies by aligning thermodynamic physics with **ecological economics**.

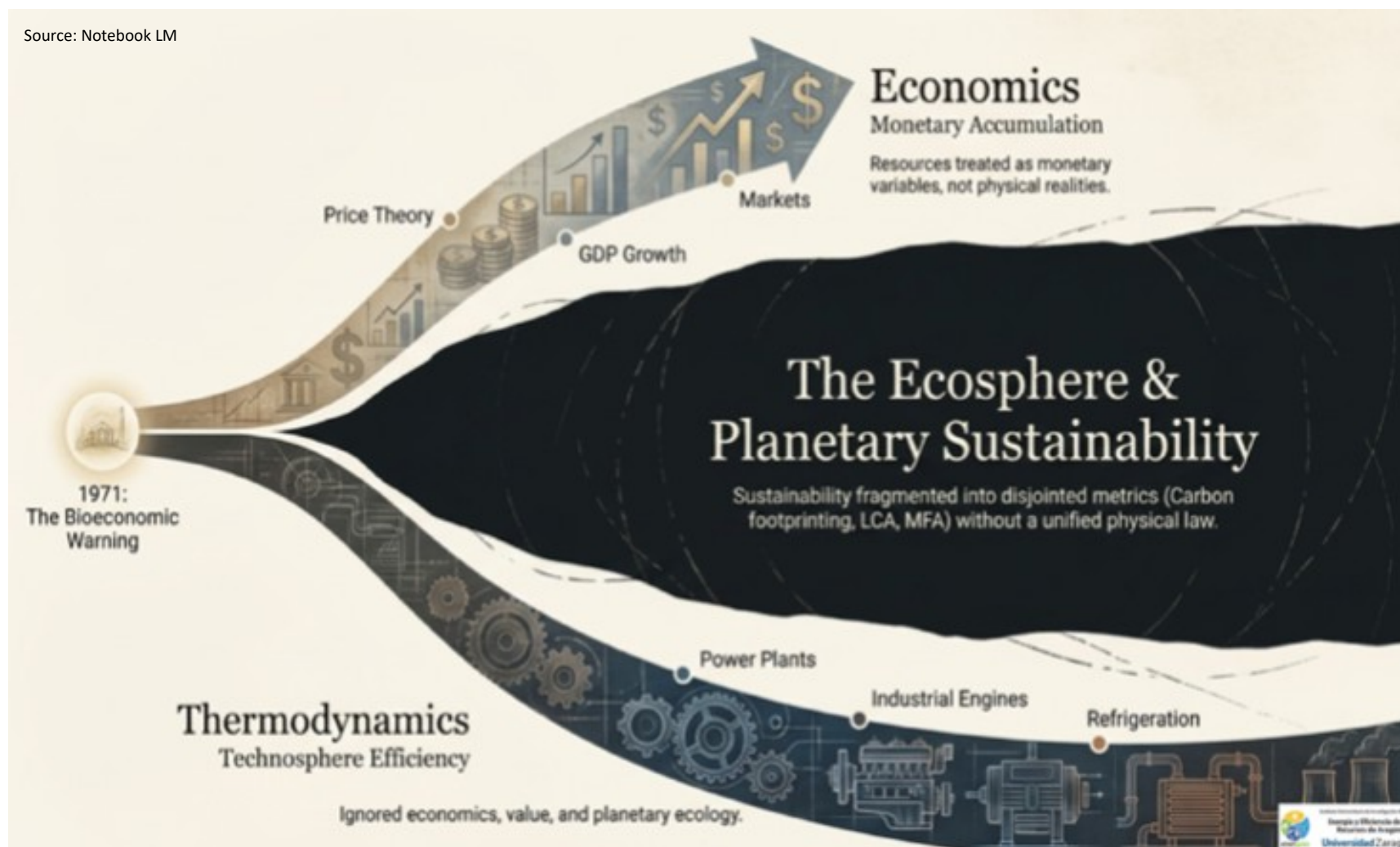
Providing data-driven insights for legislation that addresses physical degradation.

4. The Coalition: Spearheaded by the THERSAURUS project and supported by specialists from the **ECOS International Society**, bridging the gap between thermodynamics and global policy.

A collaborative effort to standardize exergy accounting in policy.

The ecosphere and planetary sustainability

Source: Notebook LM



Learn more and collaborate





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Thank you

Special thanks to the Friede-Gard Foundation.

Thank you for your attention.