

What Is a Resource Worth? A Thermodynamic Journey from Scarcity to Sustainability

Award Lecture

Alicia Valero Delgado



Instituto Universitario de Investigación Mixto de la

Energía y Eficiencia de los
Recursos de Aragón

Universidad Zaragoza

THE THERMODYNAMIC VISION FOR RESOURCE ASSESSMENT

Friede-Gard-Preis 2026



H O C H
S C H U L E
T R I E R

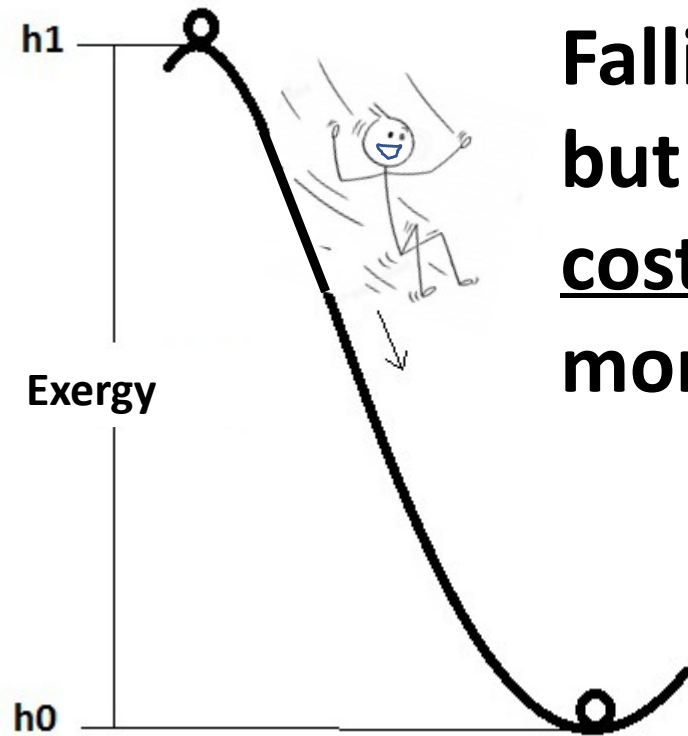
The value of scarcity



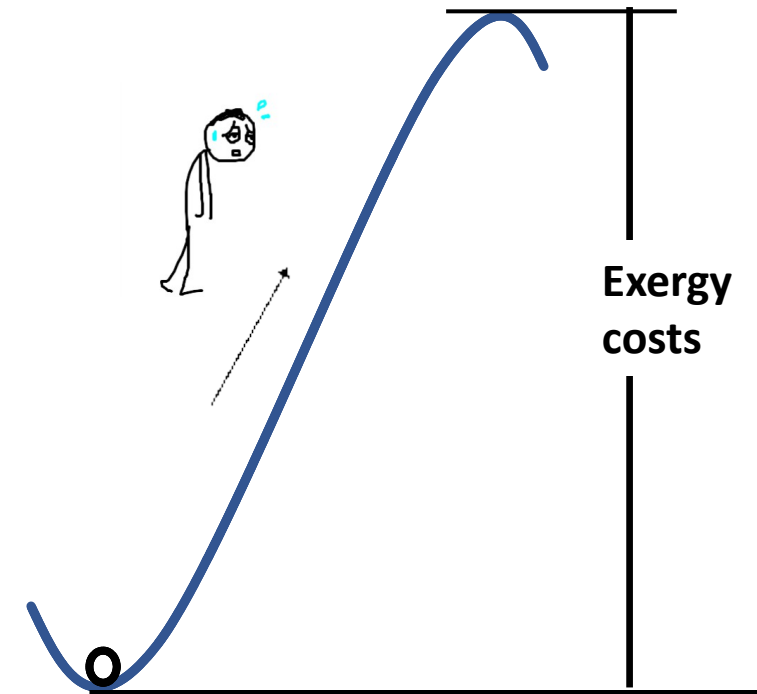
Source: AI generated image inspired by the Film: The Lord of the Rings, 2001

- We value that which we find difficult to attain.
- The **improbability of finding things, the uniqueness, the distinction** from the commonness make things valuable.

Some basic ideas of Thermodynamics



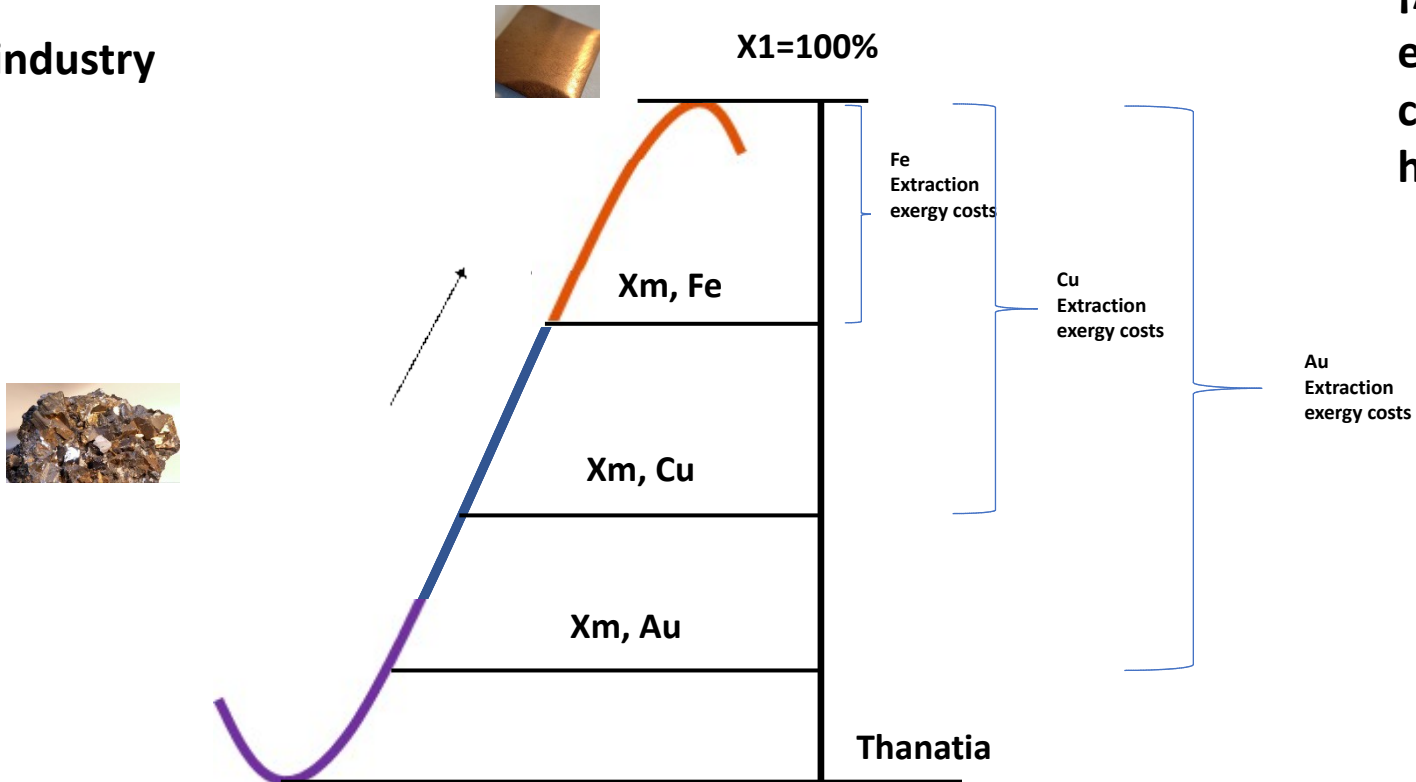
Falling down is easy,
but climbing the hill
costs exponentially
more energy!



Exergy costs >>>Exergy

Some basic ideas of Thermodynamics

From mine to industry



¡A mine saves us a lot of energy! The lower the concentration in the mine, the higher the exergy costs

Exergy

First lesson: Everything that differs from the surrounding environment (ground), has exergy. It depends on both, the height and the ground.

Corolary:

Each resource can be characterized through exergy with a single unit of measure (kJ). height=purity; ground=crustal concentration (total dispersion)

Baselines



THANATIA

Physical depletion of a mine or the entire planet. Maximum degradation. Measure: The exergy cost of restoration/replacement



PRISTINIA

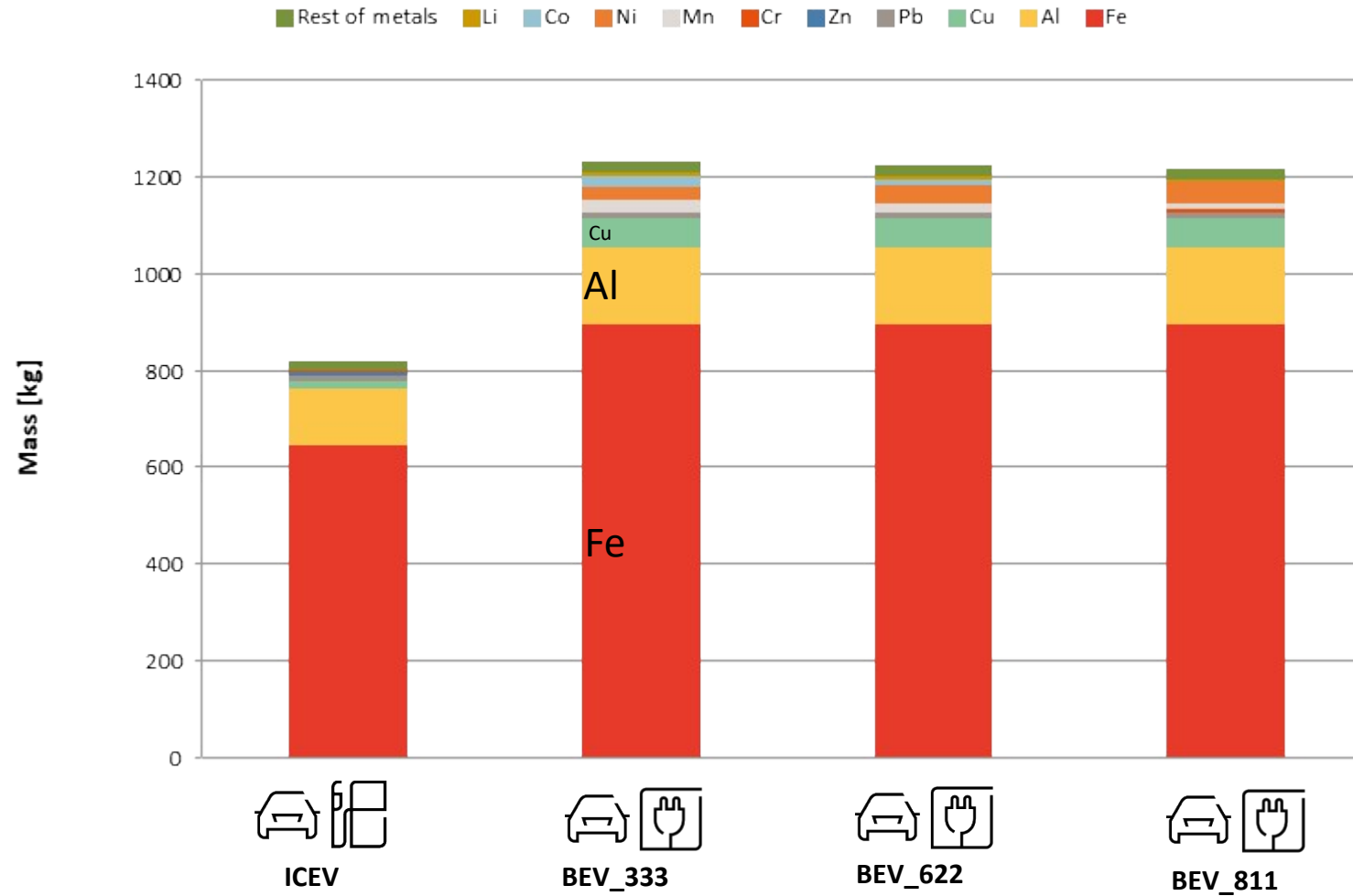
Maximum soil fertility (local), biodiversity and functionality. Measure: The exergy cost of regenerating a degraded ecosystem

Thermodynamic rarity of some elements: physical criticality of minerals

H																	He
Li 558	Be 260											B	C	N	O	F	Ne
Na 47	Mg											Al 638	Si 1	P 1	S	Cl	Ar
K 1,227	Ca 3	Sc	Ti 23	V 1,191	Cr 5	Mn 16	Fe 18	Co 10881	Ni 776	Cu 139	Zn 26	Ga 754,828	Ge 24,247	As 409	Se	Br	Kr
Rb	Sr	Y 1,357	Zr 1,393	Nb	Mo 1,043	Tc	Ru	Rh	Pd	Ag 8,652	Cd 6,162	In 363,917	Sn 442	Sb 445	Te 2,825,085	I	Xe
Cs	Ba 39	La 336	Hf	Ta 405,910	W 7,642	Re 103,087	Os	Ir	Pt	Au 691,420	Hg 28,455	Tl	Pb 37	Bi 493	Po	At	Rn
Fr	Ra	Ac	Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub	Uut	Uuq	Uup	Uuh	Uus	Uuo
			Ce 620	Pr 873	Nd 670	Pm	Sm	Eu	Gd 4,085	Tb	Dy	Ho	Er	Tm	Yb	Lu	
			Th	Pa	U 1,090	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	

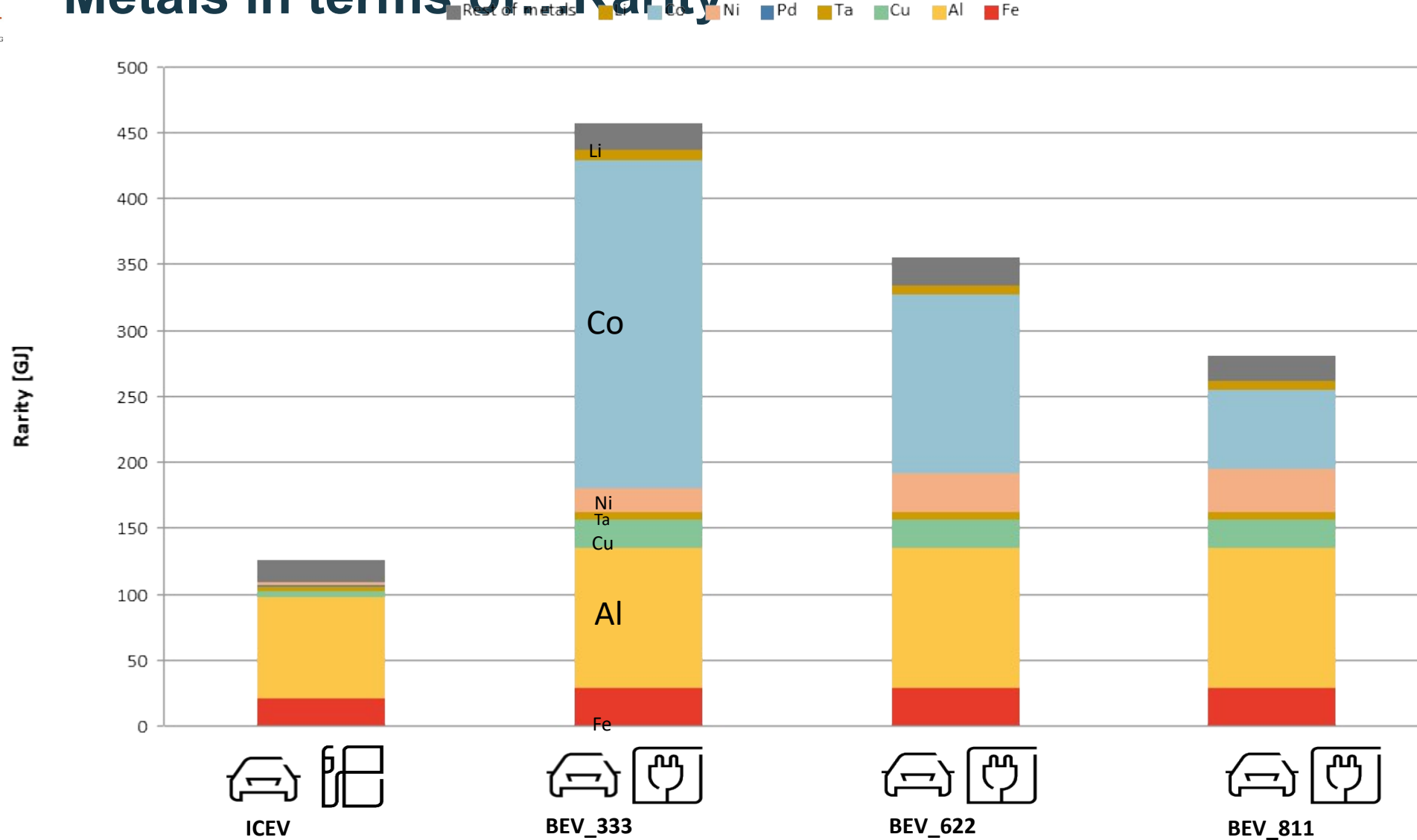
	>10,000 GJ/t
	10,000-1,000 GJ/t
	1,000-100 GJ/t
	<100 GJ/t

Metals in terms of...Mass

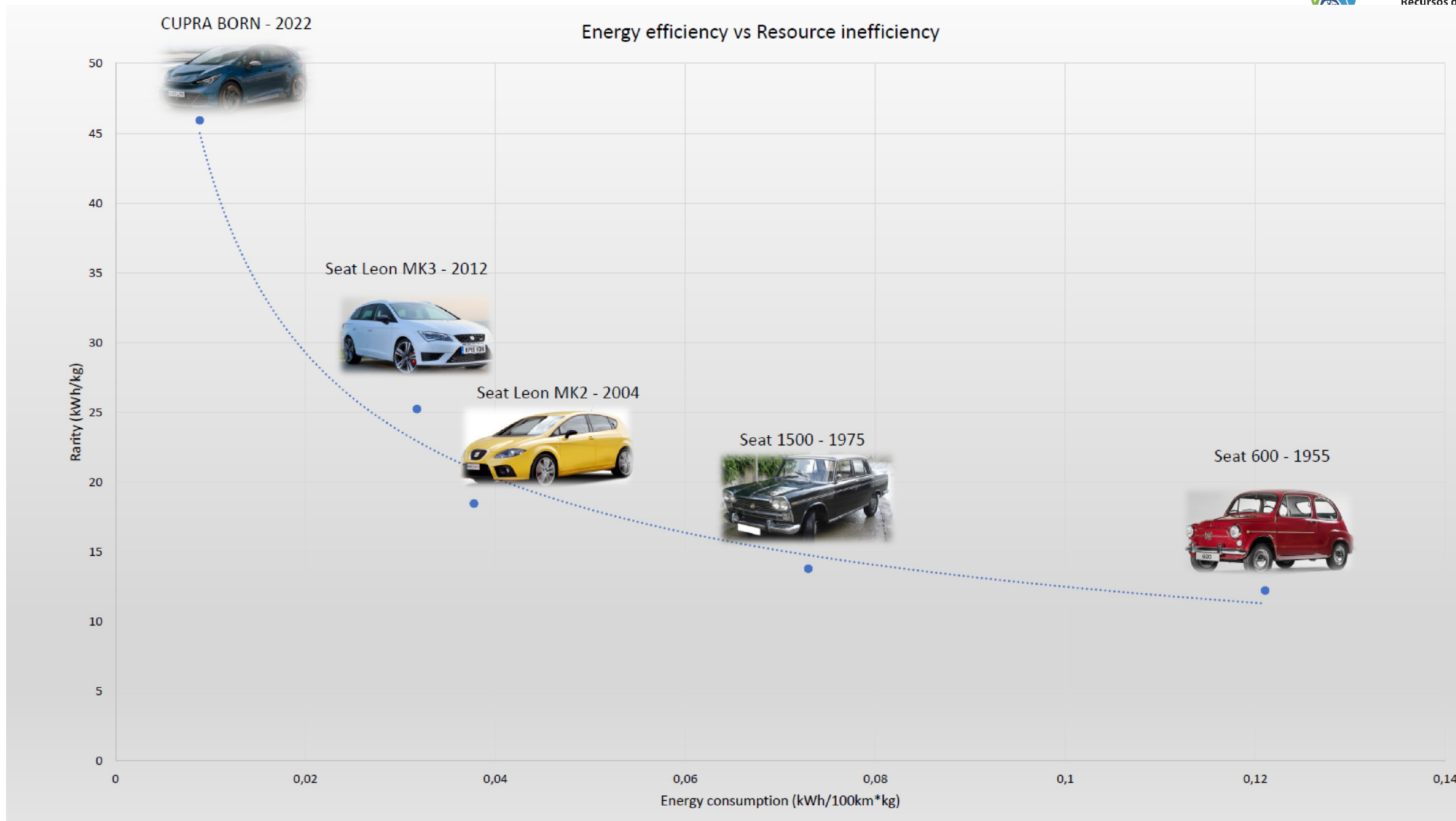


Legislation: 95%
of the car needs
to be recycled

Metals in terms of Rarity



With
electrification
this will
become
worse!



Source: own elaboration

Friede-Gard-Preis 2026

Mixing sugar and salt

From concentration to dispersion



The frightening Second Law of Thermodynamics

Second Lesson: All natural and man-made processes tend spontaneously to degradation and the way back is very costly or even impossible.

Corollary:

Mixing is the most entropic process that exists!
Keep purity as much as you can!



How can thermodynamics answer the following questions?

- How renewable are renewable energies?
- How circular is the circular economy?
- How sustainable is sustainable agriculture?



Instituto Universitario de Investigación Mixto de la

Energía y Eficiencia de los
Recursos de Aragón

Universidad Zaragoza

1. HOW RENEWABLE ARE RENEWABLE ENERGIES?

Friede-Gard-Preis 2026

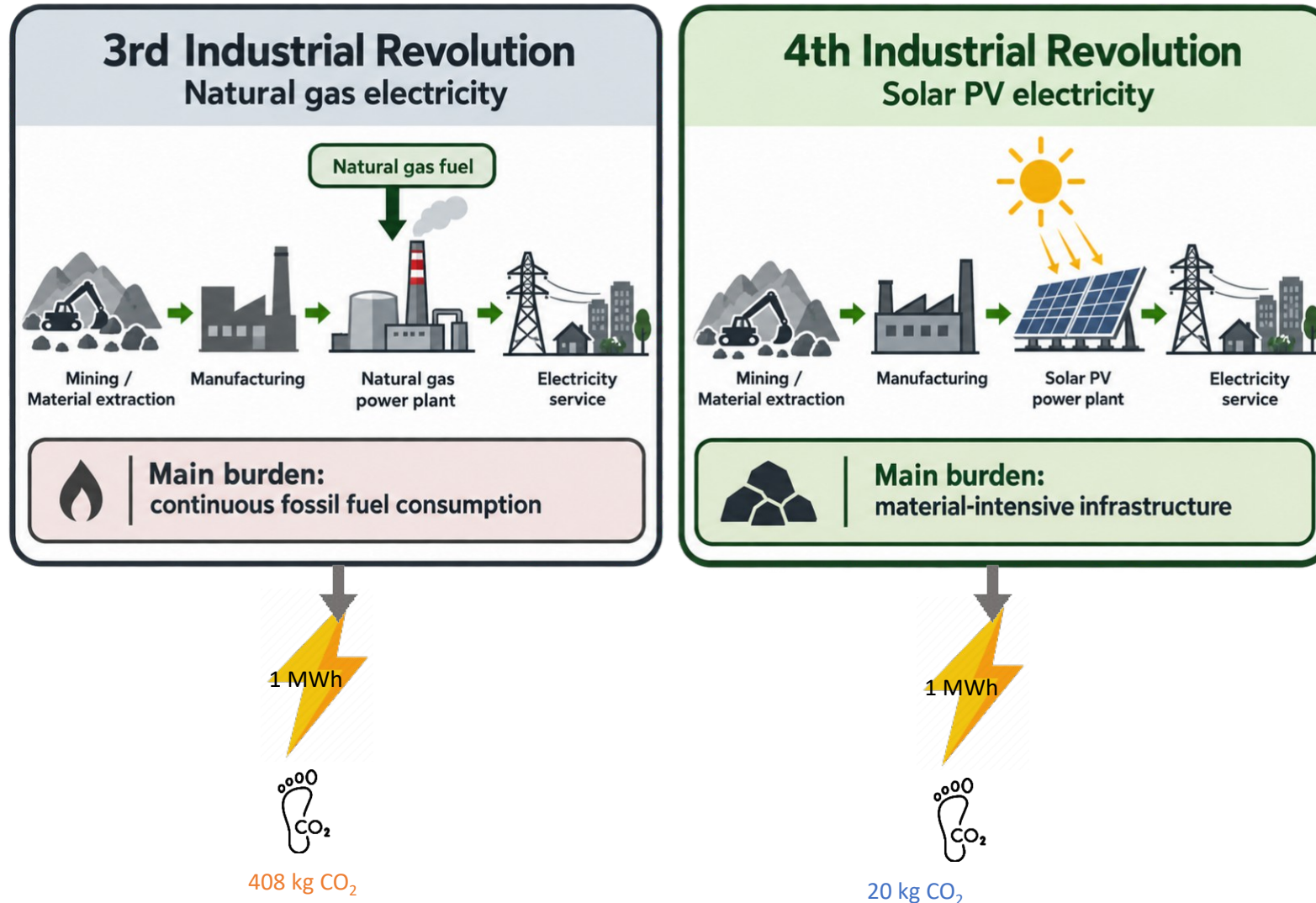


Umwelt-Campus
Birkenfeld

H O C H
S C H U L E
T R I E R

The industrial “progress”

Difference between the 3rd and 4th Industrial Revolution



- Fossil fuel use (MJ) → 0 vs 7200
- Emissions (kg-CO₂) → 20 vs 408
- + Materials (kg) → 8 vs 0.3
- + Mining energy (MJ) → 431 vs 8.3
- + Wastes (kg) → 8 vs 0.3

Exergy cost of Electricity

How renewable are renewable energies?

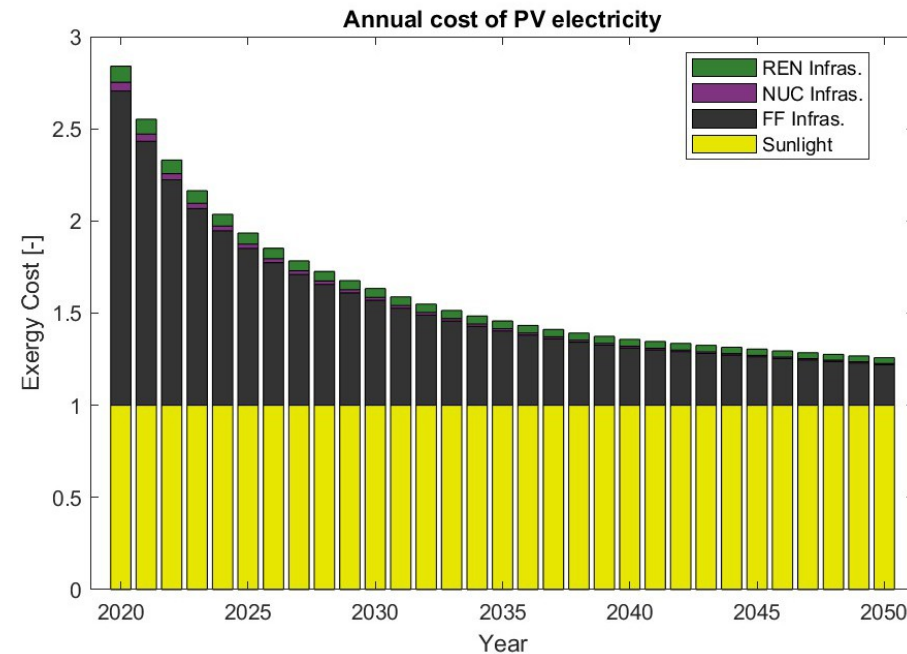
IEA NZE Scenario

Non-renewable exergy cost of fuel decrease

Non-renewable exergy cost of infrastructure increase

PV 2020 → 250% Non-renewable

PV 2050 → 20% Non-renewable



How renewable are renewable energies?

1

THE QUESTION

If sunlight and wind are renewable, does that make the technologies themselves renewable?

2

THE HIDDEN PROBLEM

Solar panels, turbines, batteries and grids depend on minerals, manufacturing and other non-renewable resources.

3

WHAT THERMODYNAMICS REVEALS

Exergy accounting reveals the non-renewable physical cost of fuels and infrastructure across the electricity life cycle.

4

WHAT THIS MEANS FOR SUSTAINABILITY

Decarbonise electricity while reducing material demand, improving durability and preserving scarce resources.

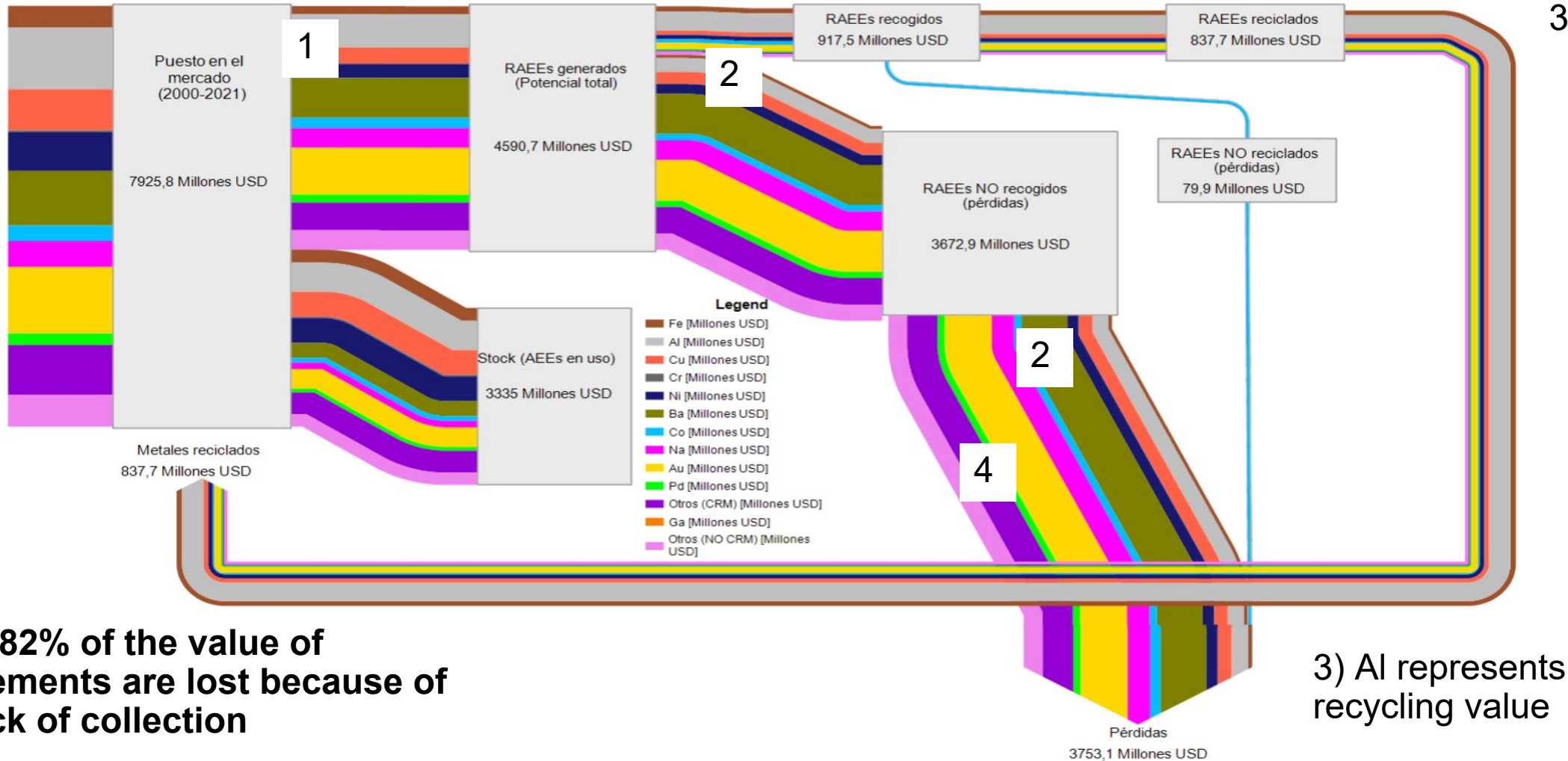
KEY MESSAGE · Renewable energy is not resource-free energy.

2. HOW CIRCULAR IS THE CIRCULAR ECONOMY?

1. A collection problem

RAEEs reciclados en USD (2000-2021)

The case of Spain



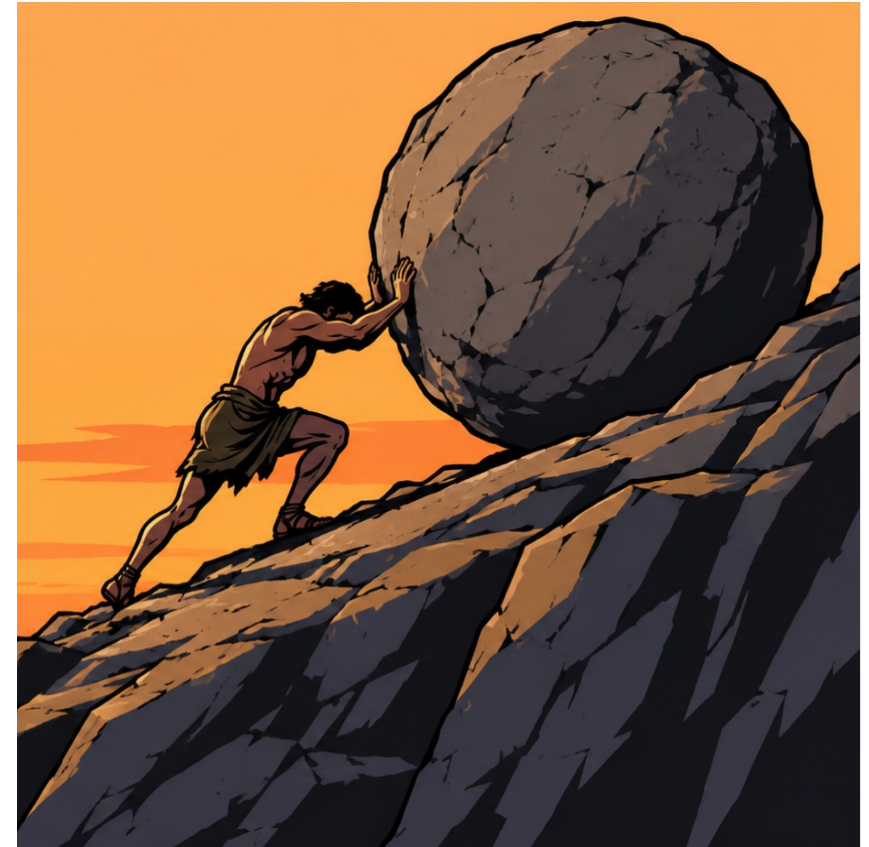
2) 82% of the value of elements are lost because of lack of collection

3) Al represents 50% of the recycling value

4) 99% CRMs (Co, Pd, Ga y Otros-CRM) are lost

2. A disassemblability problem

Extracting REE from the motor of an electric vehicle



Source: AI-generated illustration using OpenAI ChatGPT (2026). Inspired by the Greek myth of Sisyphus.

Chemodiversity in common products

TENDENCY:
Increasingly complex products and materials with better functionalities

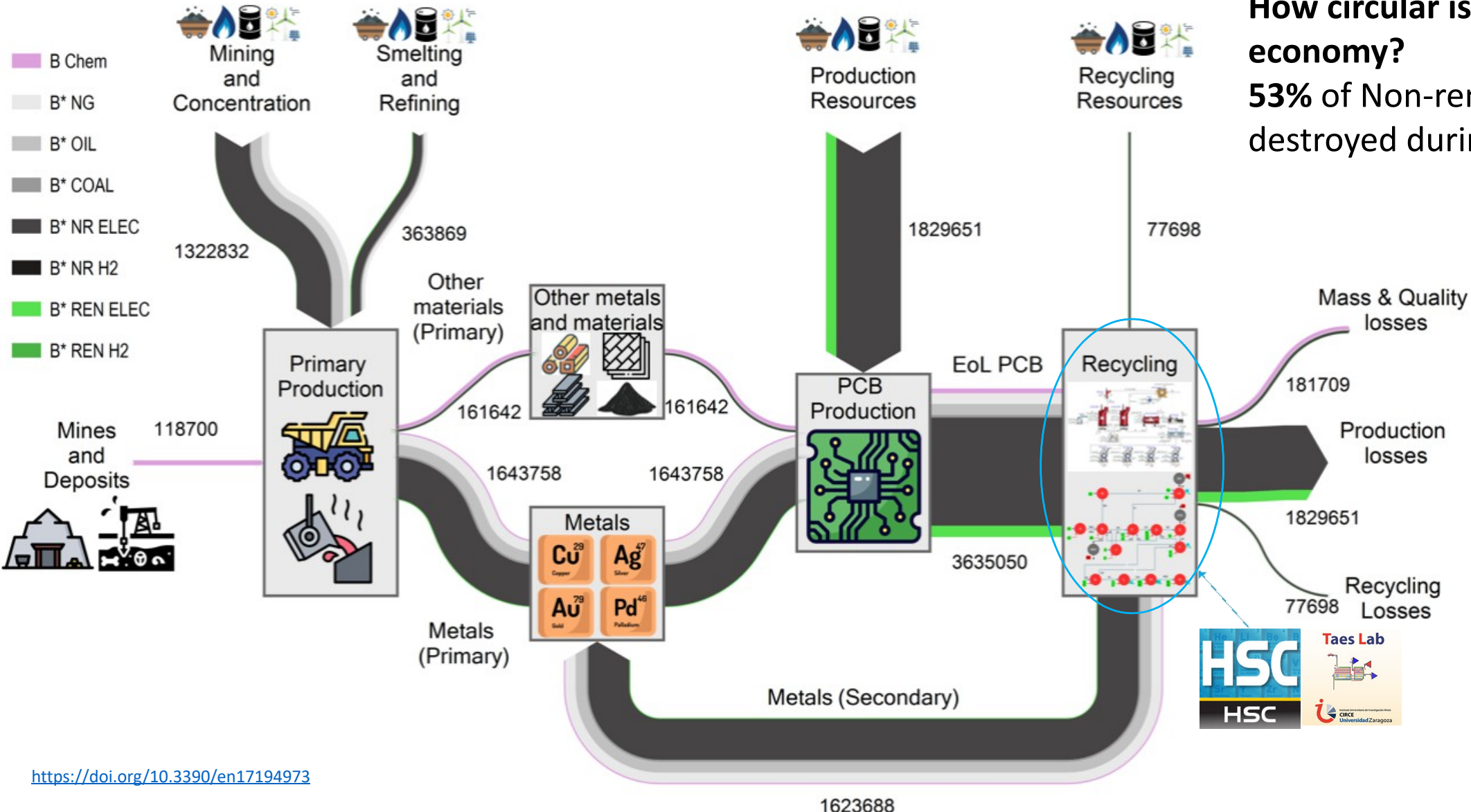


SourceSource: AI-generated illustration using OpenAI ChatGPT (2026).

RESULT:
scarce elements in common products difficult to recycle

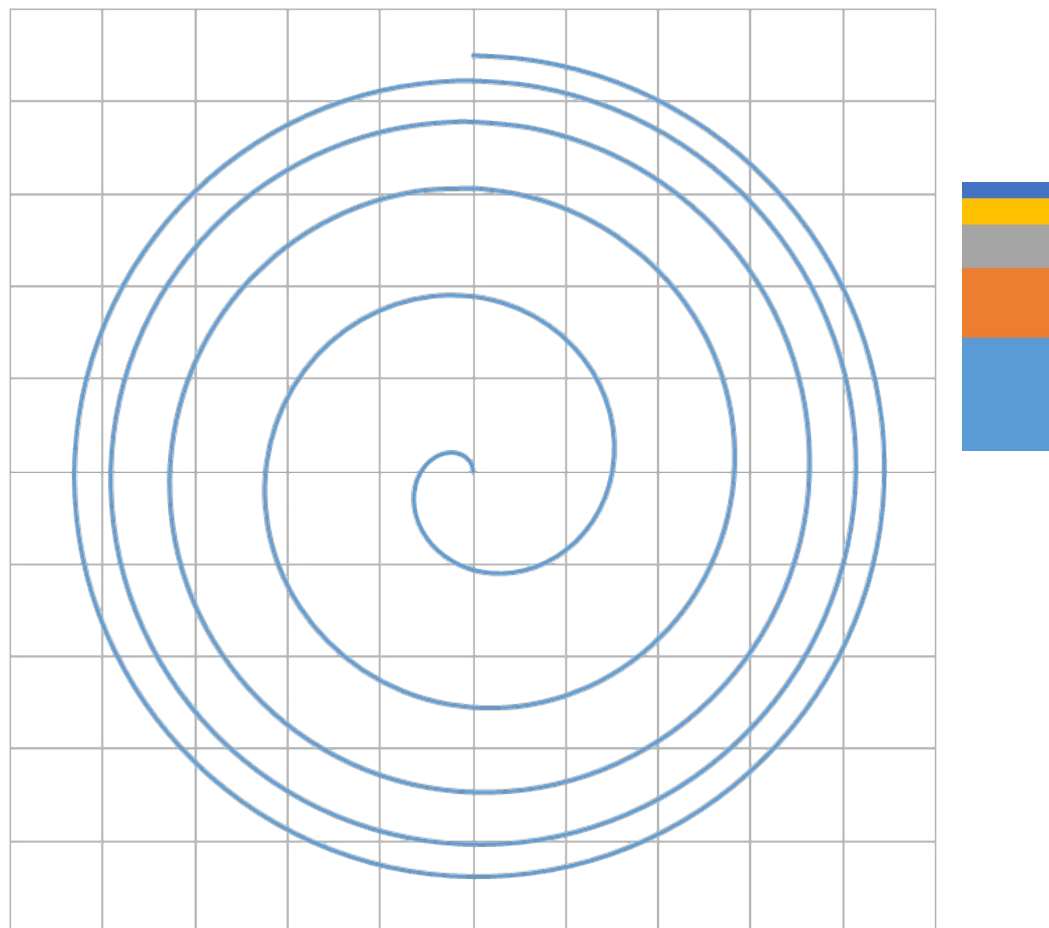
Circular Thermoeconomics:

2020 case (Conventional Resources)



How circular is the circular economy?
53% of Non-renewable exergy is destroyed during recycling

Growing degradation of the Spiral Economy



How circular is the circular economy?

1

THE QUESTION

Can we really keep materials circulating forever?

2

THE HIDDEN PROBLEM

Complex products mix many elements. Collection, disassembly and recycling lose materials and material quality.

3

WHAT THERMODYNAMICS REVEALS

Recycling involves unavoidable irreversibilities: recovering mass does not mean recovering its original physical value.

4

WHAT THIS MEANS FOR SUSTAINABILITY

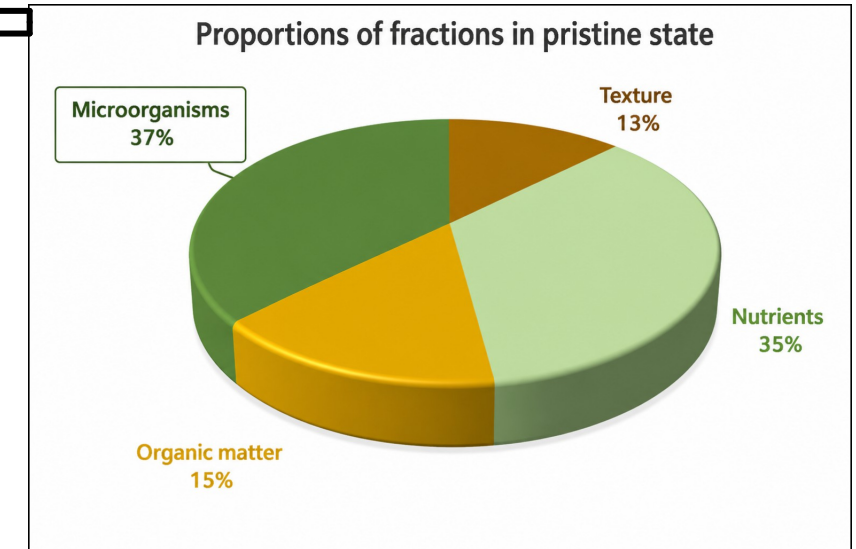
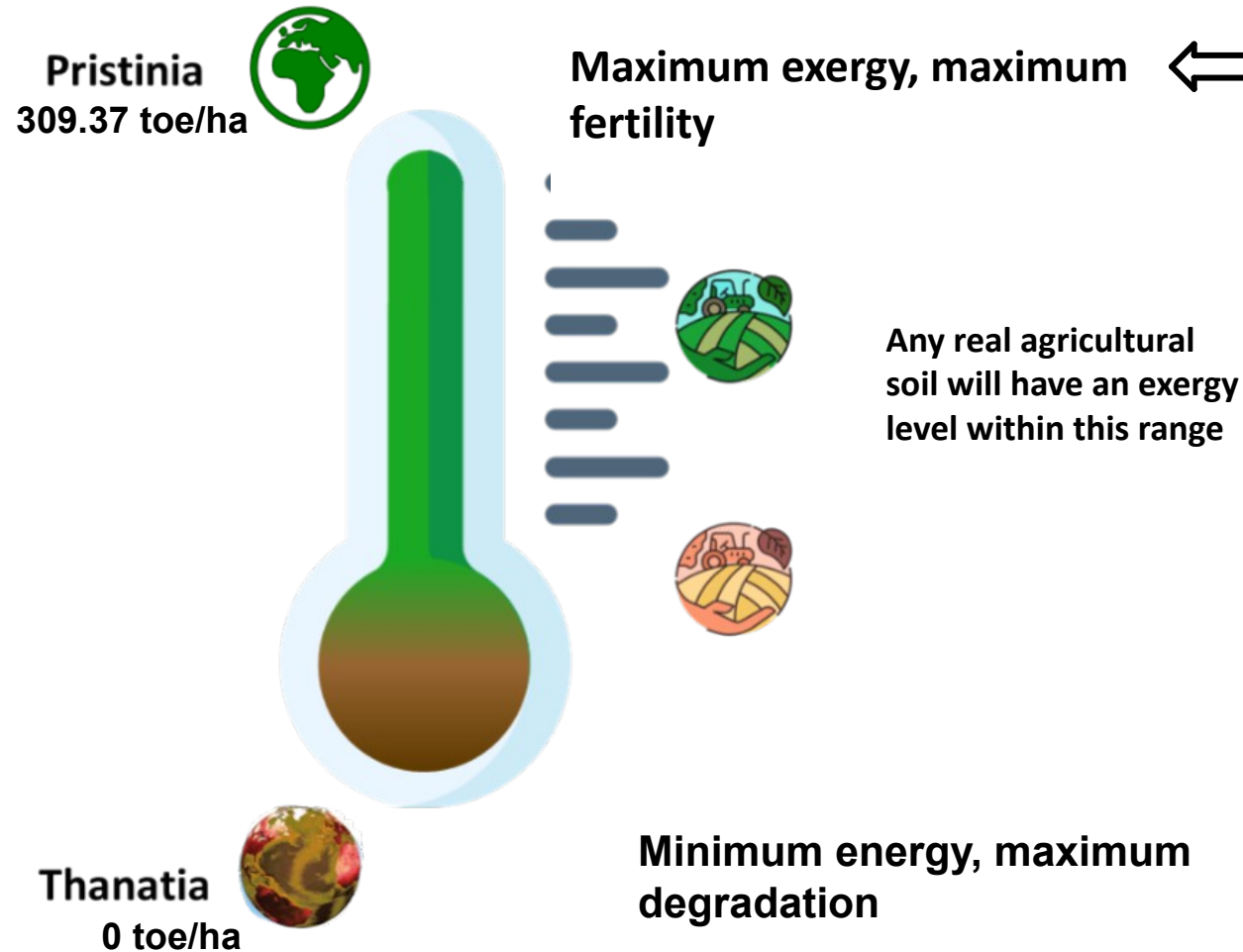
Prevent waste, design for repair and disassembly, extend lifetimes and recover materials at the highest possible quality.

KEY MESSAGE · Preserve resource quality, not only material mass.

3. HOW SUSTAINABLE IS SUSTAINABLE AGRICULTURE?

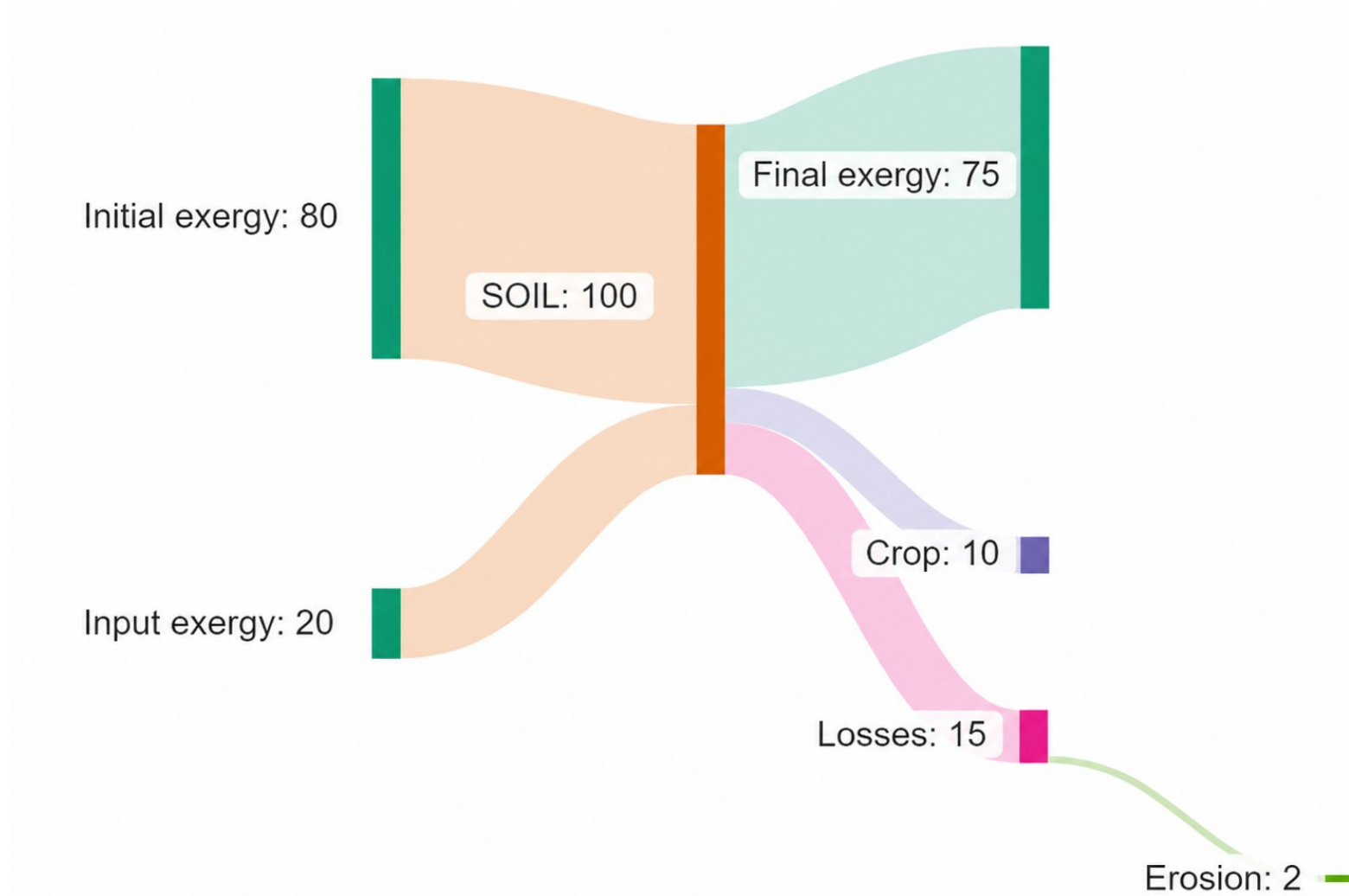
Exergetic characterisation of soils

Pristinia: The fertile planet



Exergetic characterisation of soils

Exergy soil balance



How sustainable is sustainable agriculture?

1

THE QUESTION

Is using fewer inputs enough to make agriculture sustainable?

2

THE HIDDEN PROBLEM

Soil fertility is natural capital. Erosion and degradation can erode it even when production remains high.

3

WHAT THERMODYNAMICS REVEALS

Exergy provides a physical lens on soil quality and the resources required to regenerate degraded soils.

4

WHAT THIS MEANS FOR SUSTAINABILITY

Protect and restore fertile soils, rather than treating soil as a replaceable production input.

KEY MESSAGE · Fertile soil is natural wealth worth preserving.

What does this mean for economics?

1

THE QUESTION

What should count as wealth—and what should count as a cost?

2

THE HIDDEN PROBLEM

Market prices and GDP do not fully reflect mineral depletion, loss of material quality or declining soil fertility.

3

WHAT THERMODYNAMICS REVEALS

Physical accounting makes the irreversible consumption of natural resources visible alongside monetary flows.

4

WHAT THIS MEANS FOR SUSTAINABILITY

Combine physical, social and economic indicators to favour sufficiency, long-lived products and regeneration.

KEY MESSAGE · Count the natural wealth we preserve—and the value we destroy

Welcome to the Exergoecology Portal

You are here: [Home](#)

EXERGY MANIFESTO



[SIGN UP THE EXERGY MANIFESTO](#)

SUPPORTED BY



Introduction

This portal is the first scientific web space devoted to the dissemination of the novel discipline "Exergoecology"

What you will find...

Information about Exergoecology



Answers to what is Exergoecology, Thanatia, the Reference Environment, Thermoecological costs and Thermodynamic rarity.

[READ MORE...](#)

Flow Exergy Calculator



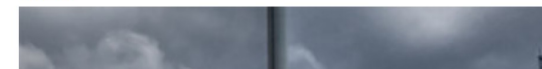
Chemical Exergy Calculator



The first online chemical exergy calculator. It calculates automatically the exergy of near 2000 inorganic substances just by entering the formula

[READ MORE...](#)

TaesLAB



WHAT IS A RESOURCE REALLY WORTH?

Beyond market prices, the value of resources is also a question of justice and responsibility.

BEYOND PRICES

Nature takes millions of years to create resources we can destroy in decades.

BEYOND SCARCITY

Competition for resources can fuel inequality, injustice and conflict.

BEYOND SCIENCE

We have a responsibility to use resources fairly and wisely.

Sustainability is not only about preserving resources. It is about peace, justice and well-being for all.

Thank you · Vielen Dank