



Instituto Universitario de Investigación Mixto de la
**Energía y Eficiencia de los
Recursos de Aragón**
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THE EXERGY OF THE EARTH RESOURCES

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ICES FOUNDATION
2/10/2026

energaia

What do these places have in common?



Iran



Venezuela

The search for
the last
resources



South Sudan



Niger

Resources are increasingly becoming a central dimension of geopolitical conflicts



**Gaia is responding. We are in a critical
moment for Humanity**

Heatwaves

Droughts

Floods

Biodiversity collapse

**Nature is not taking revenge. It is simply obeying the laws of
physics**

An aerial photograph of a vast open-pit mine. The mine's structure is characterized by numerous terraced levels of reddish-brown earth and rock, creating a complex, stepped pattern. A prominent, light-colored dirt road or path winds through the mine, curving around the edges of the terraces. In the background, dark, forested hills rise against a clear sky. The overall scene conveys a sense of large-scale industrial extraction and significant land alteration.

We have lived as if the planet were infinite

For more than two centuries our economic model has assumed:

- **Infinite resources**
- **Infinite capacity to absorb waste**

But neither assumption is true

Exponential demand of raw materials

Nature's depredation is growing at a rate of 2.8% per year. In one generation we will consume twice as much as we do today and in 25 years we will have consumed as much as in the entire history of mankind.

We must **abandon the ledger** and learn the language of the **Earth**

Economics (The Illusion)

Vocabulary: Markets, GDP, €

Core Assumption:
Infinite Resources & Waste

Mechanism:
Compromise & Policy

Time Horizon:
Quarterly / Immediate

Thermodynamics (The Reality)

Vocabulary: Energy, Matter, Entropy

Core Assumption:
Physical Limits & Irreversibility

Mechanism:
Action & Reaction

Time Horizon:
Millions of years of natural capital

THE THERMODYNAMIC VISION FOR RESOURCE ASSESSMENT

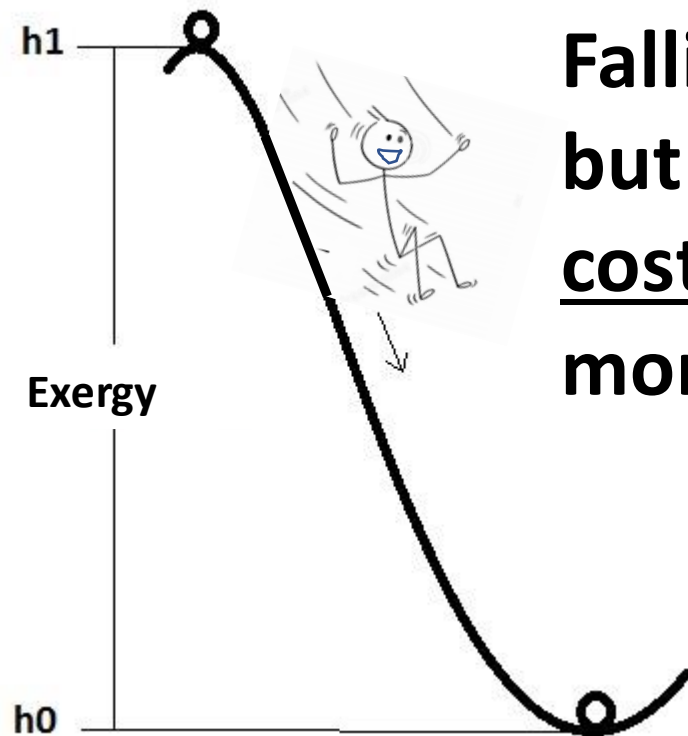
The value of scarcity



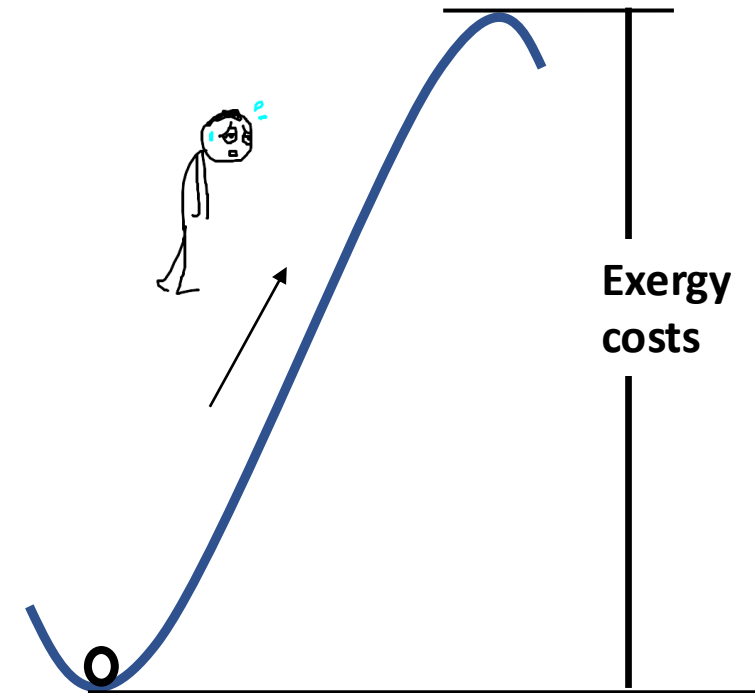
Source: Film: The Lord of the Rings, 2001

- 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



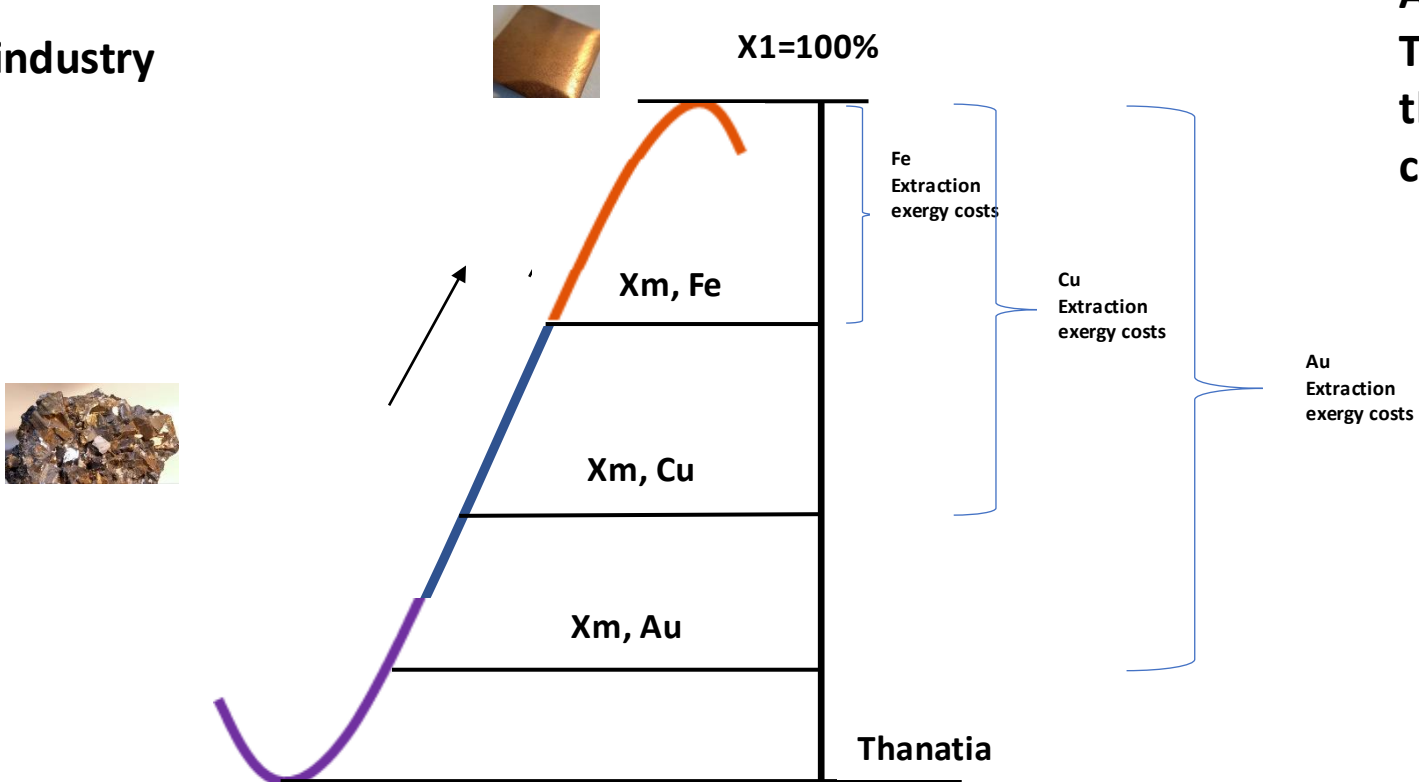
Falling down is easy,
but climbing the hill
costs exponentially
more energy!



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)

Reference Baselines: Thanatia and Pristinia

Thanatia

Represents maximum global degradation—a fully depleted Earth with exhausted minerals and fuels.

Used to calculate the Exergy Replacement Cost (ERC) required to reconcentrate dispersed materials.

Pristinia

Represents maximum ecological functionality and optimal soil fertility.

Used to evaluate biological and agricultural degradation.

Note: The standard Szargut Reference Environment (SRE) is insufficient because it ignores scarcity, toxicity, and ecological resilience.

Local 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

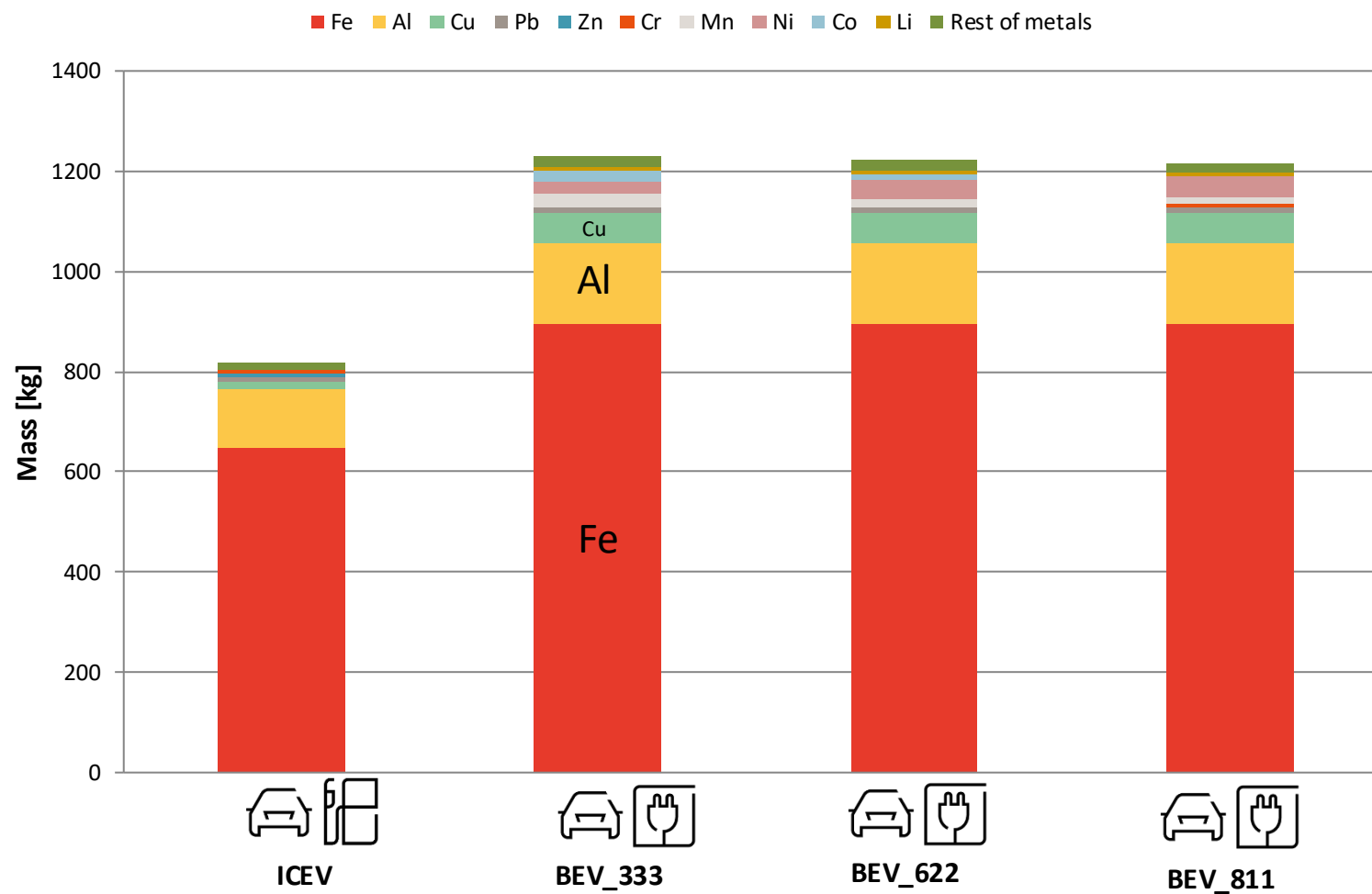
Thermodynamic rarity of some elements: physical criticality of minerals

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 485,910	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

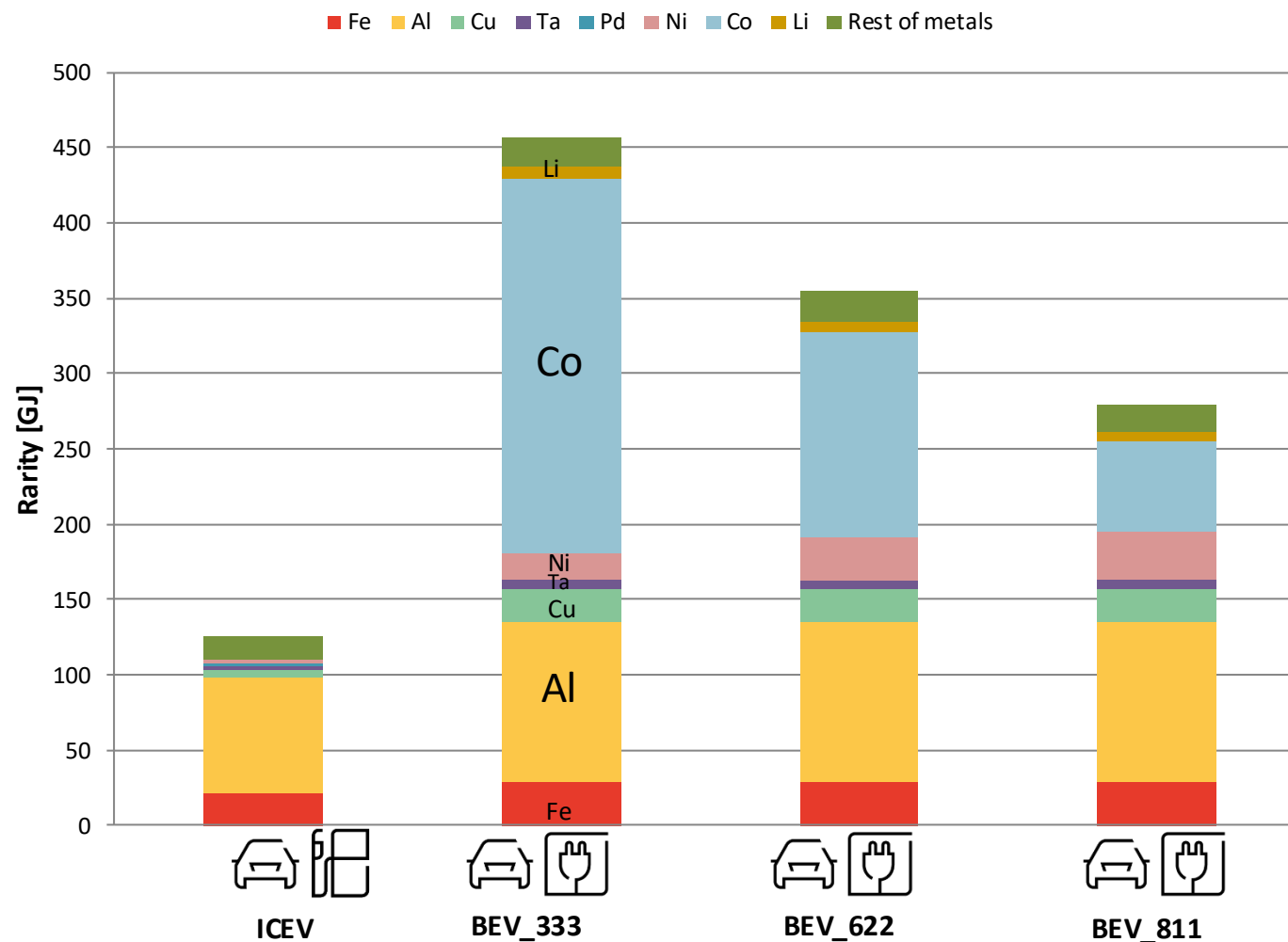
	>10,000 GJ/t
	10,000-1,000 GJ/t
	1,000-100 GJ/t
	<100 GJ/t

Metals in terms of...Mass



Legislation: 95%
of the car needs
to be recycled

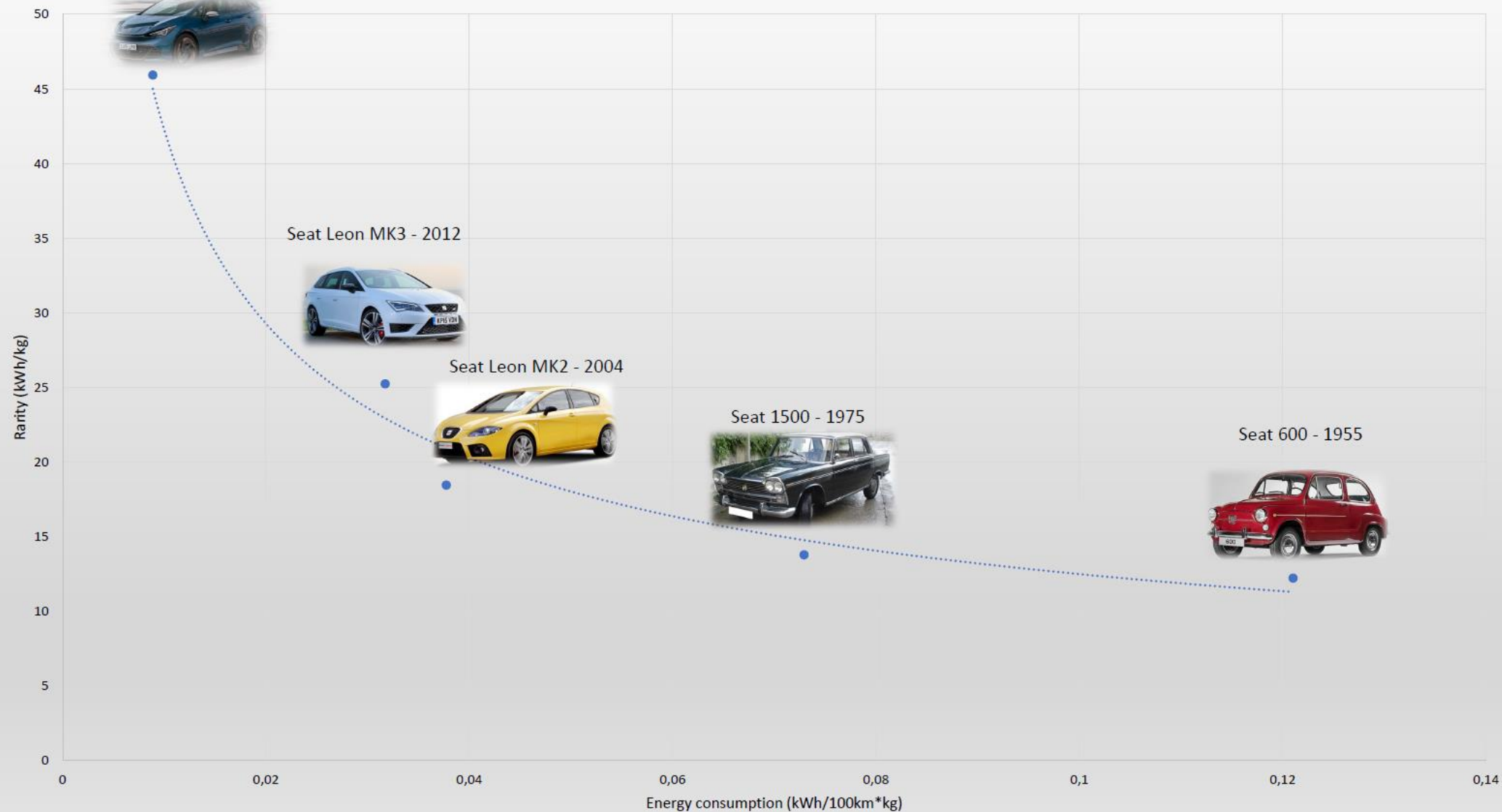
Metals in terms of...Rarity



- With electrification this will become worse!

CUPRA BORN - 2022

Energy efficiency vs Resource inefficiency



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.

Corolary:

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



Mixing sugar and salt

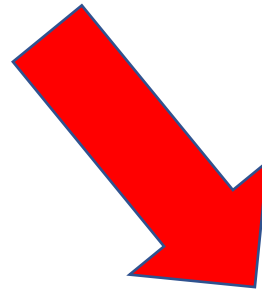


From concentration to dispersion

Chemodiversity in common products

TENDENCY:

Increasingly complex products and materials with better functionalities

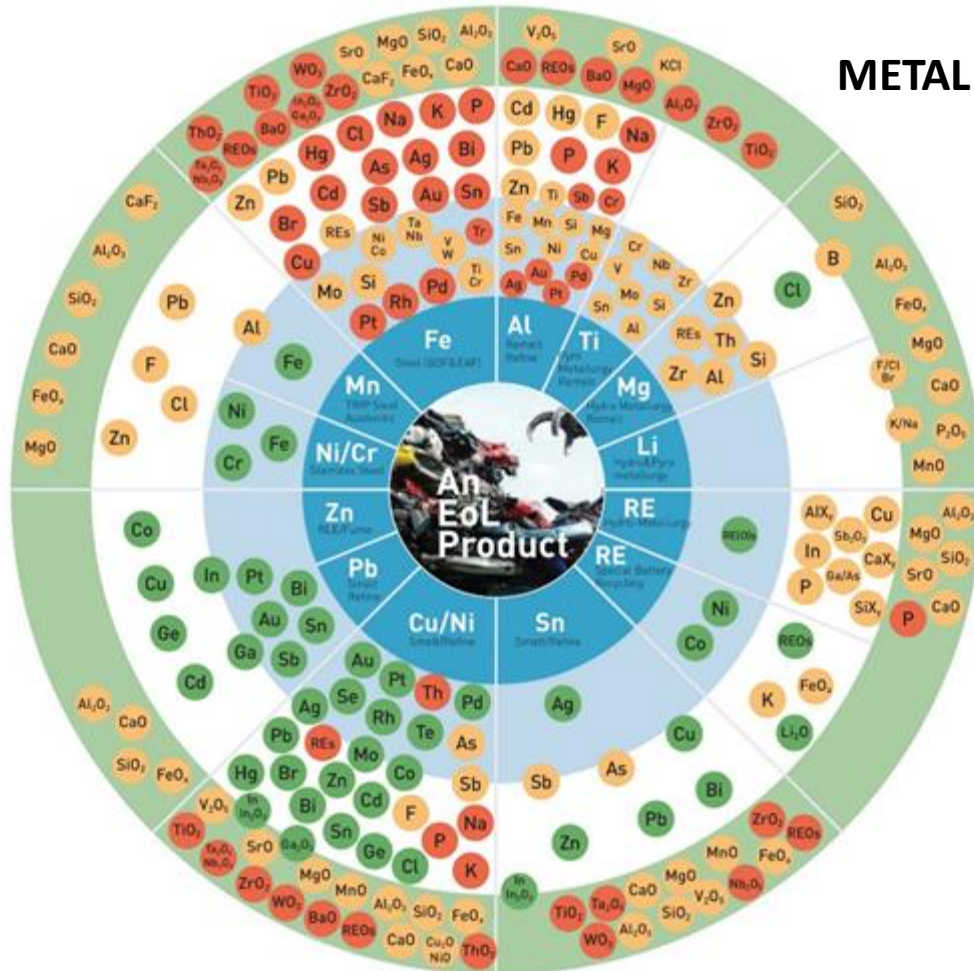


RESULT:

scarce elements in common products difficult to recycle



Metal mixology implies also irreversible losses at the EoL

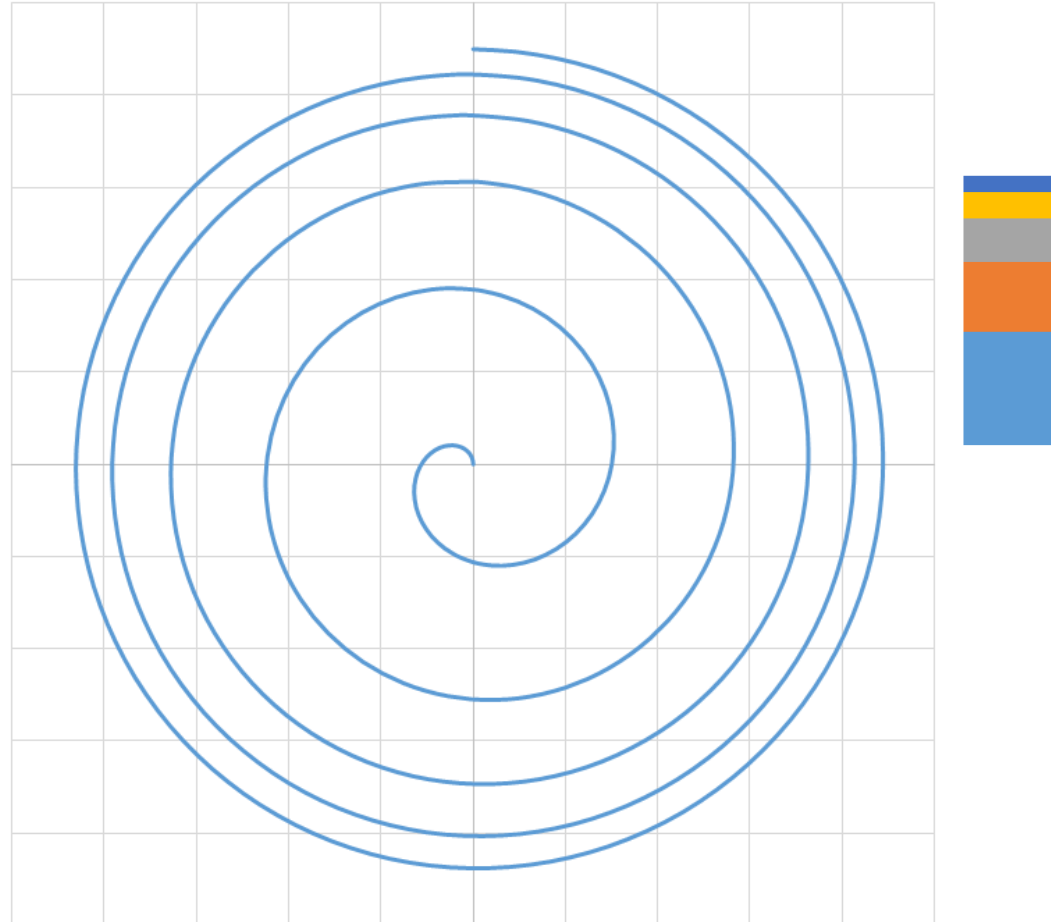


METAL WHEEL

- Society's Essential Carrier Metals: Primary Product**
Extractive Metallurgy's Backbone (primary and recycling metallurgy). The metallurgy infrastructure makes a "closed" loop society and recycling possible.
- Dissolves mainly in Carrier Metal if Metallic (Mainly to Pyrometallurgy)** Valuable elements recovered from these or lost (metallic, speiss, compounds or alloy in EoL also determines destination as also the metallurgical conditions in reactor).
- Compounds Mainly to Dust, Slime, Speiss, Slag (Mainly to Hydrometallurgy)** Collector of valuable minor elements as oxides/sulphates etc. and mainly recovered in appropriate metallurgical infrastructure if economic (EoL material and reactor conditions also affect this).
- Mainly to Benign Low Value Products** Low value but inevitable part of society and materials processing. A sink for metals and loss from system as oxides and other compounds. Comply with strict environmental legislation.

- EL** **Mainly Recovered Element** Compatible with Carrier Metal as alloying Element or that can be recovered in subsequent Processing.
- EL** **Mainly Element in Alloy or Compound in Oxidic Product, probably Lost** With possible functionality, not detrimental to Carrier Metal or product (if refractory metals as oxidic in EoL product then to slag/slag also intermediate product for cement etc.).
- EL** **Mainly Element Lost, not always compatible with Carrier Metal or Product** Detrimental to properties and cannot be economically recovered from e.g. slag unless e.g. iron is a collector and goes to further processing.

Growing degradation of the Spiral Economy

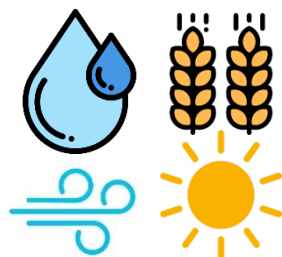


How can exergy answer the following questions?

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

Exergy disaggregated by its origin:

- Non-Renewable exergy cannot be replaced by nature in the short-time
- Renewable exergy

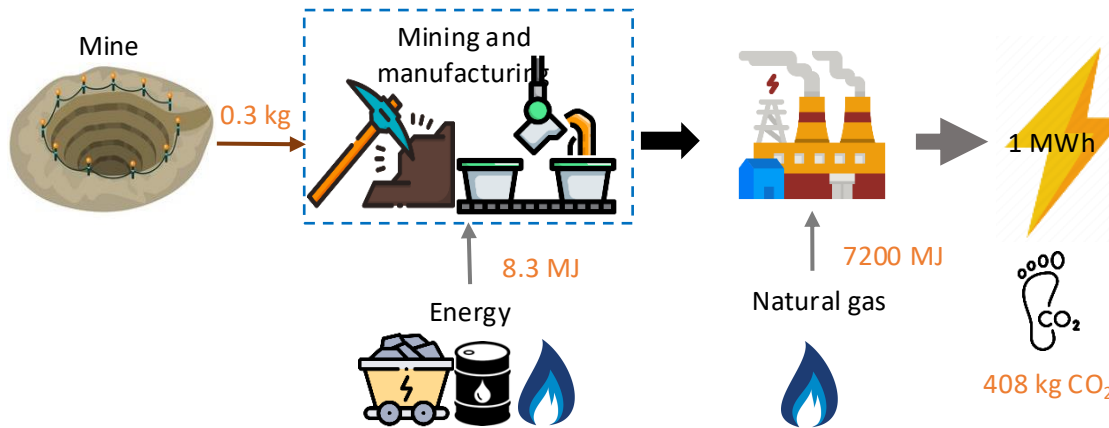


1. HOW RENEWABLE ARE RENEWABLE ENERGIES?

The industrial “progress”

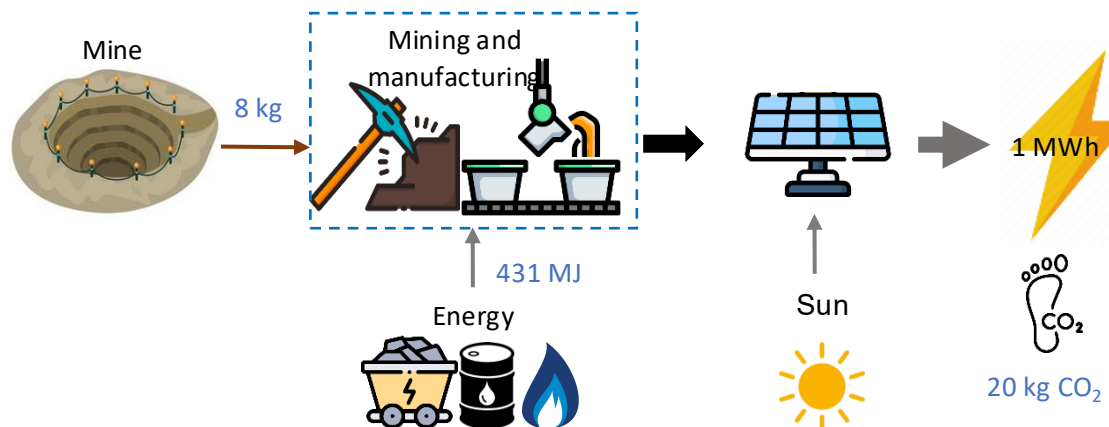
Difference between the 3rd and 4th Industrial Revolution

3rd Industrial revolution → Natural gas power plant



- Fossil fuel use (MJ) → 0 vs 7200
- Emissions (kg-CO₂) → 20 vs 408

4th Industrial revolution → Solar panel



- + 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?

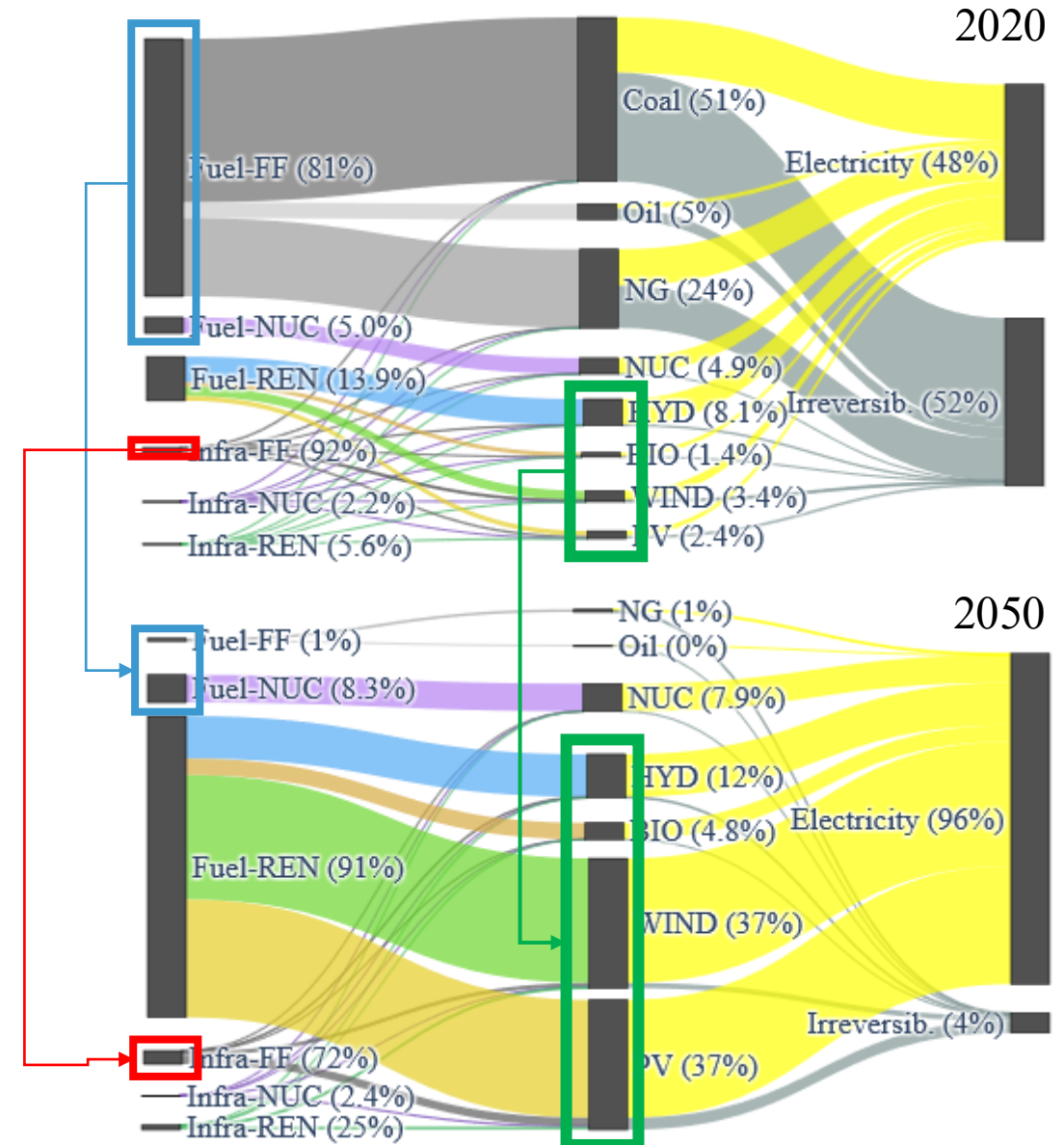
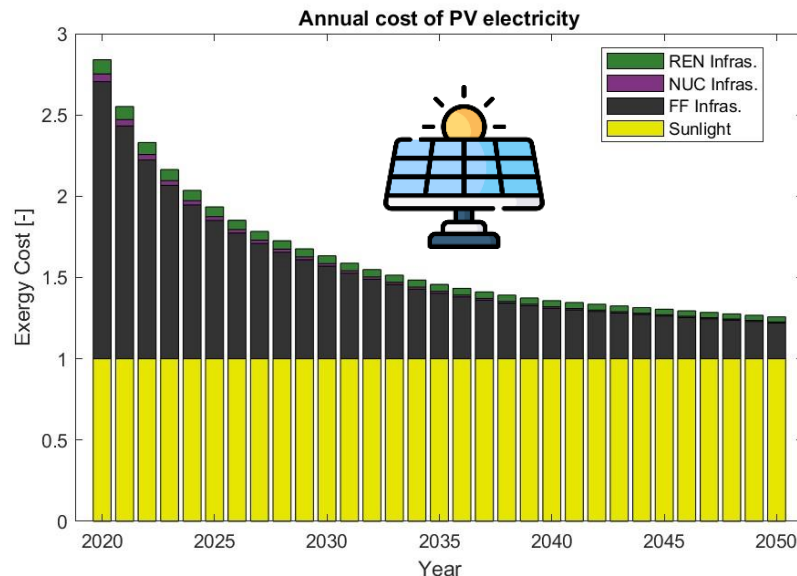
IEA NZE Scenario

Non-renewable exergy cost of fuel decrease

Non-renewable exergy cost of infrastructure increase

PV 2020 → 250% Non-renewable

PV 2050 → 20% Non-renewable

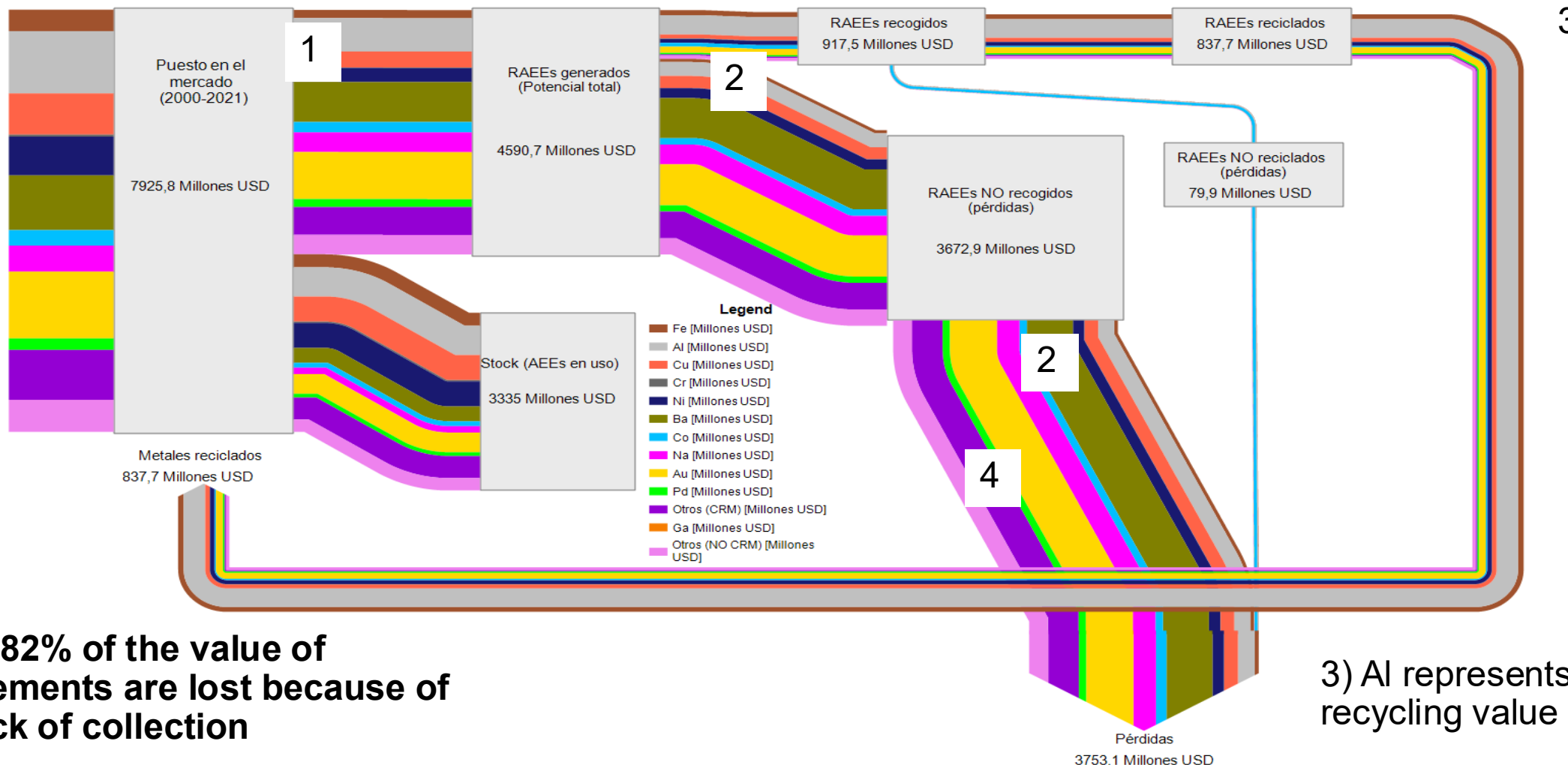


2. HOW CIRCULAR IS THE CIRCULAR ECONOMY?

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

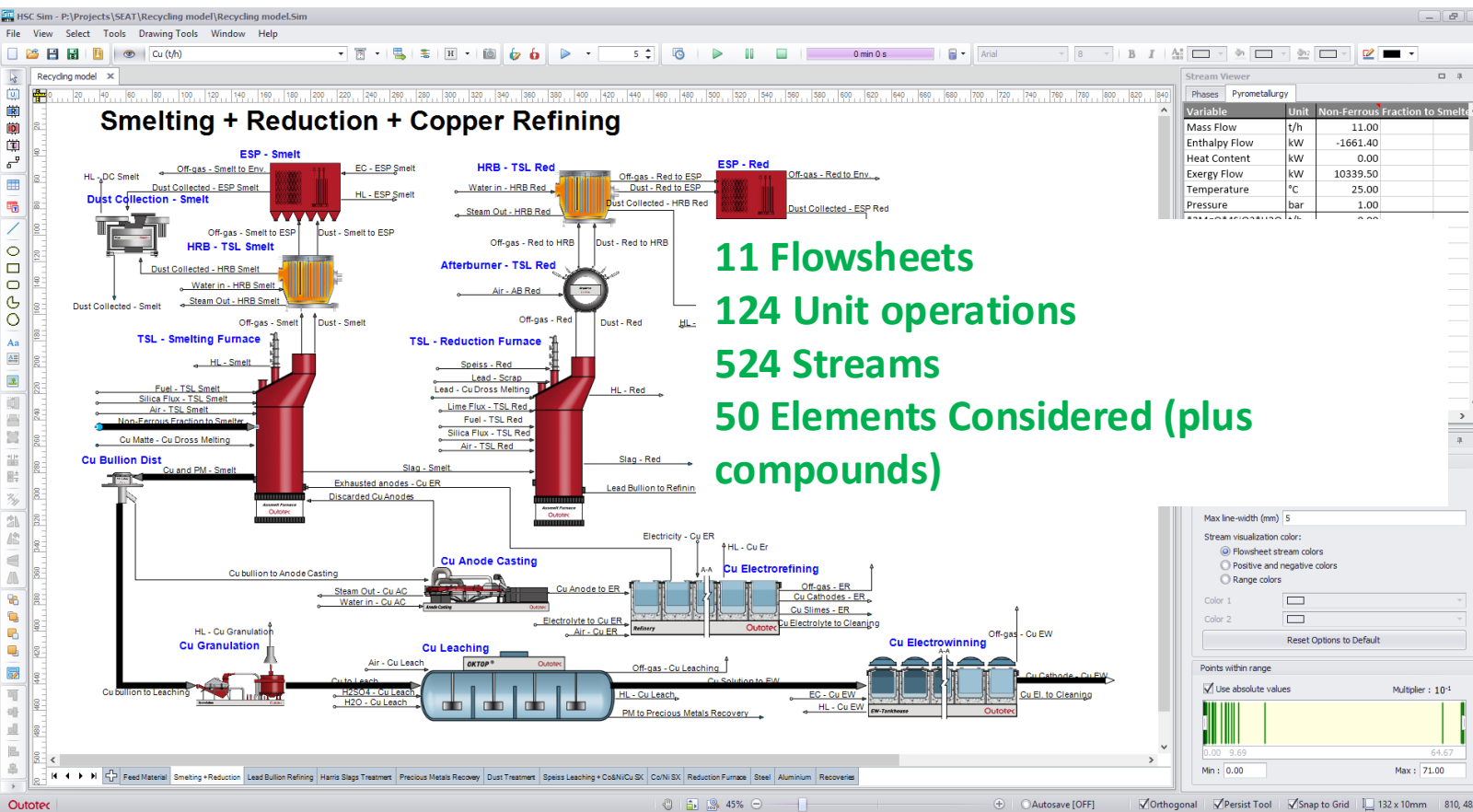
2. A disassemblability problem

Extracting REE from the motor of an electric vehicle



3. A Recyclability problem

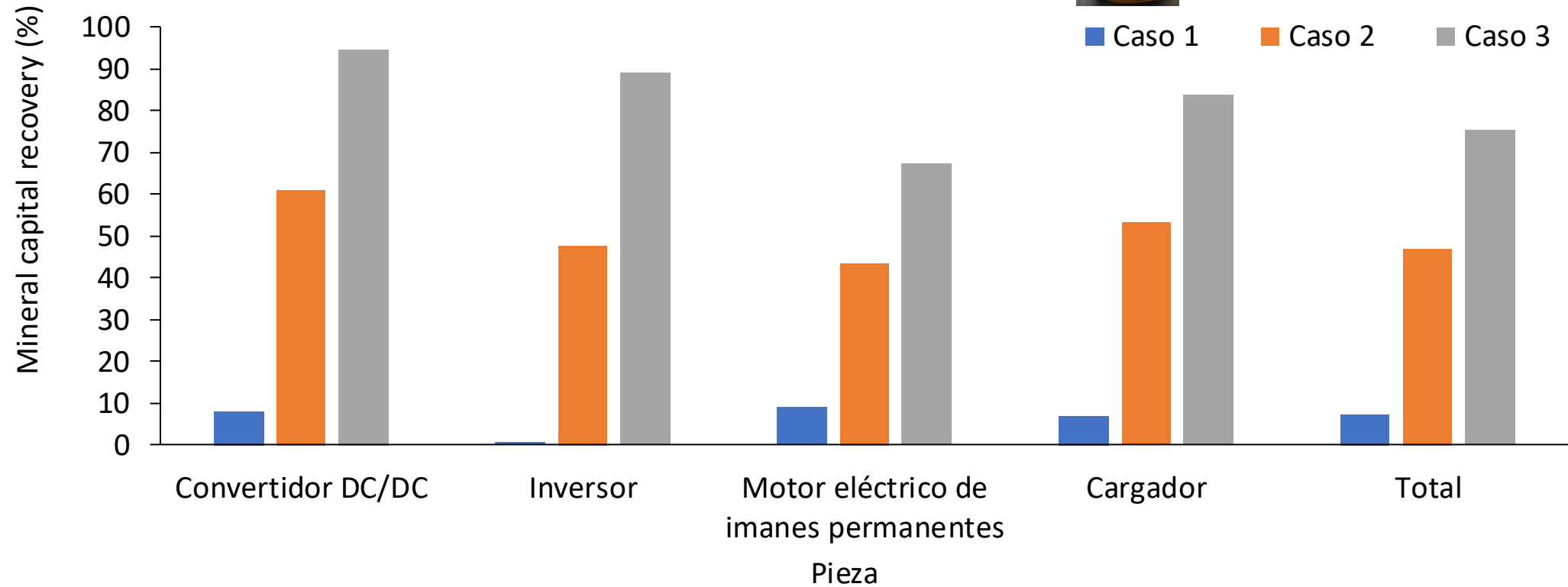
Example: Non-ferrous stream



- Metals recovered to a large extent (>90%):
 - Precious metals: Ag, Au, PGMs.
 - Base metals: Cu, Co, Ni, Pb and Zn.
 - Bi, Cd, Sb, Se, Te.
- Other metals recovered (>50%):
 - Ge, In, Sn.
- Metals lost (to Slags):
 - Al, B, Ba, Cr, Fe, Ga, Mg, Mn, Mo, Nb, P, Si, Sr, Ti, V, W, Y, Zr.
 - REEs.
 - Li, Ta.

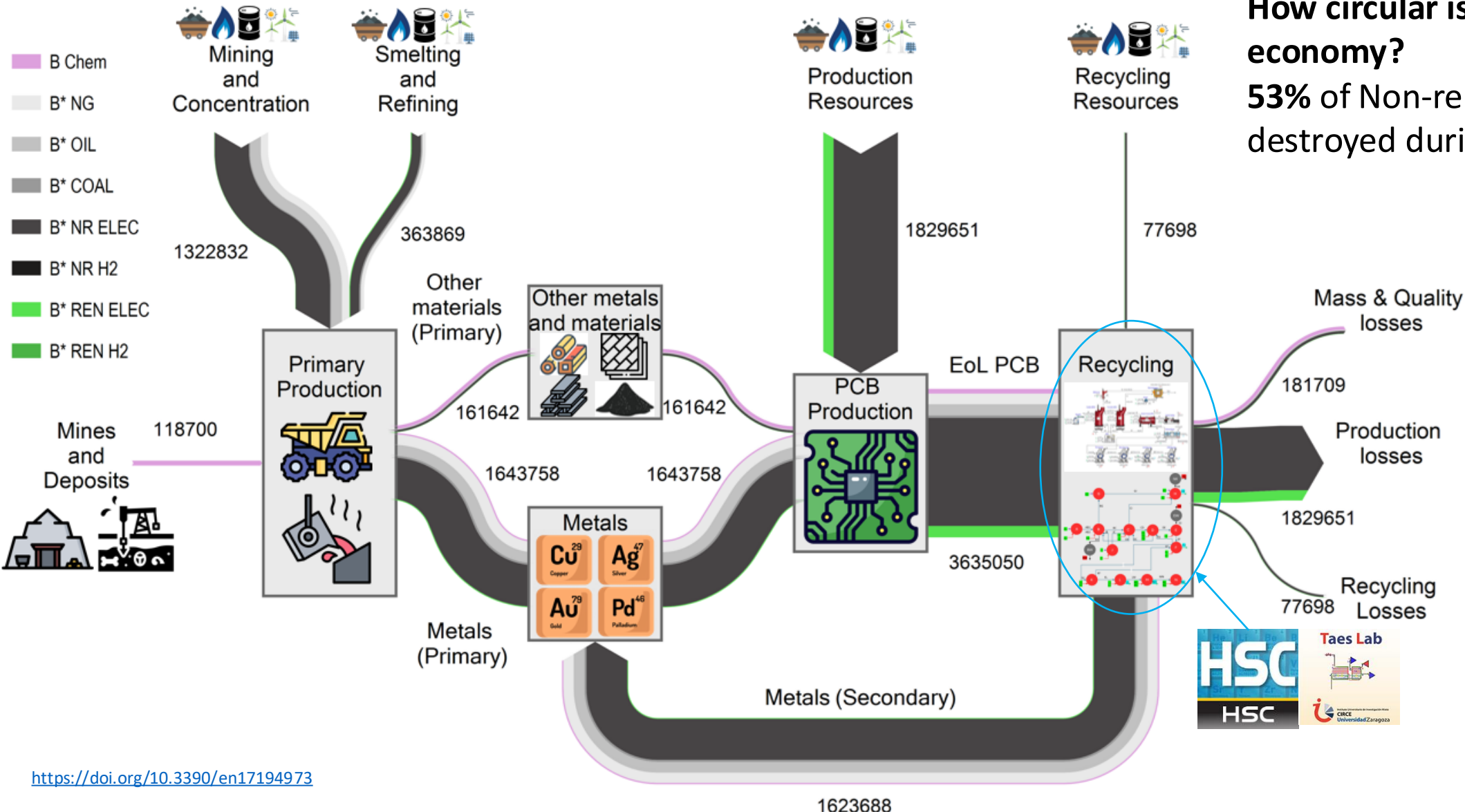


- Recyclability assessment:



Circular Thermoeconomics:

(a) 2020 case (Conventional Resources)



How circular is the circular economy?

53% of Non-renewable exergy is destroyed during recycling

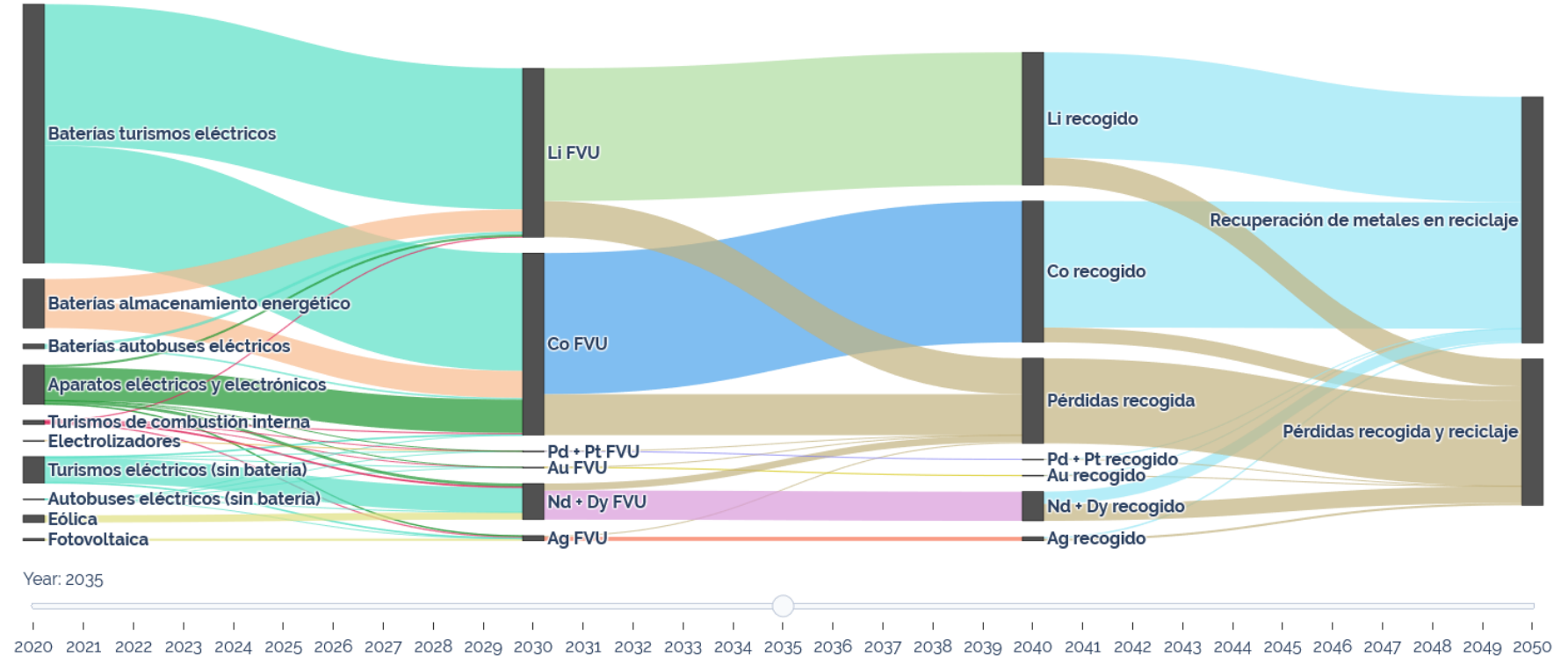
Can recycling overcome potential supply disruptions?

The demand for metals for the energy and digital transition is primarily driven by **electric mobility**.

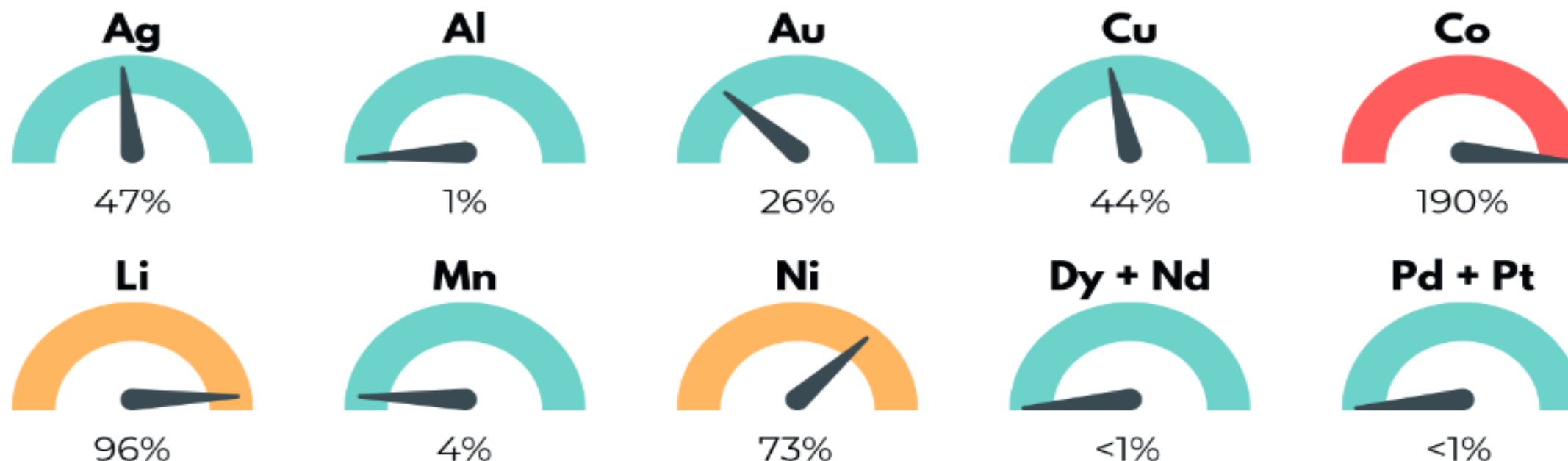
Ambitious collection and recycling systems could cover **half of the metal** demand between 2020 and 2050 for the case of Spain

Fin vida útil anual [t]

Lallana, Torrubia & Valero (2023). Metals for energy & digital transition in Spain: demand, recycling and sufficiency alternatives

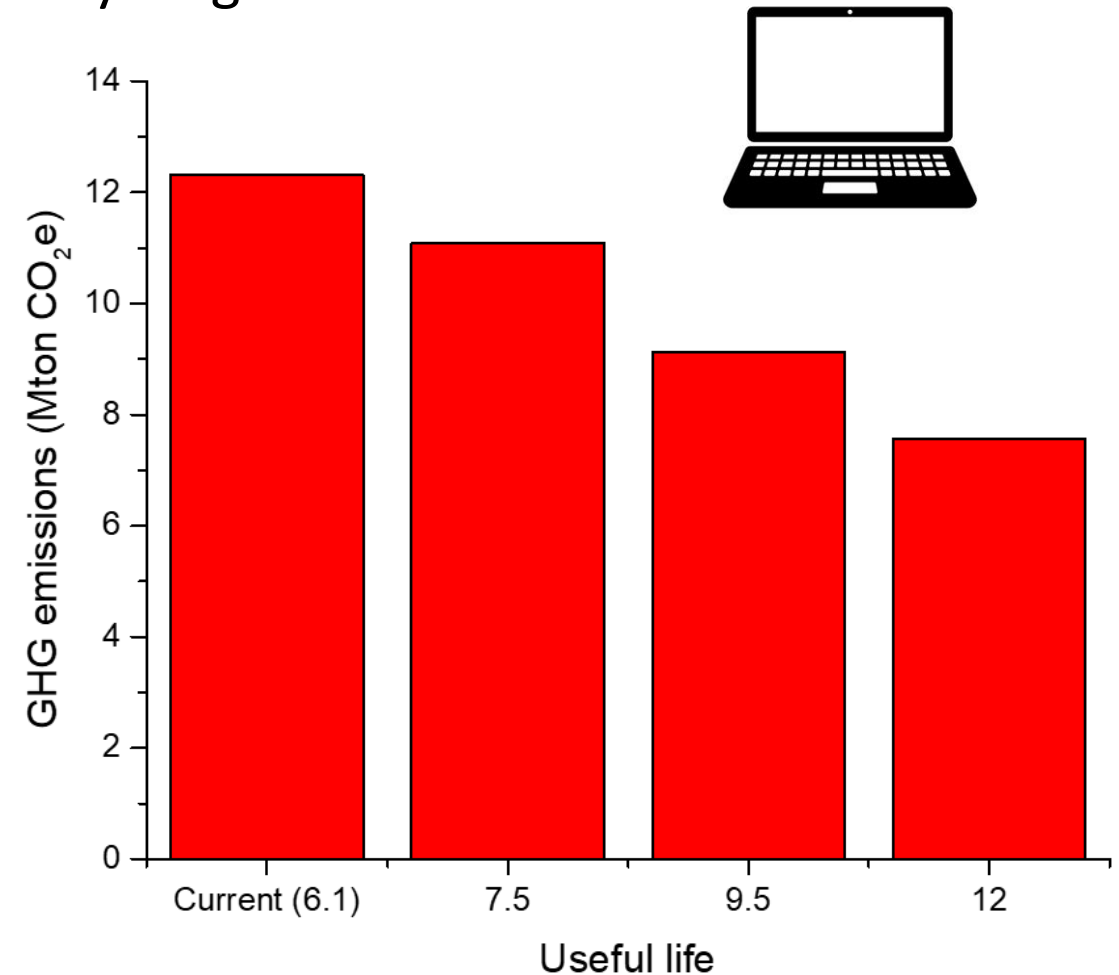
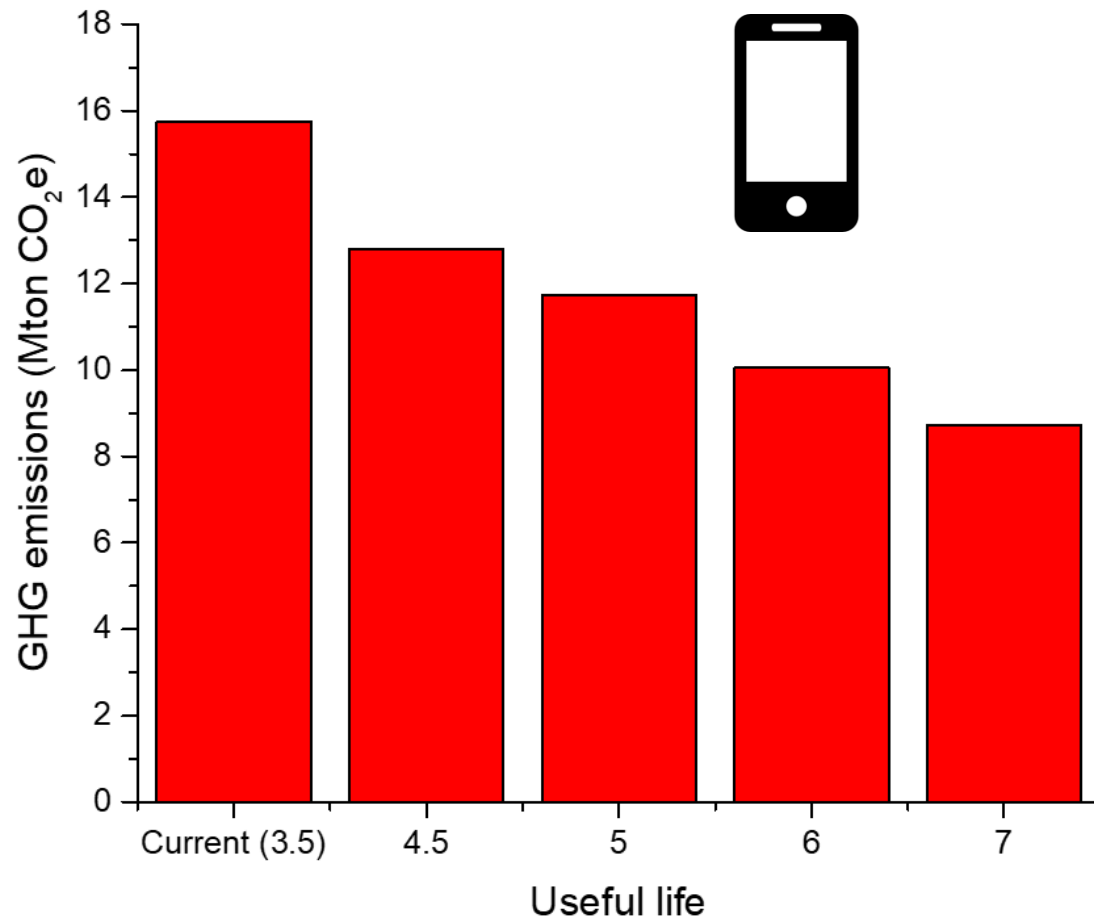


Are there enough reserves to fuel the transition?



The effect of increasing the life span

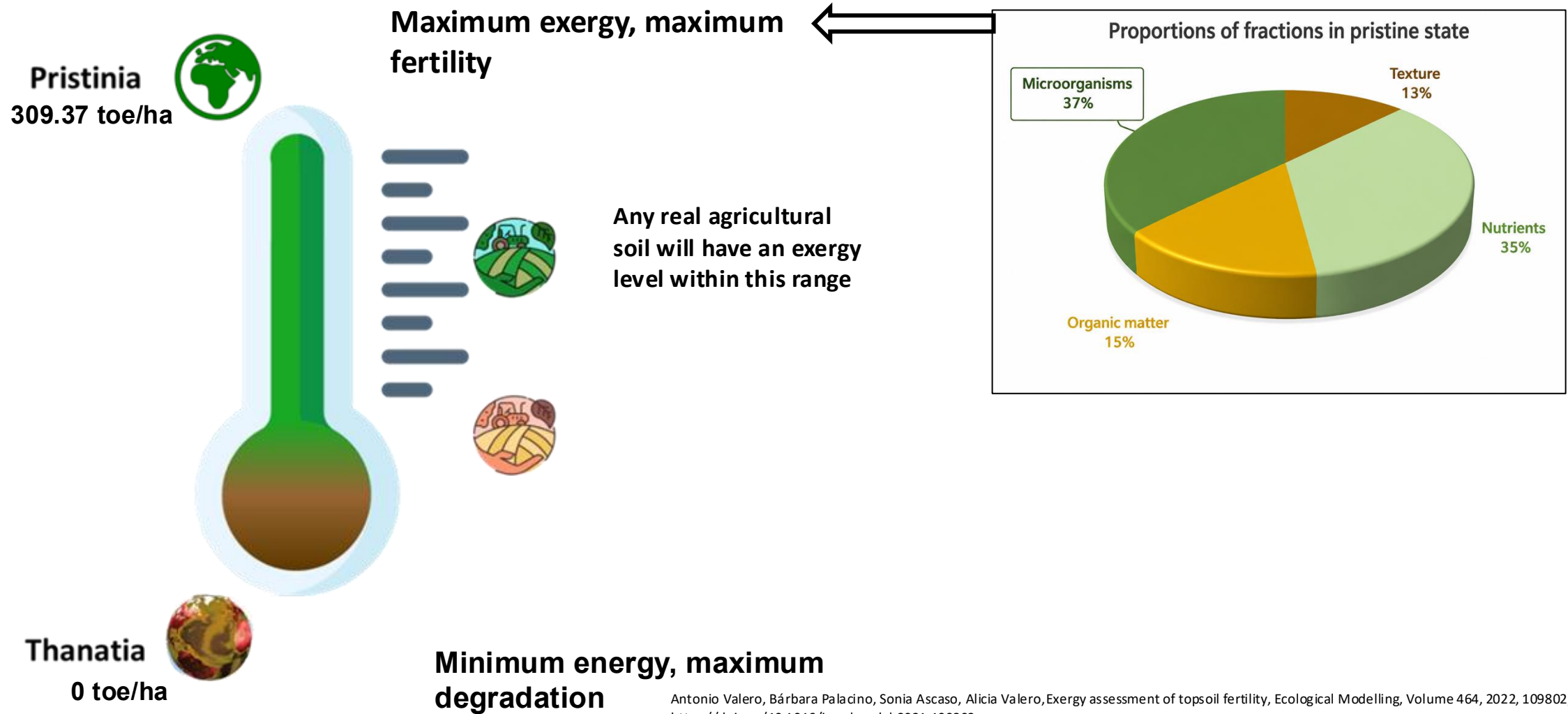
With recycling



3. HOW SUSTAINABLE IS SUSTAINABLE AGRICULTURE?

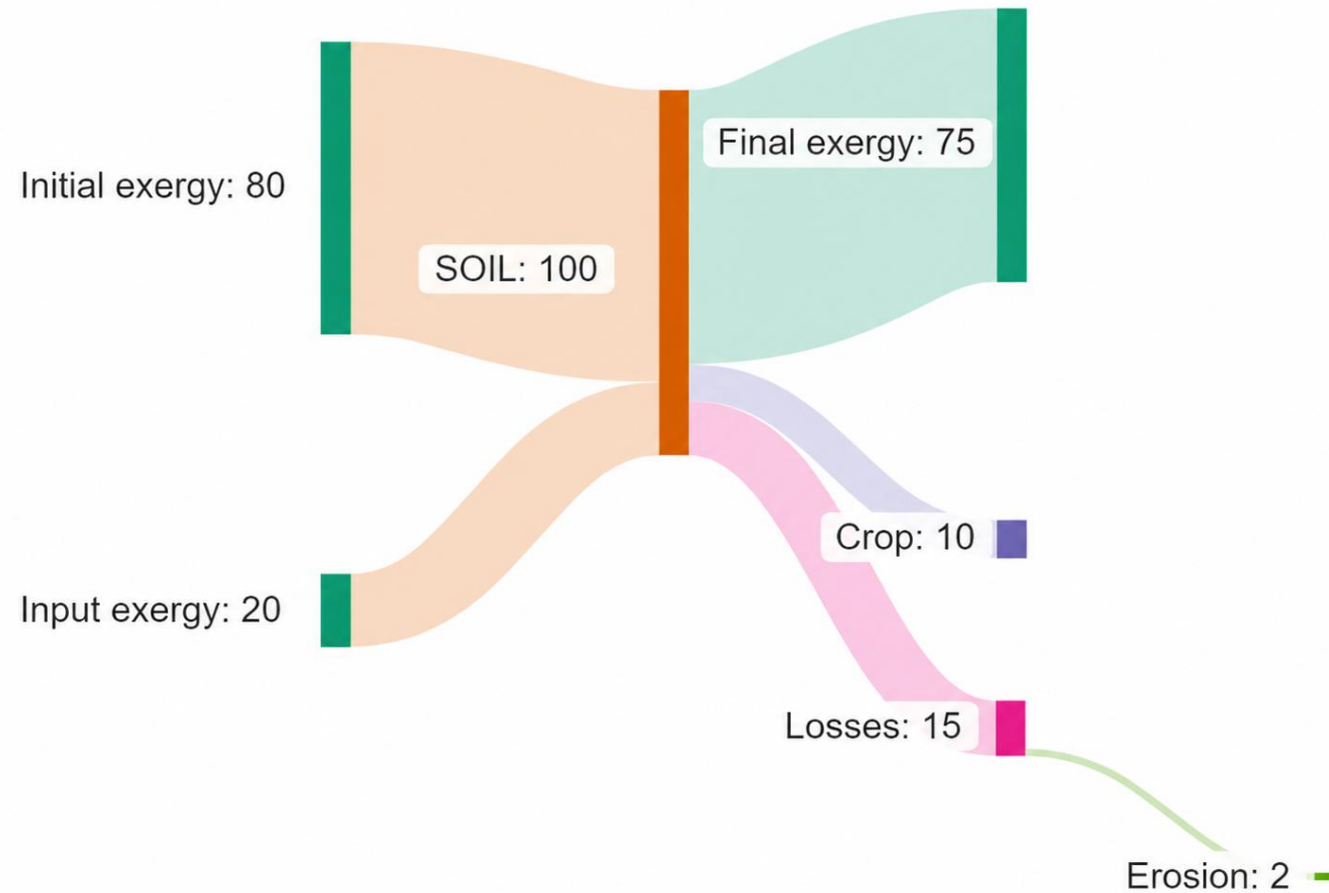
Exergetic characterisation of soils

Pristinia: The fertile planet



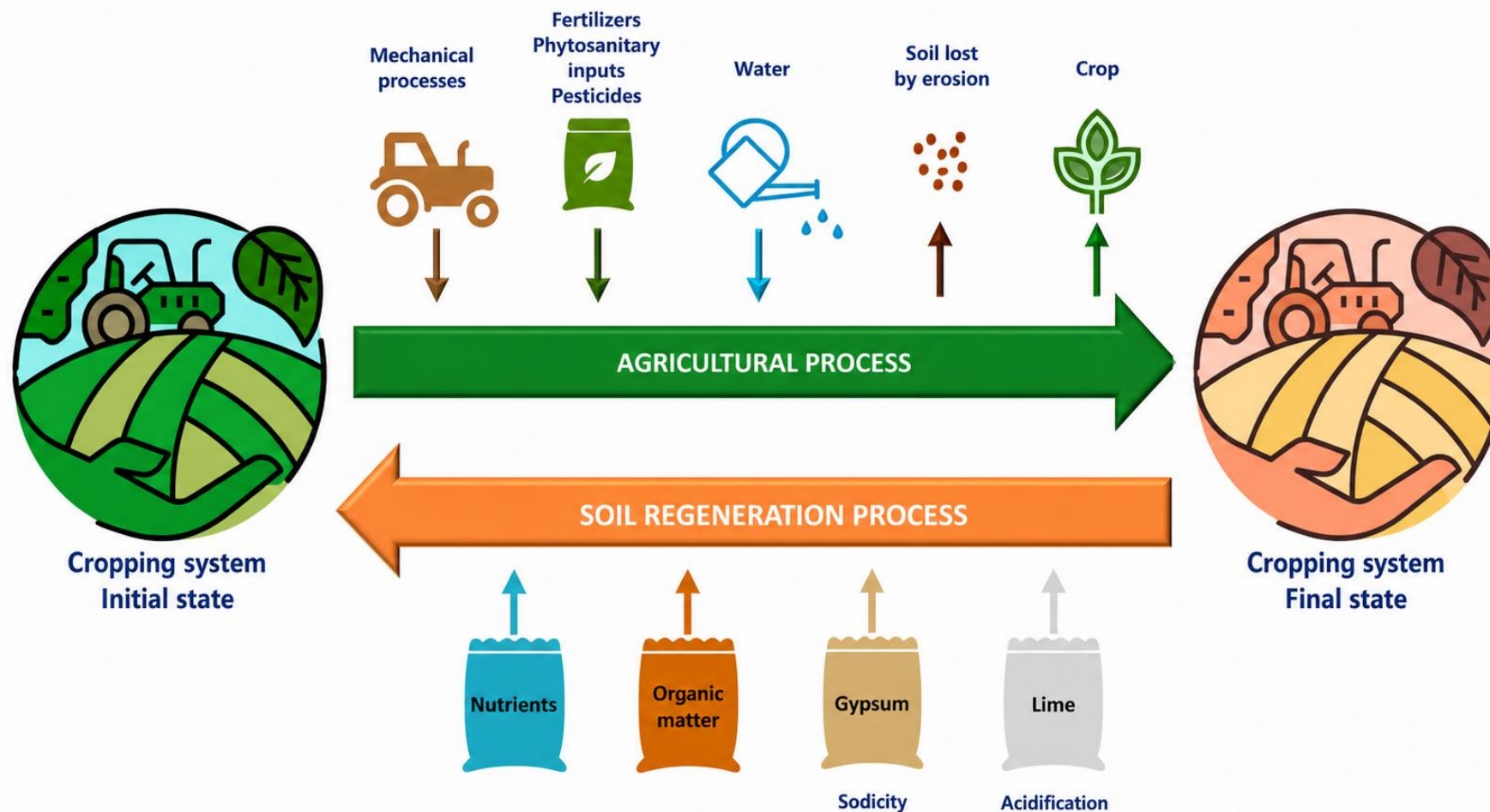
Exergetic characterisation of soils

Exergy soil balance



Exergy: the sole unit of measurement for studying soil

Exergy Cost in Agriculture



4. FINAL REFLECTIONS

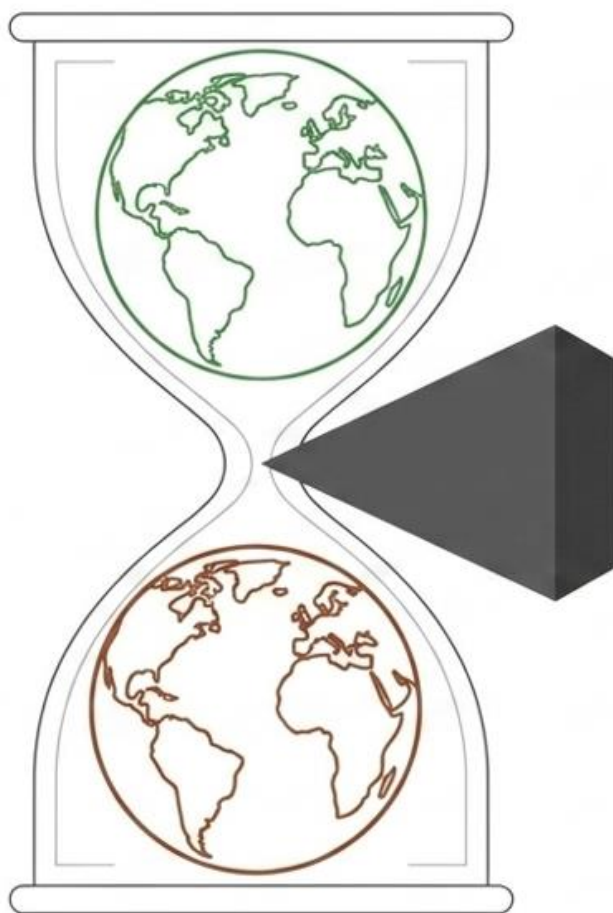
The new mandate for thermodynamicists

As thermodynamicists, we already possess the language capable of describing the real state of the planet.

The planet does not understand money.
It only understands action and reaction,
depletion and regeneration,
irreversibility and physical limits.

Our greatest challenge is no longer to understand thermodynamics.
It is to use it to give the Earth a voice.

Honesty in a Finite World



Sustainability cannot rely on intentions or monetary indicators. It must be grounded in physical reality.

Join us in building the thermodynamic compass to preserve options for present and future generations



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Thanks for your attention
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<https://energaia.unizar.es>

Proyecto PID2023-1484010B-I00 financiado por
MICIU/AEI/10.13039/501100011033 y por FEDER, UE



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