



Instituto Universitario de Investigación Mixto de la

Energía y Eficiencia de los
Recursos de Aragón

Universidad Zaragoza

Thermodynamic applications to renewable energy, circularity and resource preservation

Alicia Valero · 16 October 2026



Umwelt-Campus
Birkenfeld

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

How can exergy answer the following questions?

How renewable are renewable energies?

How circular is the circular economy?

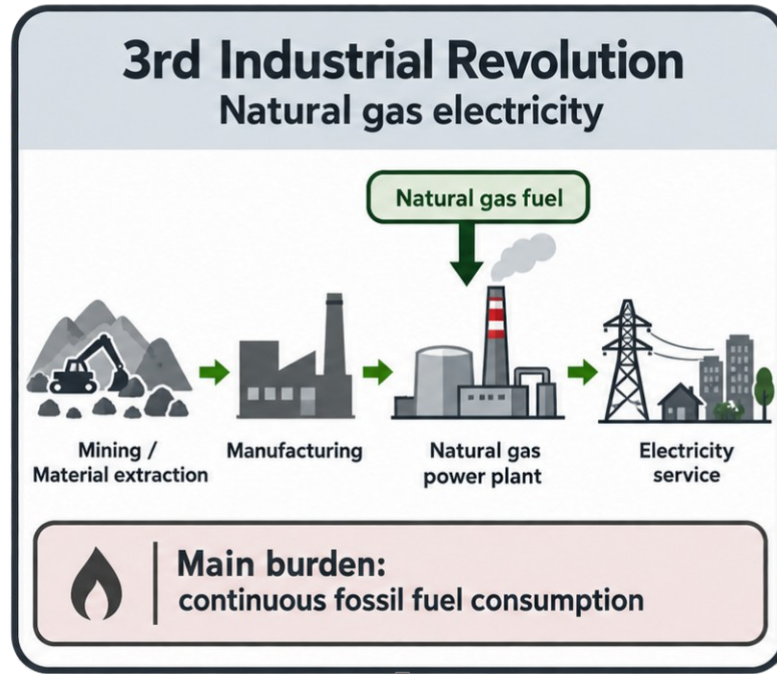
How can we reduce irreversible resource losses?

1. HOW RENEWABLE ARE RENEWABLE ENERGIES?

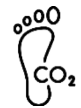
Renewables = ↓ CO₂?

The industrial “progress”

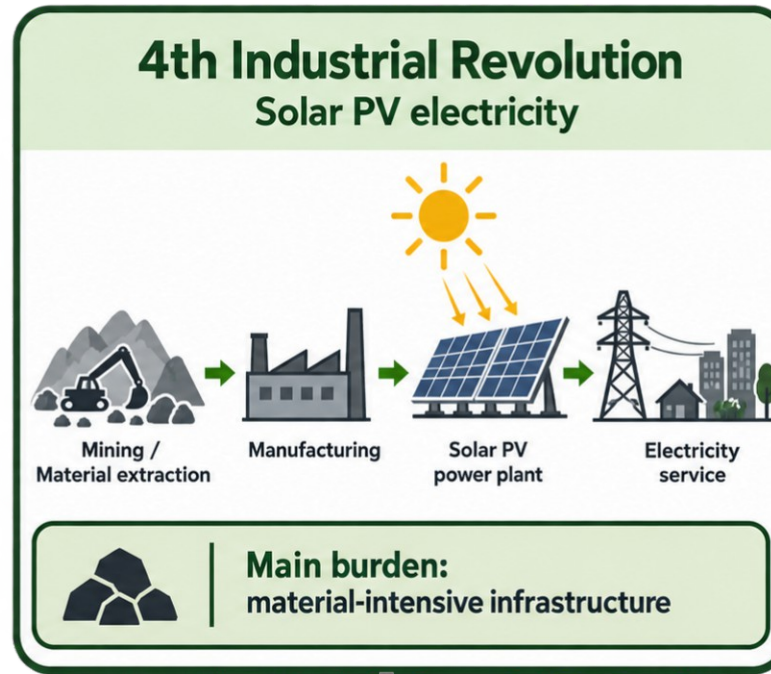
Difference between the 3rd and 4th Industrial Revolution



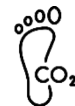
1 MWh



408 kg CO₂



1 MWh



20 kg CO₂

- 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

Renewables = ↓ CO2?



- Emissions (kg-CO₂/MWh)

→ 20 vs 408



BUT:

+ Materials (kg/MWh)

→ 8 vs 0.3

+ Mining energy(MJ/MWh)

→ 431 vs 8.3

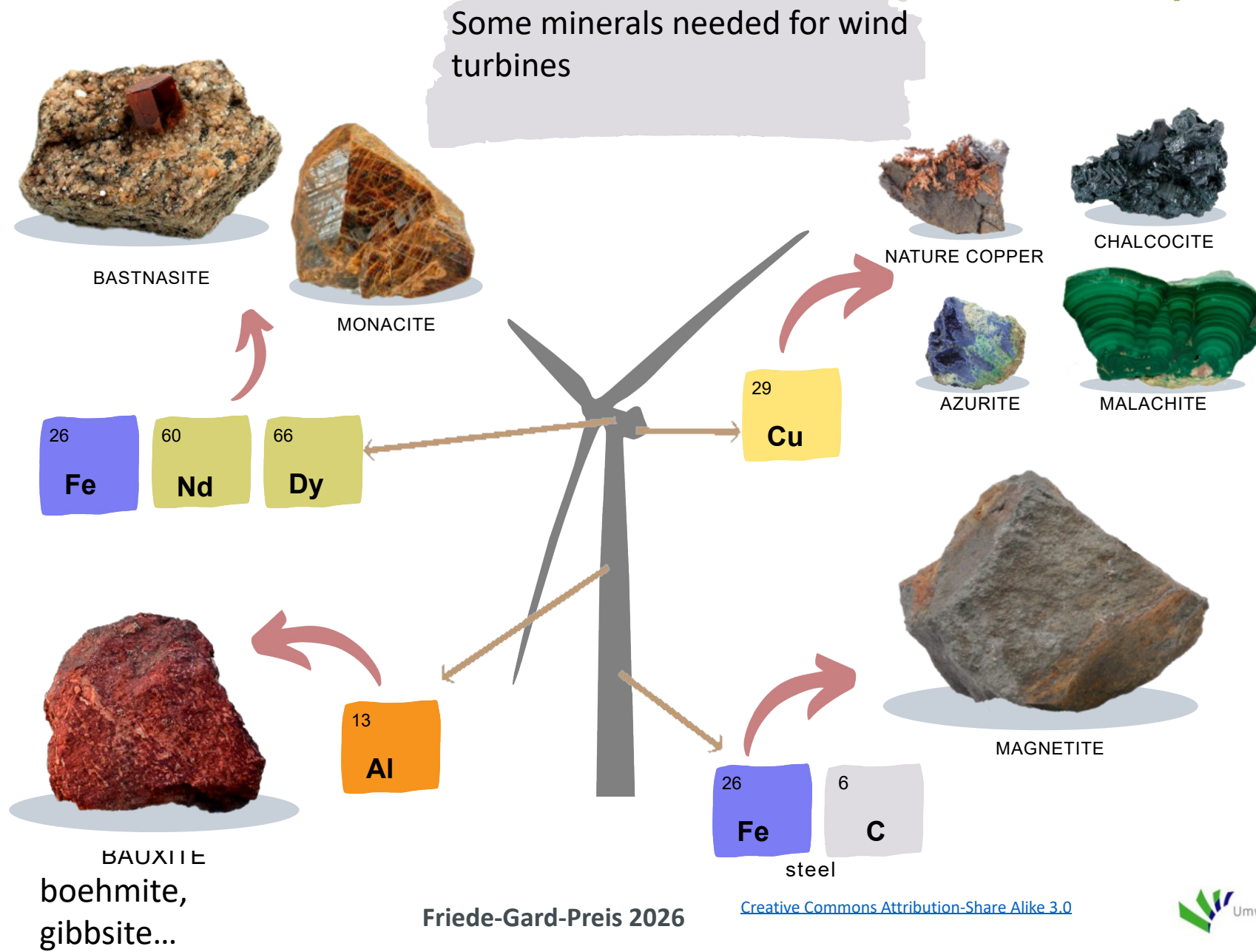
+ Waste (kg/MWh)

→ 8 vs 0.3



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SOME USES AND INTERESTING FACTS



New materials for the “green” economy



Al	Cu	Dy	Fe	Nd	Ni
----	----	----	----	----	----



Ag	Cd	Cu	Ga	Ge	In	Mg
Mo	Ni	Pb	Se	Sn	Te	Zn

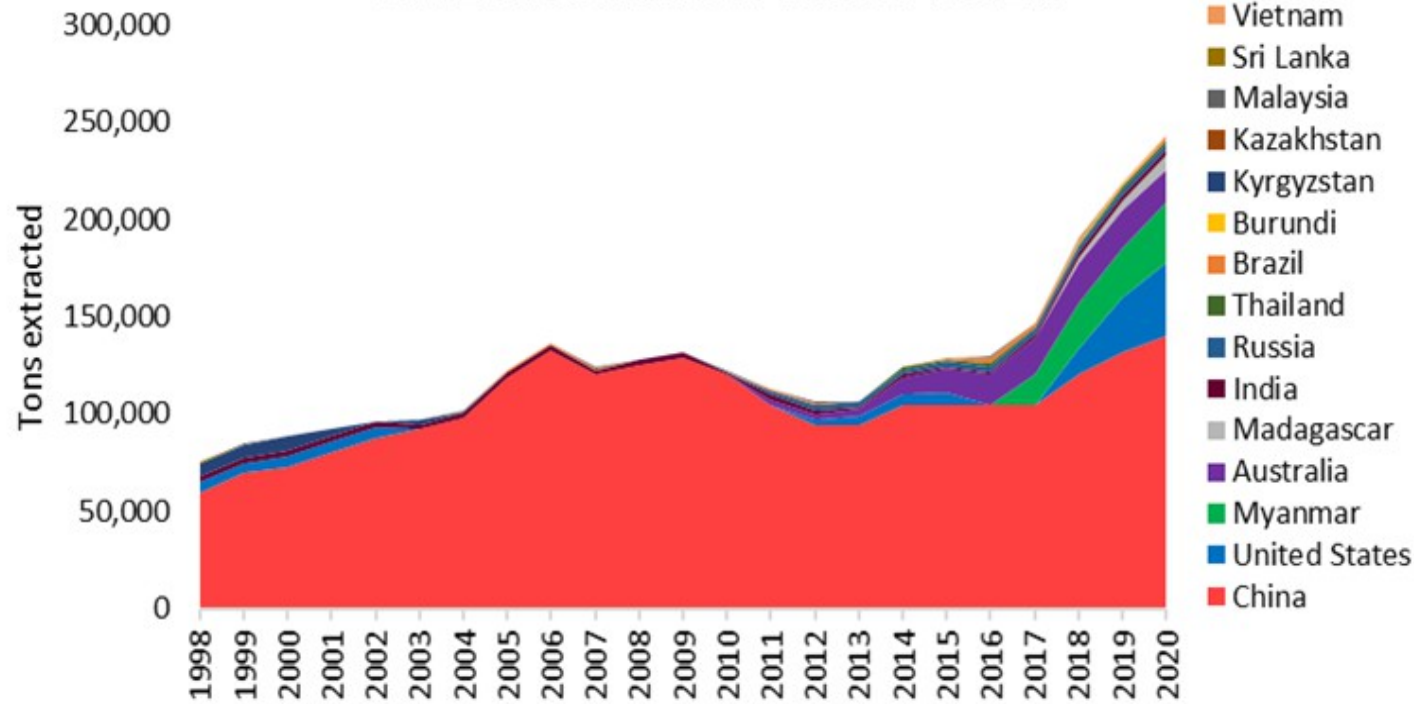


Ag	Al	Ce	Co	Cr	Cu	Dy	Fe
Ga	Gd	In	La	Li	Mn	Mo	Nb
Nd	Ni	Pd	Pr	Pt	Ta	V	

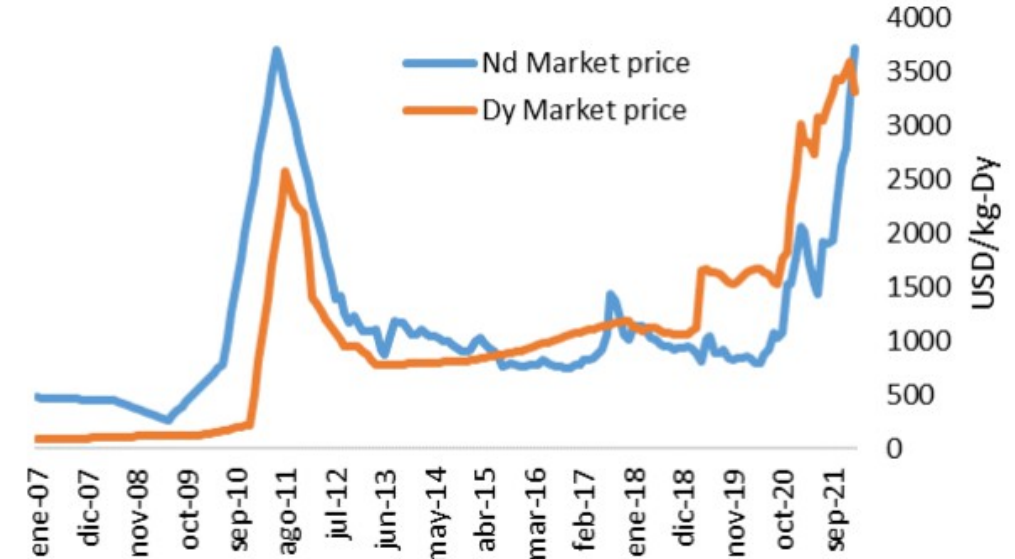
Source: <https://doi.org/10.1007/978-3-030-78533-8ration>

2017–2020: production increased by 85%, from 130,000 to 240,000 tonnes (China: 57%).

REE extraction 1998-2020



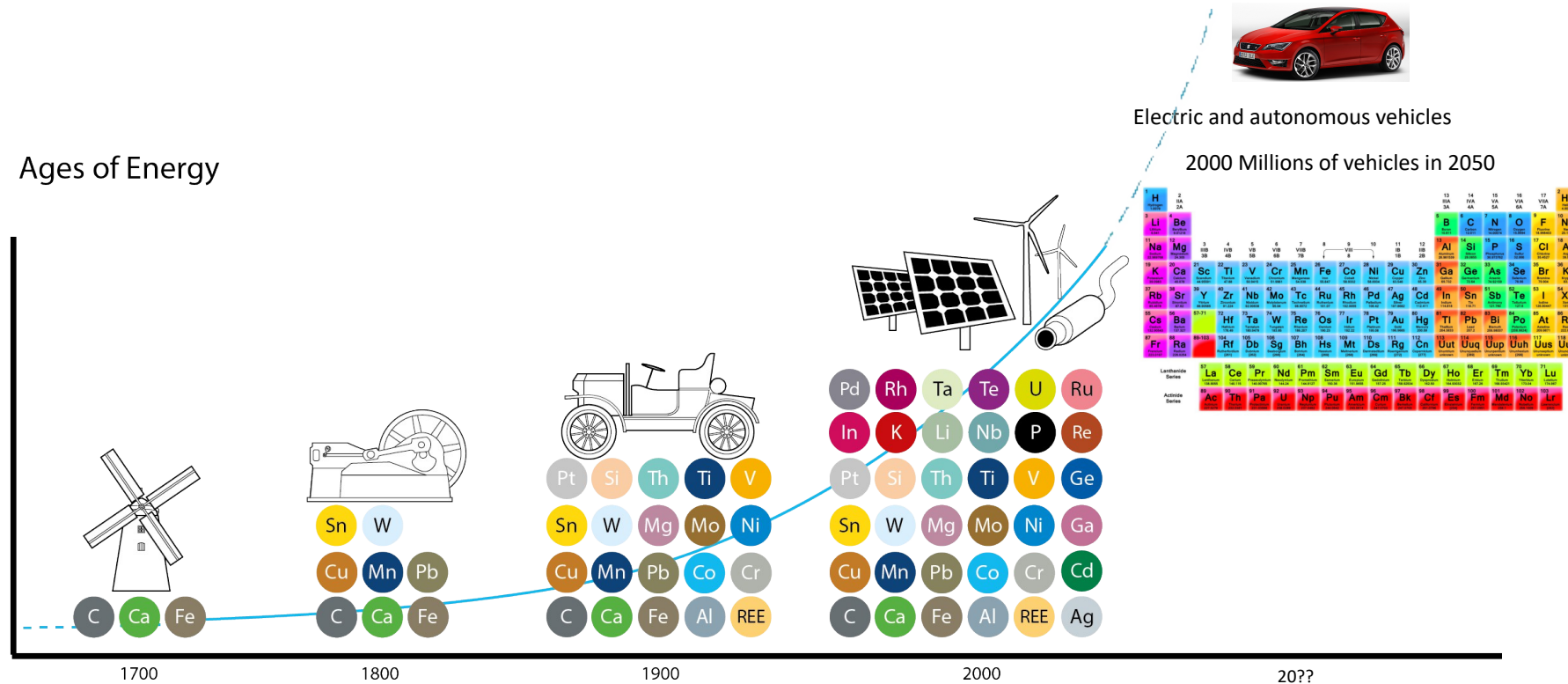
Price evolution: Nd and Dy (2007-2021)



Nd x10; Dy x 23

The age of the periodic table

Ages of Energy



Source: Adapted from Achzet et al. (2011), Materials Critical to the Energy Industry:
An Introduction, University of Augsburg.

Exponential growth in raw material extraction

At an assumed annual growth rate of 2.8%, material consumption doubles in about one generation. Over the next 25 years, cumulative use would approach the total consumed throughout human history.

Exponential growth in raw material extraction

In the 21st century, we have extracted as much copper as in all preceding human history

Gold (electronics, jewellery...): 0.5 times

Silver (solar energy, electronics, jewellery...): 0.6 times

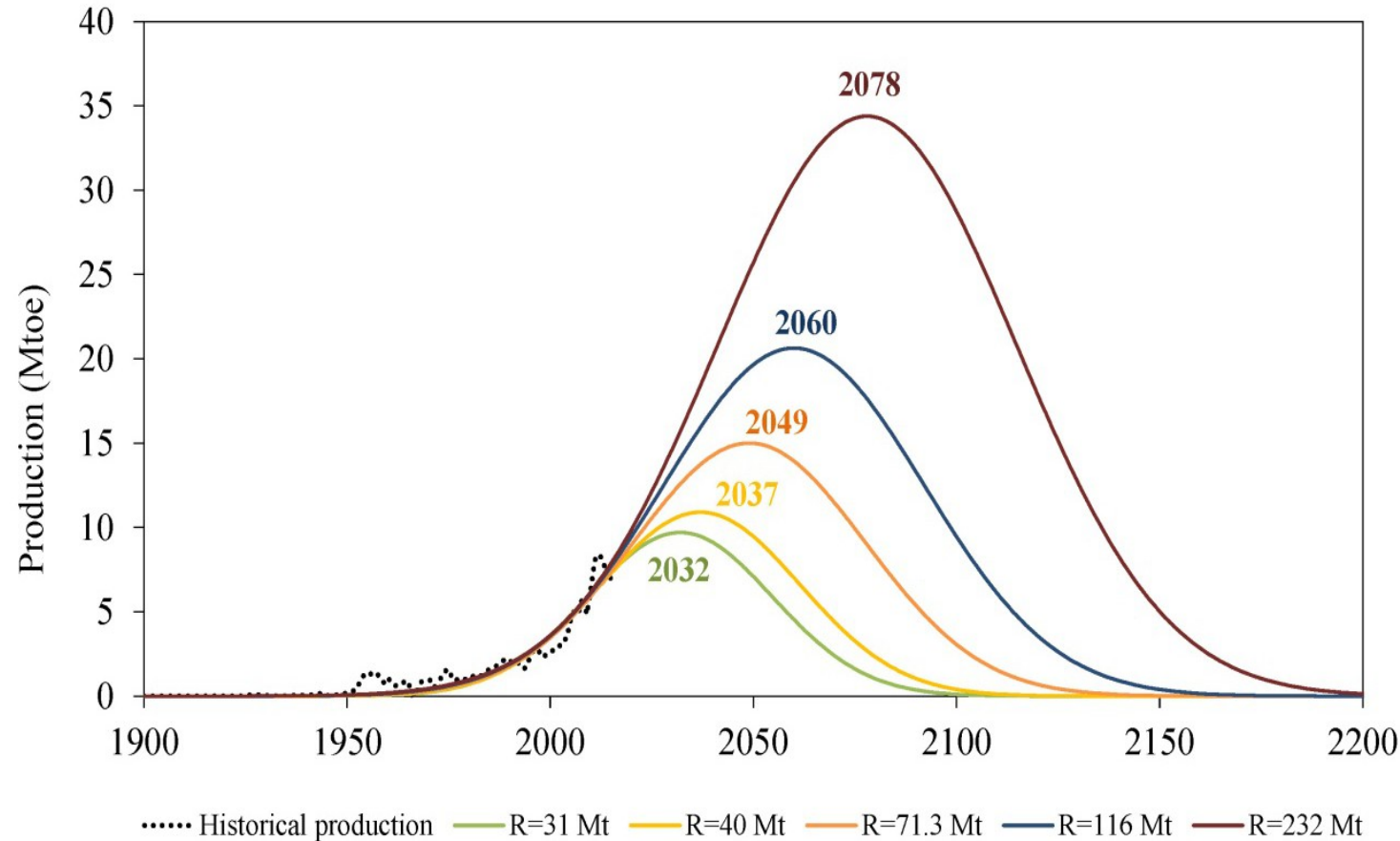
Zinc (steel, metal components...): 0.8 times

Ni (steel, batteries...): 1.2 times!

Co (batteries, pigments, motors...): 1.56 times!

Li (batteries): 1.93 times!

Case study: lithium — future availability projections



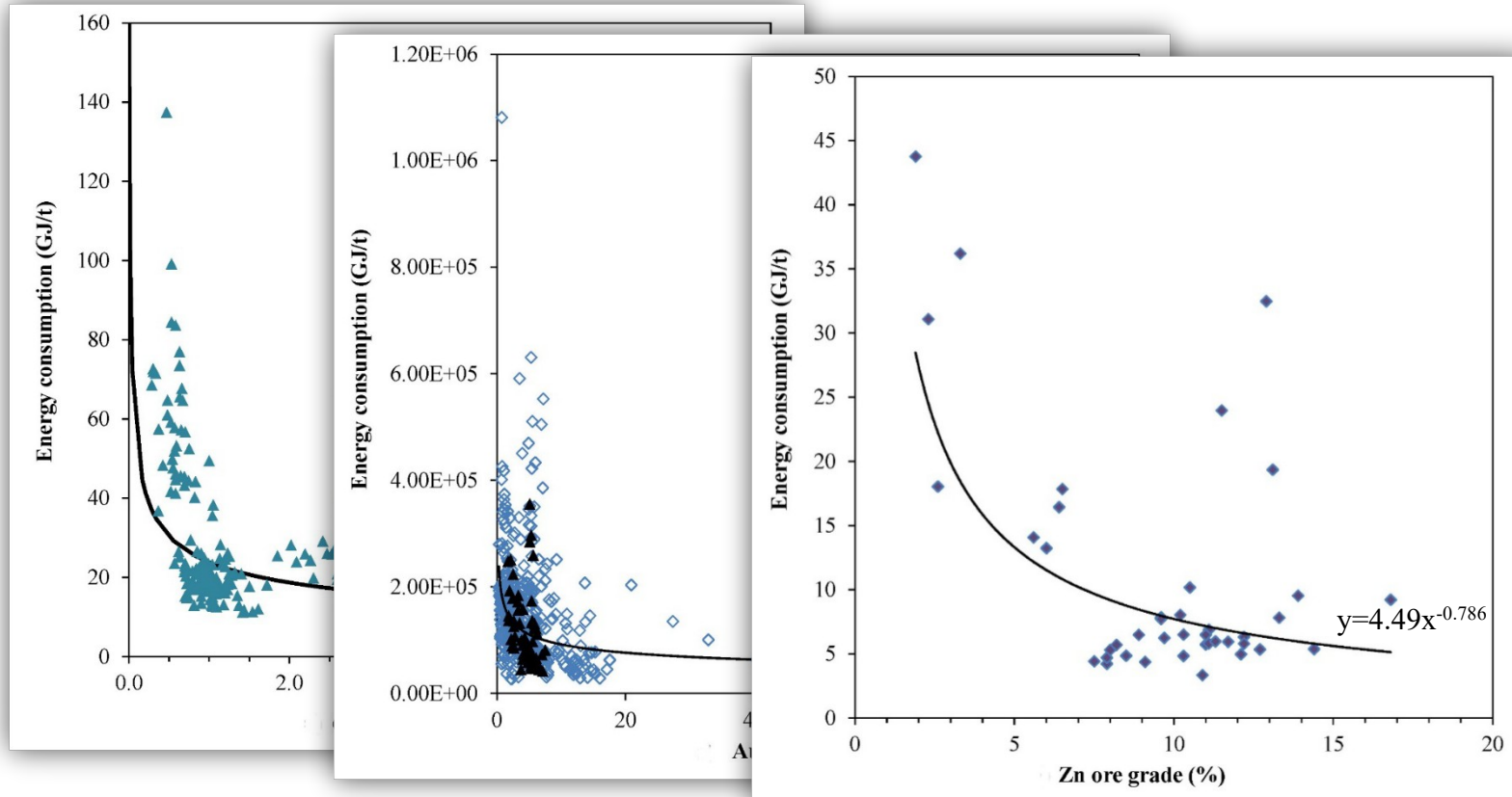
Lithium production peaks under different resource-availability estimates

Total energy consumption (GJ/t vs. ore grade)

Copper

Gold

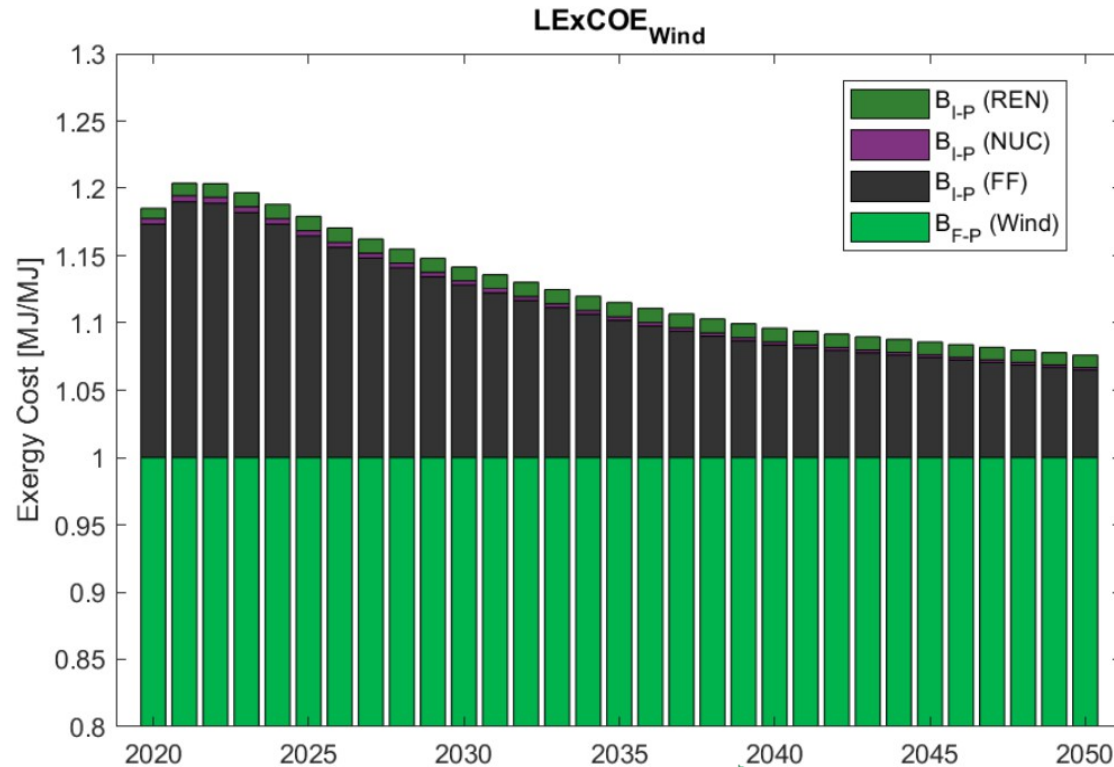
Zinc



Mining energy demand (currently largely fossil-based) may increase as ore grades decline — and emissions with it!

Source: Calvo et al. (2016). Decreasing ore grades in global metallic mining, a theoretical issue or a global reality?
Life Cycle Assessment and Other Assessment Tools for Waste Management and Resource Optimization congress. Cetraro (Italy) 5-10 June. 2016

Levelized Exergy cost of electricity (LExCOE) WIND



LExCOE wind: disaggregated:

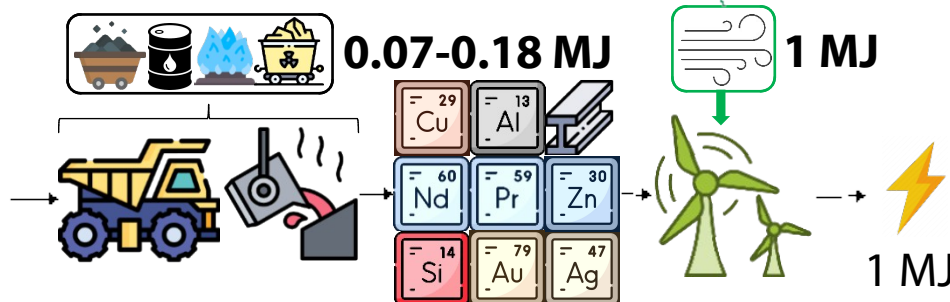
- Renewable:
 - Fuel (always renewable)
 - Infrastructure (renewable electricity embodied in the materials of infrastructure)
- Non-Renewable:
 - Infrastructure (fossil, nuclear)

1 MJ of renewable electricity from wind requires:

- MJ of renewable wind **1 MJ**
- MJ of non-renewable infrastructure **0.07 – 0.18 MJ**

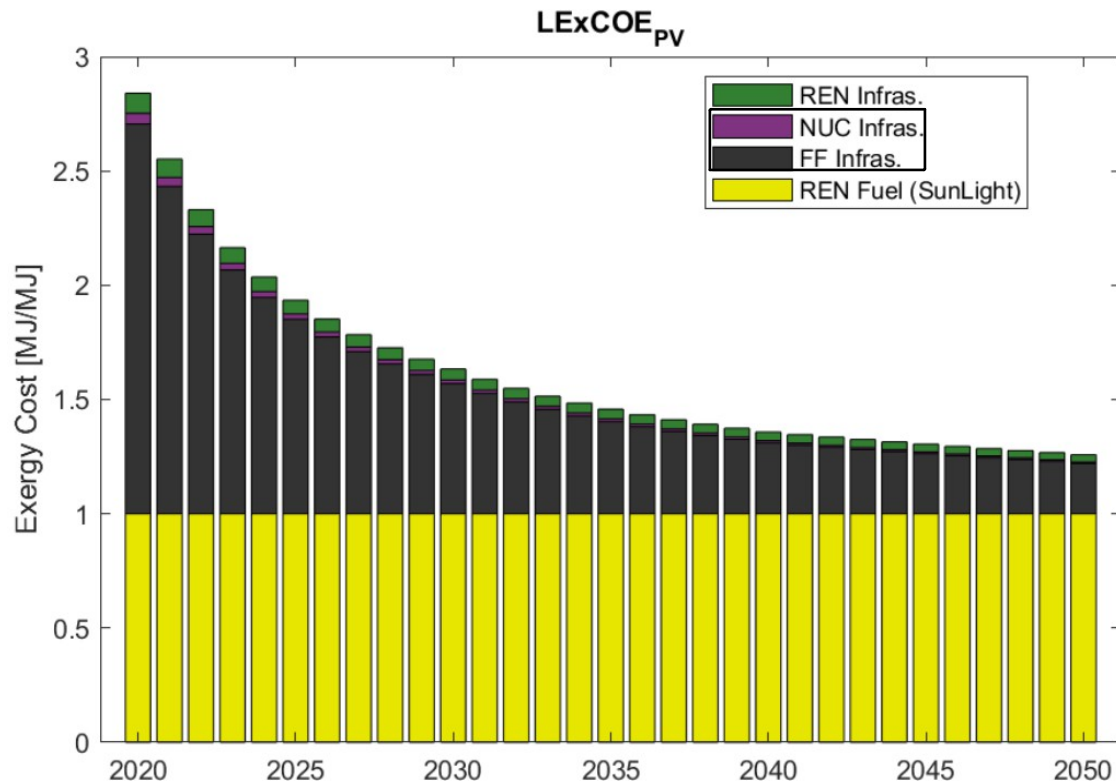
LExCOE decreases with time:

- Decrease of material intensity
- Amortization of the infrastructure



Torrubia, Valero and Valero (2025). <https://doi.org/10.1016/j.energy.2024.133987>

Levelized Exergy cost of electricity (LExCOE) SOLAR



LExCOE PV: disaggregated:

- Renewable:
 - Fuel (always renewable)
 - Infrastructure (renewable electricity embodied in the materials of infrastructure)
- Non-Renewable:
 - Infrastructure (fossil, nuclear)

1 MJ of renewable electricity from PV requires:

- MJ of renewable solar **1 MJ**
- MJ of non-renewable infrastructure **0.20 – 1.70 MJ**

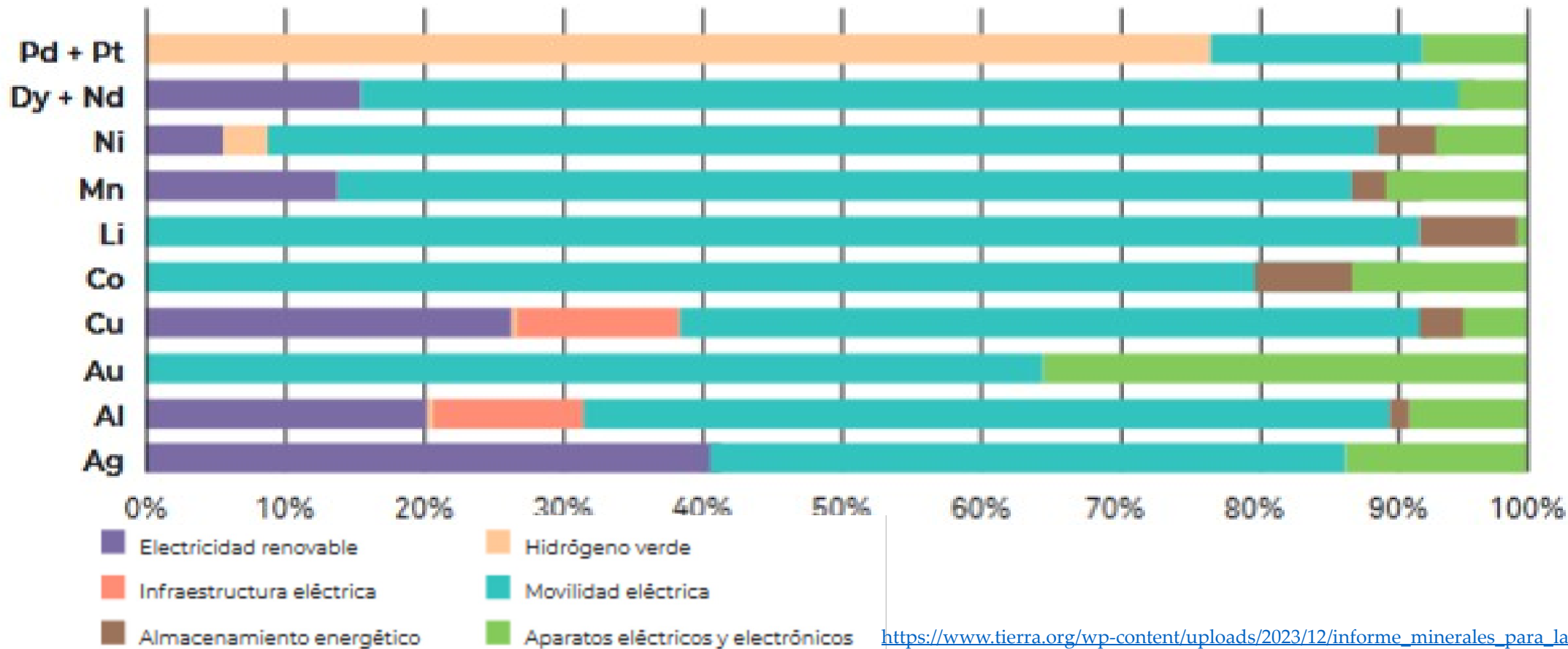
LExCOE decreases with time:

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- Amortization of the infrastructure

Torrubia, Valero and Valero (2025). <https://doi.org/10.1016/j.energy.2024.133987>

Cumulated metal consumption by Technology 2020-2050

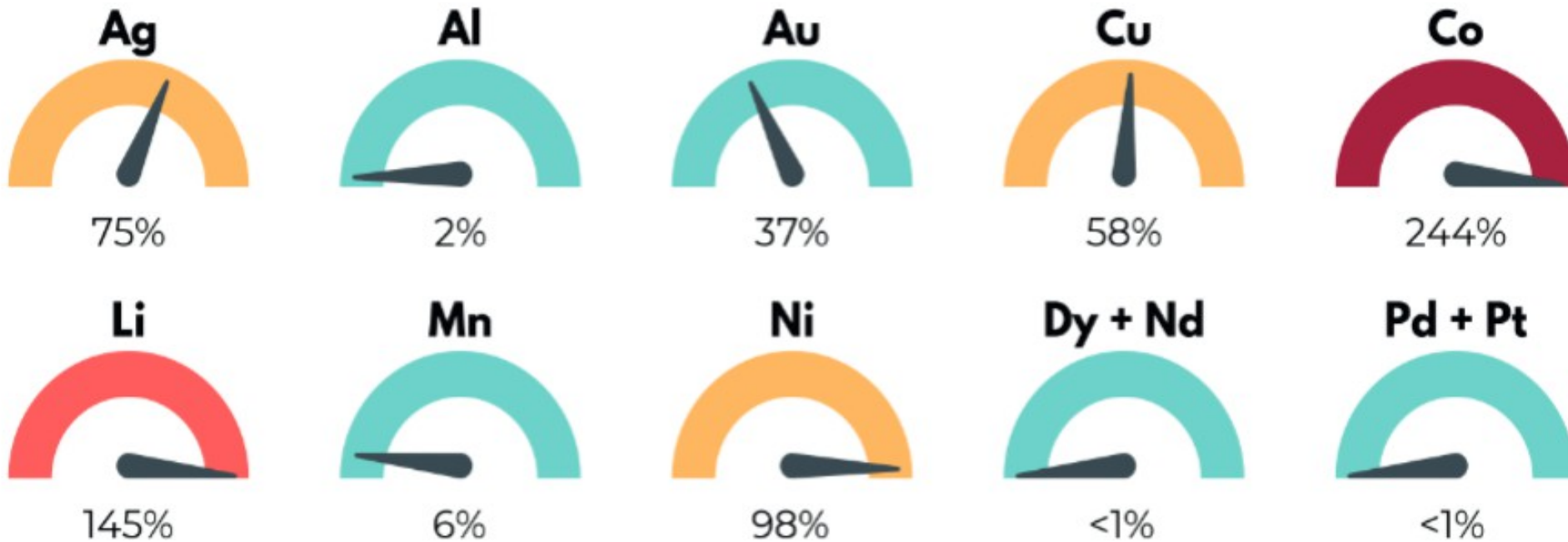
The case of Spain



https://www.tierra.org/wp-content/uploads/2023/12/informe_minerales_para_la_Transicion.pdf

There are enough raw materials
for the Energy transition

Cumulated metal demand 2020-2050



Population Spain:
0,6% world
population→
**Equitable share of
reserves: 0,6%** of
reserves (USGS,
2022)

https://www.tierra.org/wp-content/uploads/2023/12/informe_minerales_para_la_Transicion.pdf

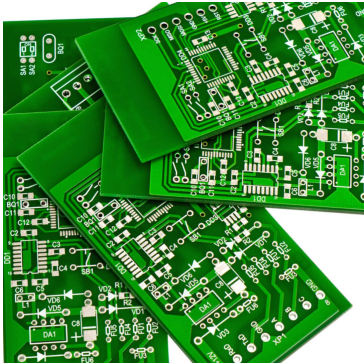
There are enough raw materials
for the Energy transition



2. HOW CIRCULAR IS THE CIRCULAR ECONOMY?

Gold in mines vs Gold in PCB

PCB



→ 860 g/ton

Largest gold mine



→ 8-10 g/ton

There is more gold in a PCB than in a mine.

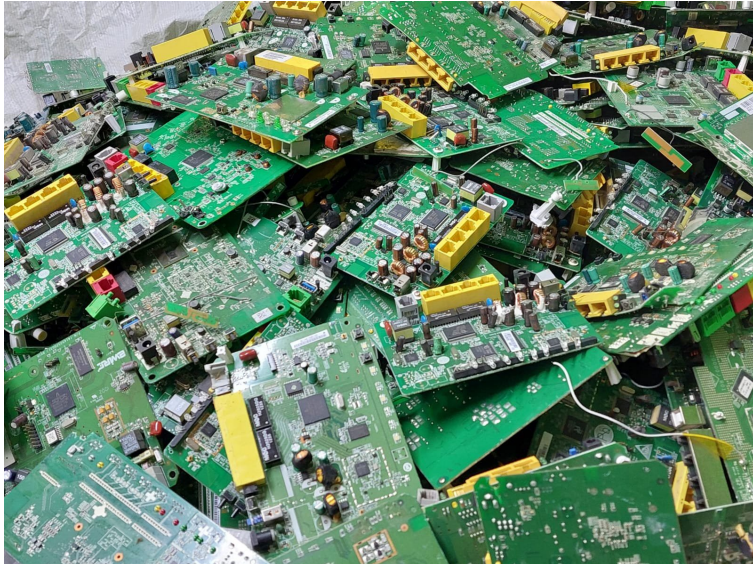
Almost 100 times more!

It would take about 5,300 PCBs to produce a 90 g pure gold ring

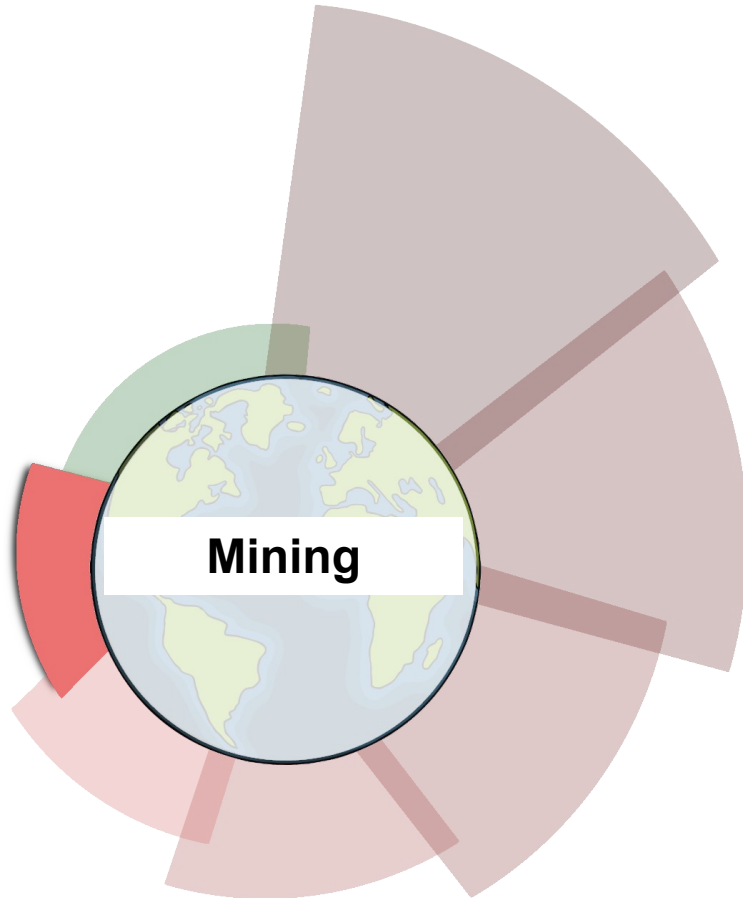
Example TOKYO 2020

80 t electronic equipment
(6,21 mobile phones)

→ 30 kg Au (1600 medals)

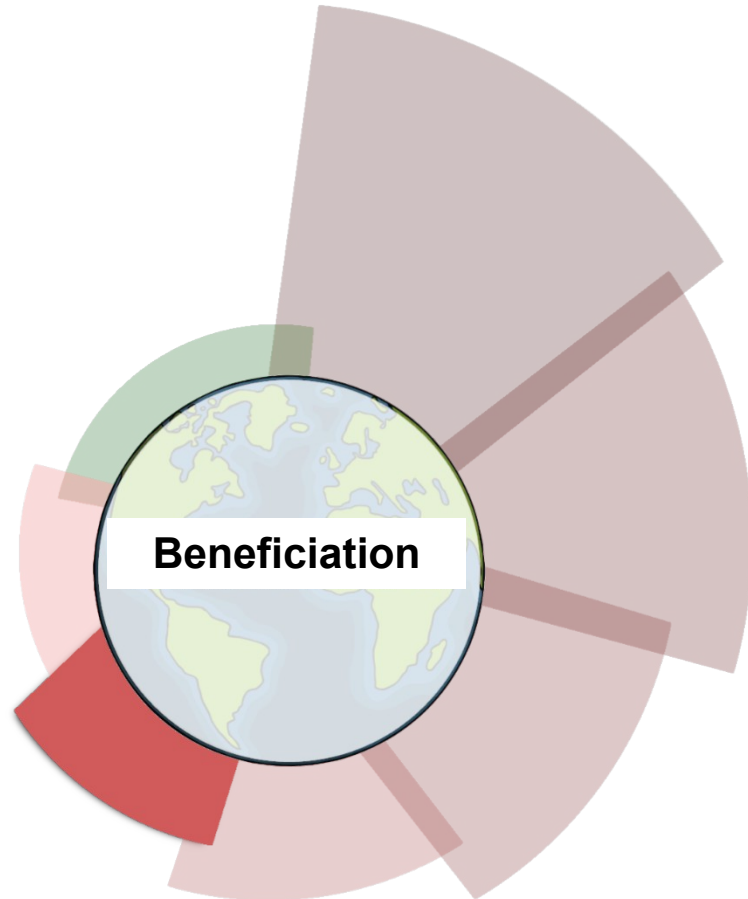


PRODUCT'S BACKPACK



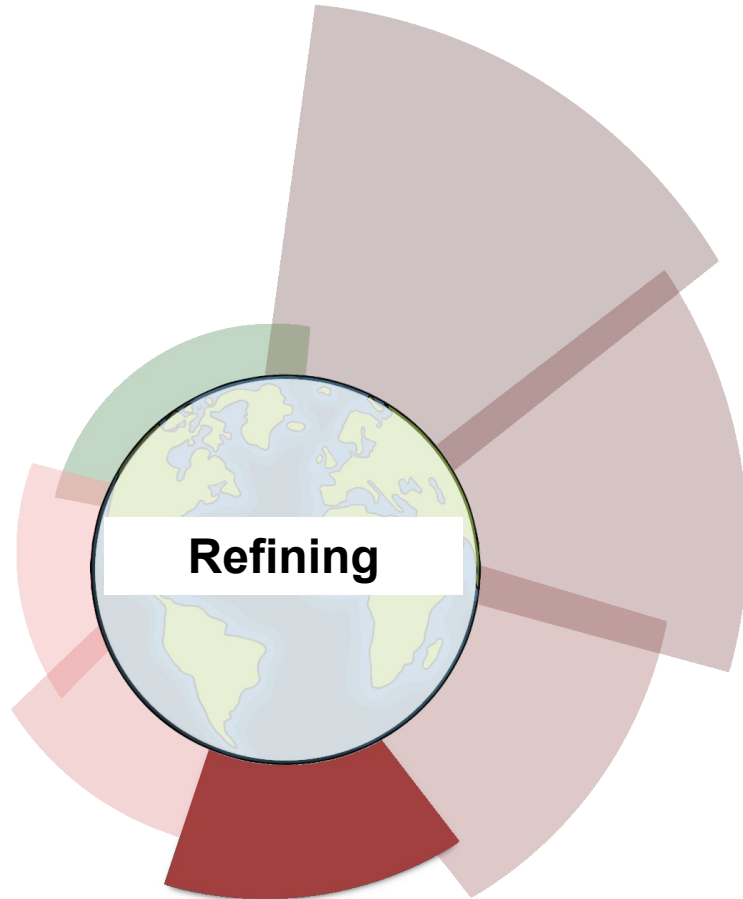
Source: [CC BY 4.0](https://commons.wikimedia.org/wiki/File:Apple_iPhone_11_Pro_Max.jpg), via Wikimedia Commons.

PRODUCT'S BACKPACK



Source: [CC BY 4.0](https://commons.wikimedia.org/wiki/File:Apple_iPhone_11_Pro_Max_(gold).jpg), via Wikimedia Commons.

PRODUCT'S BACKPACK



Source: [CC BY 4.0](https://commons.wikimedia.org/wiki/File:Apple_iPhone_11_Pro_Max_(gold).jpg), via Wikimedia Commons.

The environmental impact increases...

Grasberg mine (Papua, Indonesia): one of the world's largest gold mines



- 1,6 km crater diameter
- 80 tons of gold in 2018

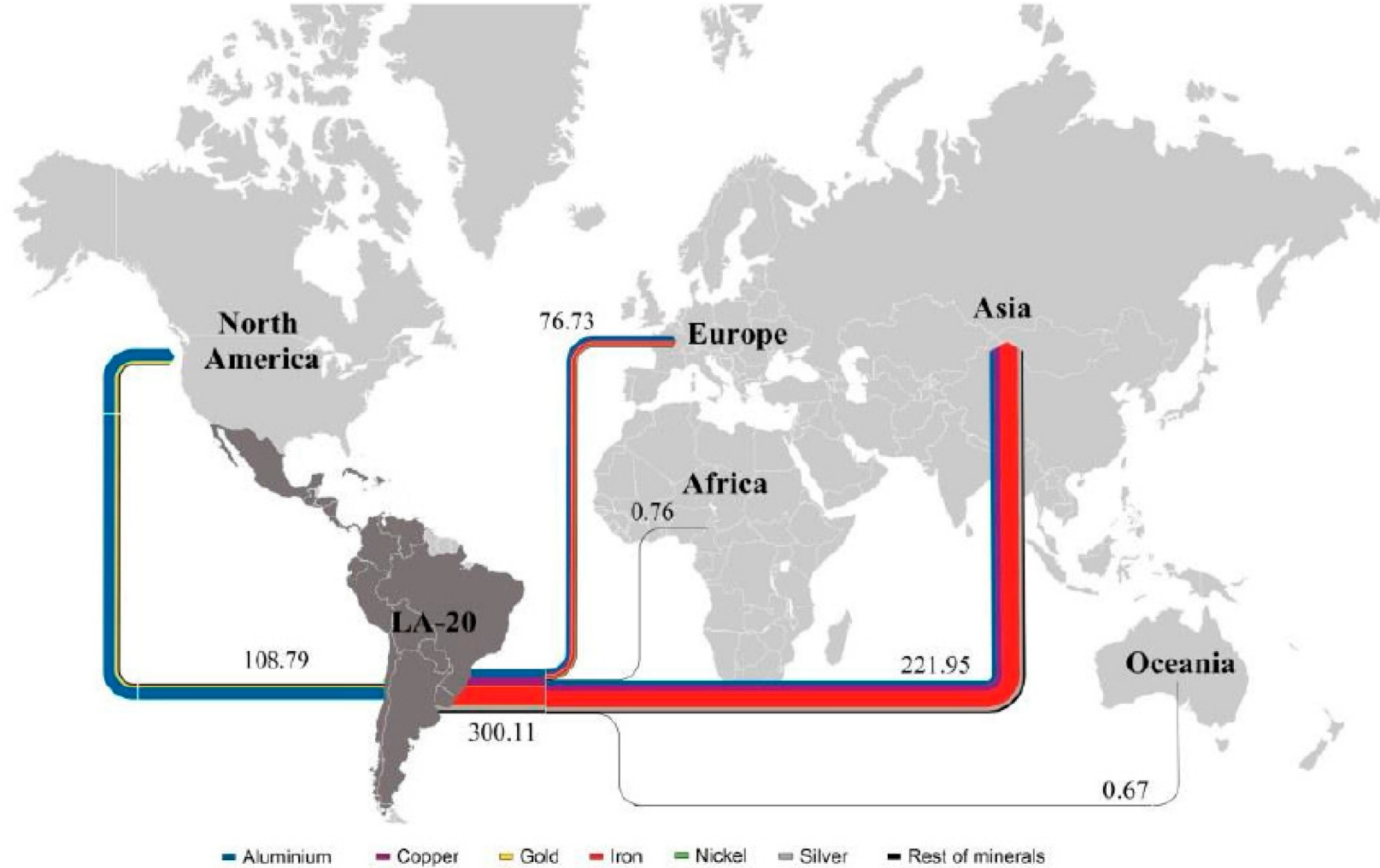


The dark purple in the river is caused by material from the mine waste (Photograph from 2003).

The fish in the Aikwa River have almost disappeared.

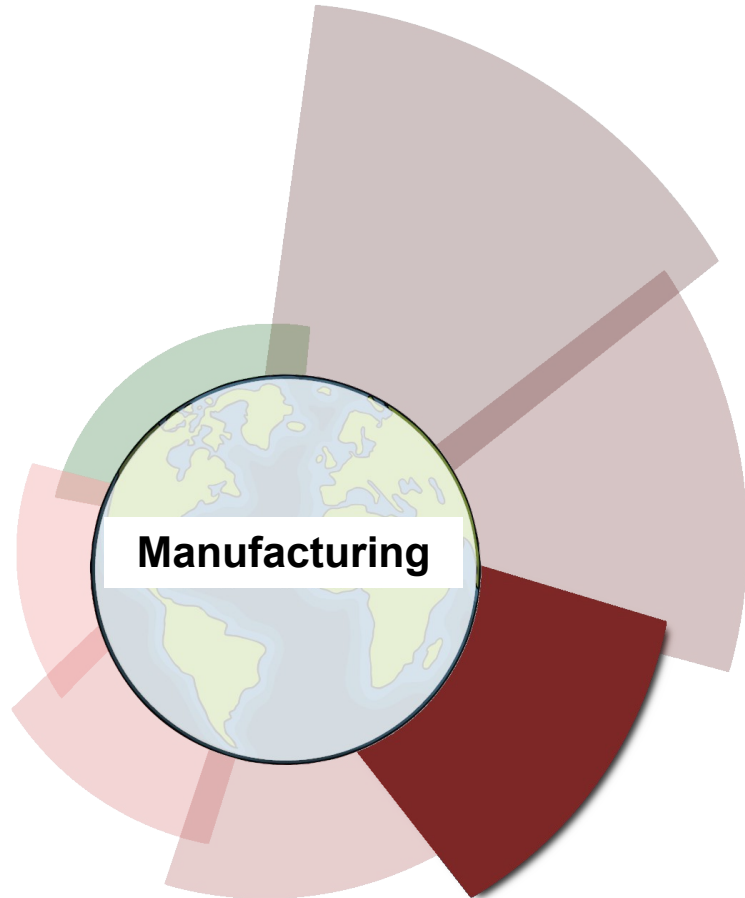
Emissions CO2

Raw material Exports from LA in Mtoe (2013)



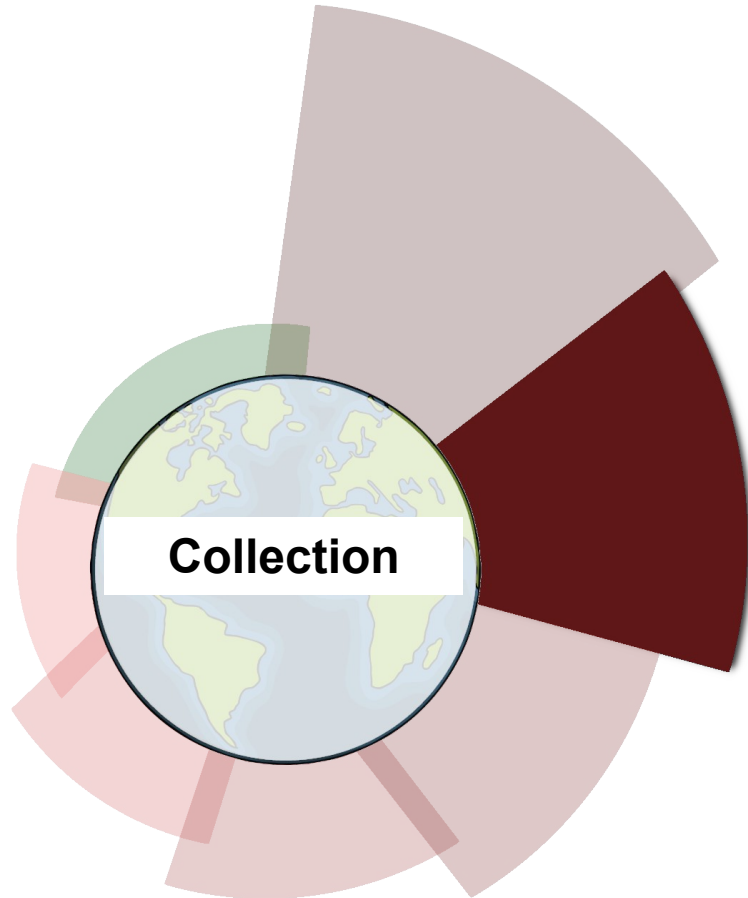
Source: doi:10.3390/su10030723

PRODUCT'S BACKPACK



Source: [CC BY 4.0](https://commons.wikimedia.org/wiki/File:Apple_iPhone_11_Pro_Max.jpg), via Wikimedia Commons.

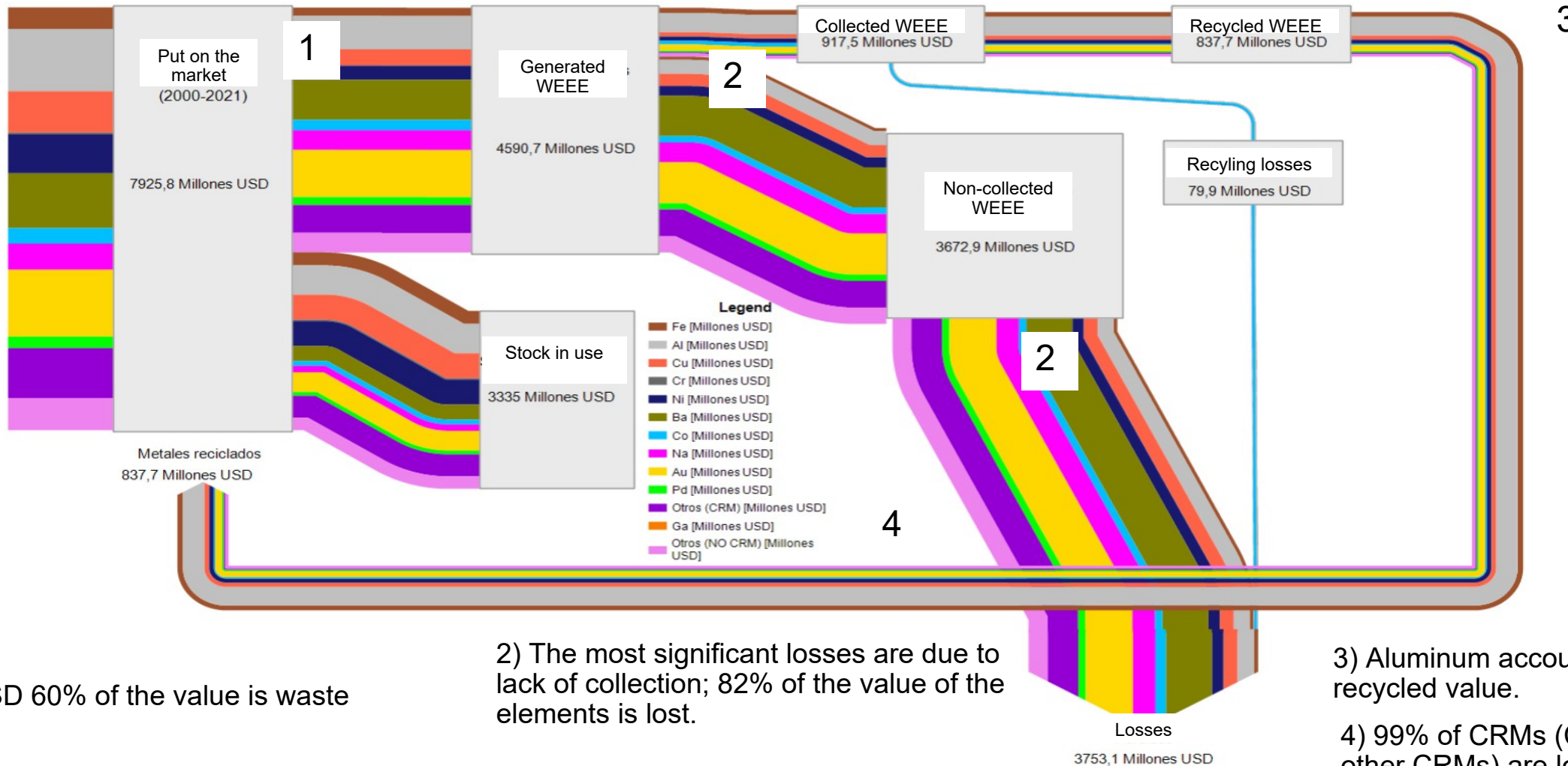
PRODUCT'S BACKPACK



Source: [CC BY 4.0](https://commons.wikimedia.org/wiki/File:Apple_iPhone_11_Pro_Max_(gold).png), via Wikimedia Commons.

How much is recycled in Spain?

WEEE recovered in USD (2000-2021)



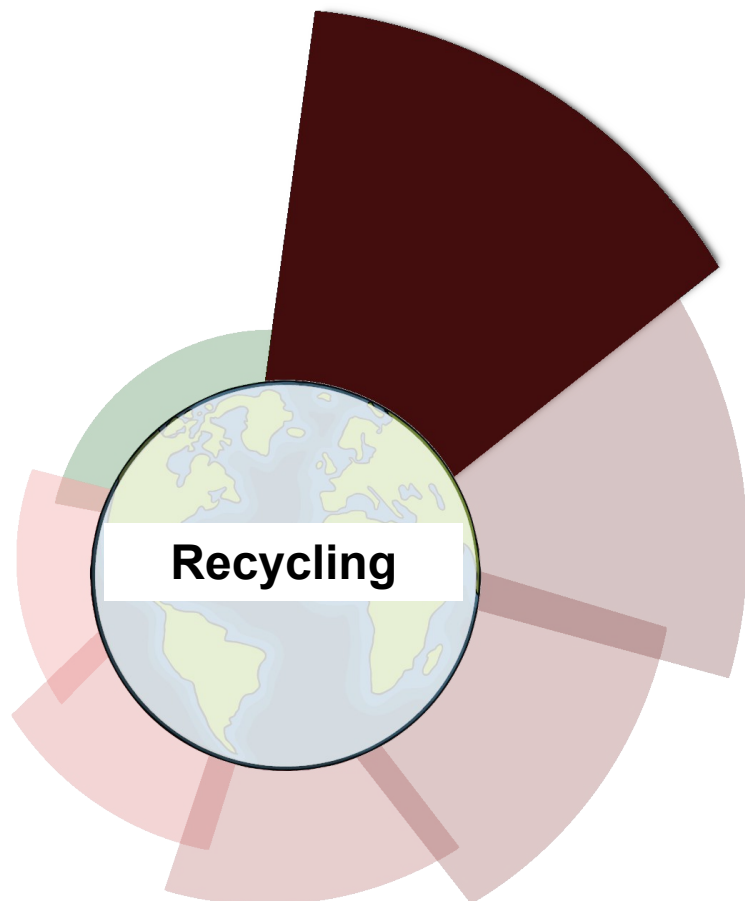
1) In USD 60% of the value is waste

2) The most significant losses are due to lack of collection; 82% of the value of the elements is lost.

3) Aluminum accounts for 50% of the recycled value.

4) 99% of CRMs (Co, Pd, Ga, and other CRMs) are lost.

SPIRAL ECONOMY



Can all materials be recycled?



Chemodiversity in new technologies

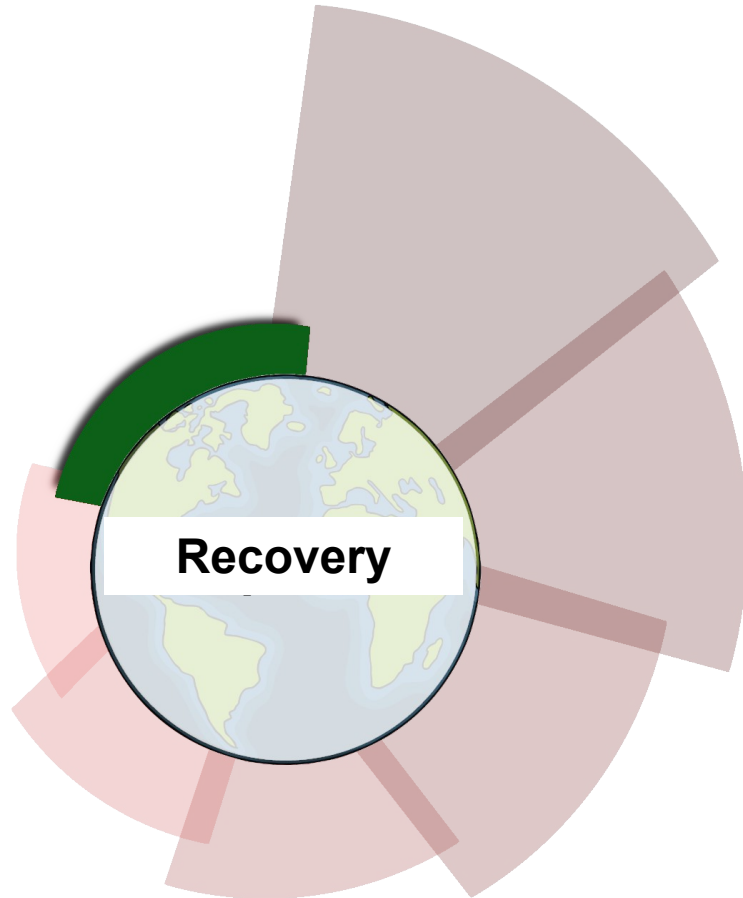
TREND:

More products and materials with better functionalities, size and weight reduction



IMPOSSIBLE TO FUNCTIONALLY RECYCLE THEM!

PRODUCT'S BACKPACK



Source: [CC BY 4.0](https://commons.wikimedia.org/wiki/File:Apple_iPhone_11_Pro_Max_(gold).jpg), via Wikimedia Commons.

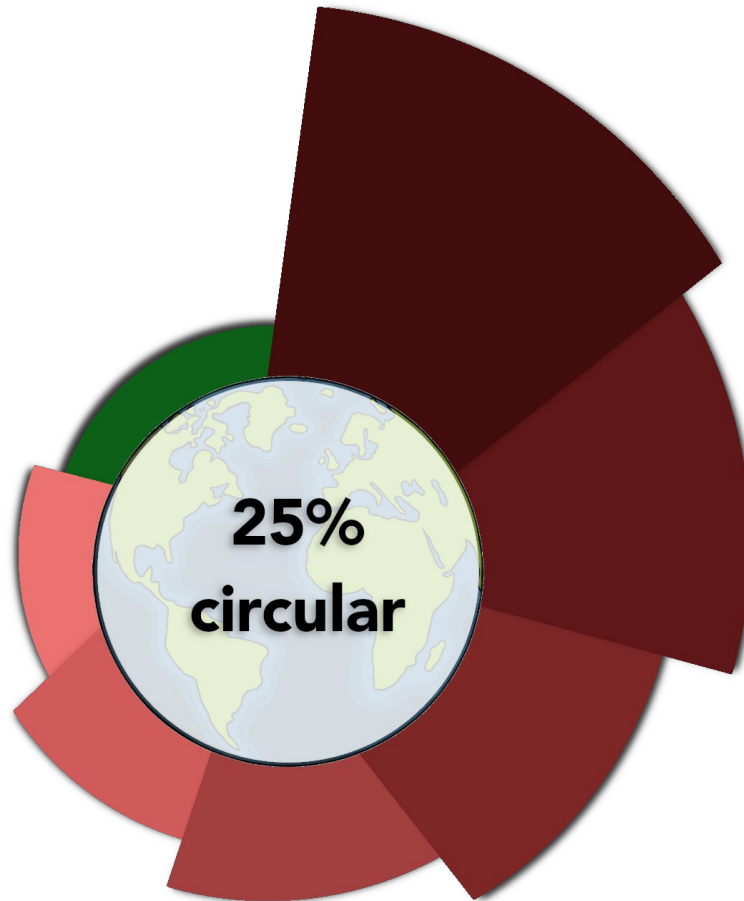
How much is recovered?

Percentage of metals recovered after their end of life

H -	70--100 % 50--70 % 30--50 % 10--30 % 0--10 %																He -
Li 3.3	Be 19											B 0.0	C -	N -	O -	F -	Ne -
Na -	Mg 9.0											Al 70	Si 0.0	P -	S -	Cl -	Ar -
K -	Ca -	Sc 0.0	Ti 3.8	V 5.2	Cr 42	Mn 21	Fe 81	Co 15	Ni 65	Cu 41	Zn 29	Ga 0.0	Ge 1.5	As 0.0	Se 0.4	Br -	Kr -
Rb	Sr 0.0	Y 6.9	Zr 2.9	Nb 9.5	Mo 24	Tc	Ru 52	Rh 54	Pd 58	Ag 57	Cd 27	In 5.0	Sn 14	Sb 18	Te 1.9	I -	Xe -
Cs	Ba 0.0	Lu 0.0	Hf 0	Ta 22	W 26	Re 44	Os 0.0	Ir 50	Pt 72	Au 91	Hg 27	Tl 0.0	Pb 77	Bi 0.0	Po	At	Rn
Fr -	Ra -	Lr -	Rf -	Db -	Sg -	Bh -	Hs -	Mt -	Ds -	Rg -	Cn -	Nh -	Fl -	Mc -	Lv -	Ts -	Og -

La 1.4	Ce 0.3	Pr 0.2	Nd 0.1	Pm	Sm 0.0	Eu 8.0	Gd 0.9	Tb 5.3	Dy 0.0	Ho 0.0	Er 0.0	Tm 0.0	Yb 0.0
Ac -	Th -	Pa -	U -	Np -	Pu -	Am -	Cm -	Bk -	Cf -	Es -	Fm -	Md -	No -

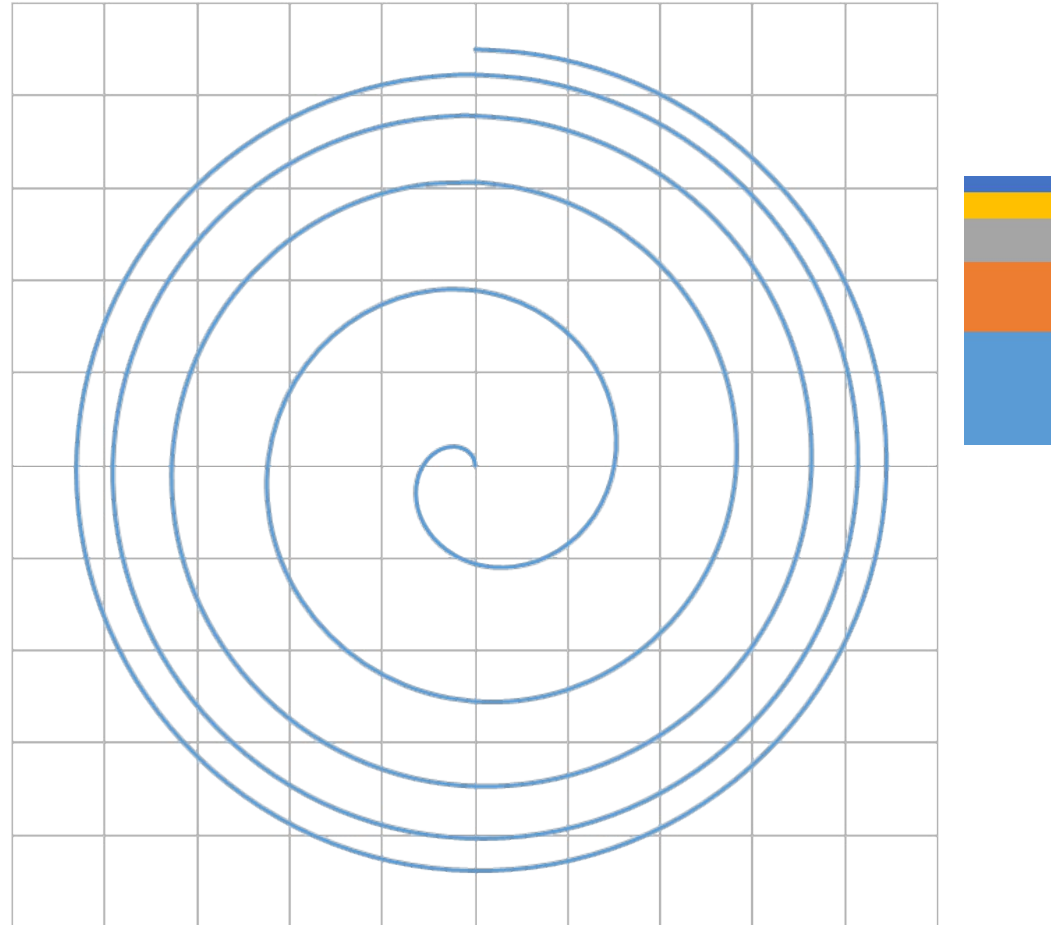
Adapted from: Poncet, A.C.; Helbig, C.; Loubet, P.; Beylot, A.; Muller, S.; Villeneuve, J.; Laratte, B.; Thorenz, A.; Tuma, A.; Sonnemann, G. Losses and lifetimes of metals in the economy. *Nature Sustainability* 5, 717-726 2023.



The creation of economic value carries a footprint in resource depletion, and most of it is lost when products reach the end of their use!

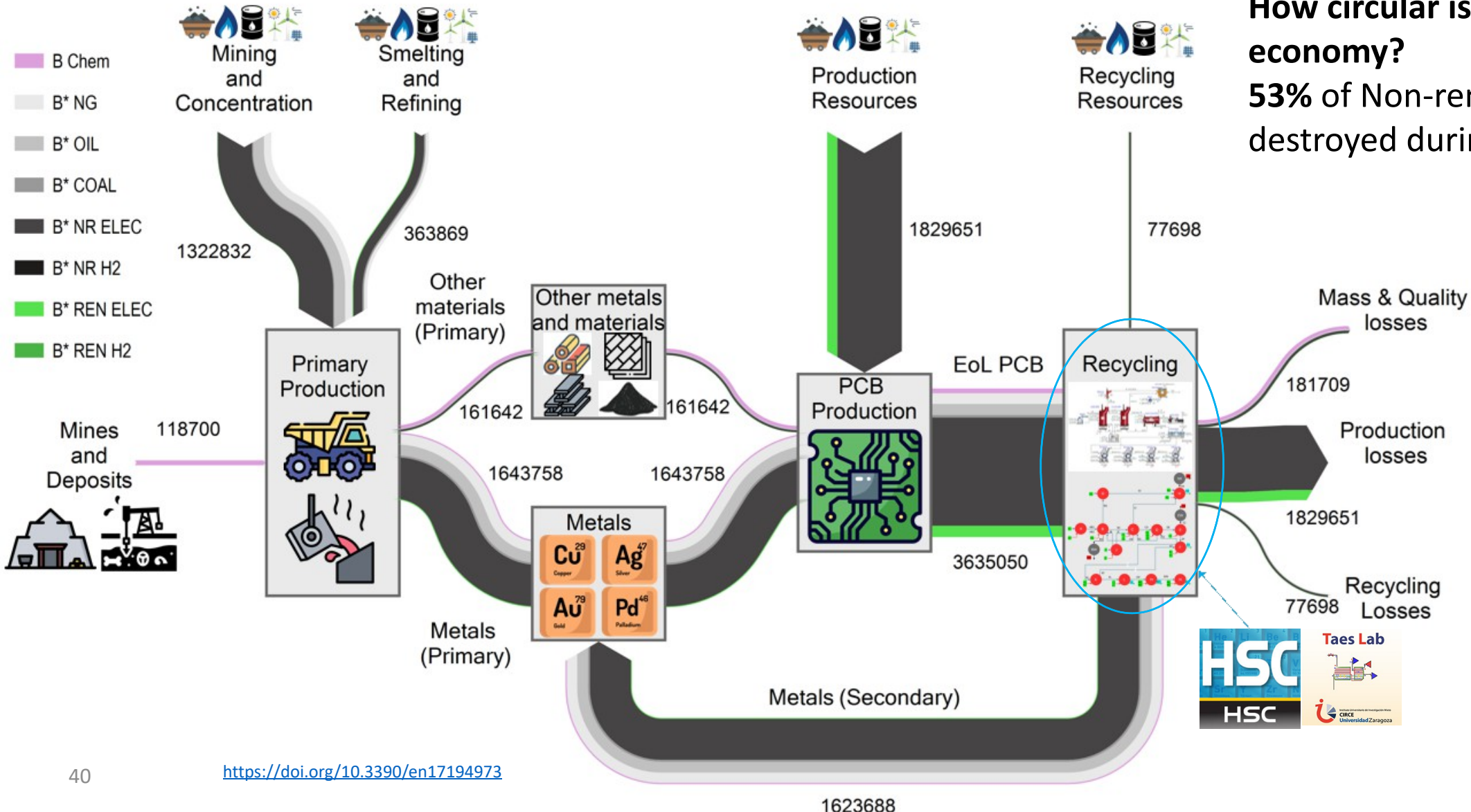
Source: [CC BY 4.0](#), via Wikimedia Commons.

Growing degradation of the Spiral Economy



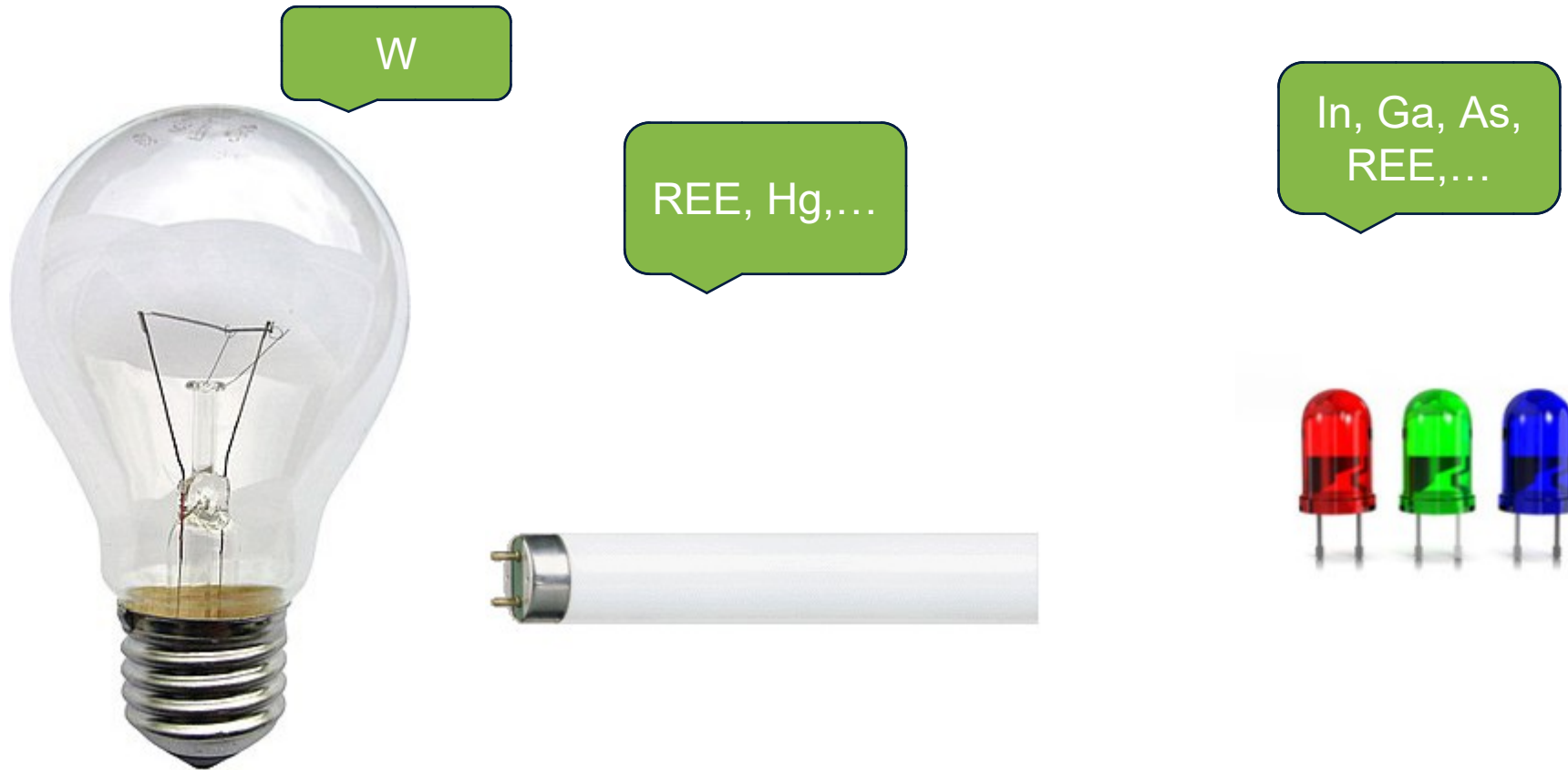
Circular Thermoeconomics:

2020 case (Conventional Resources)

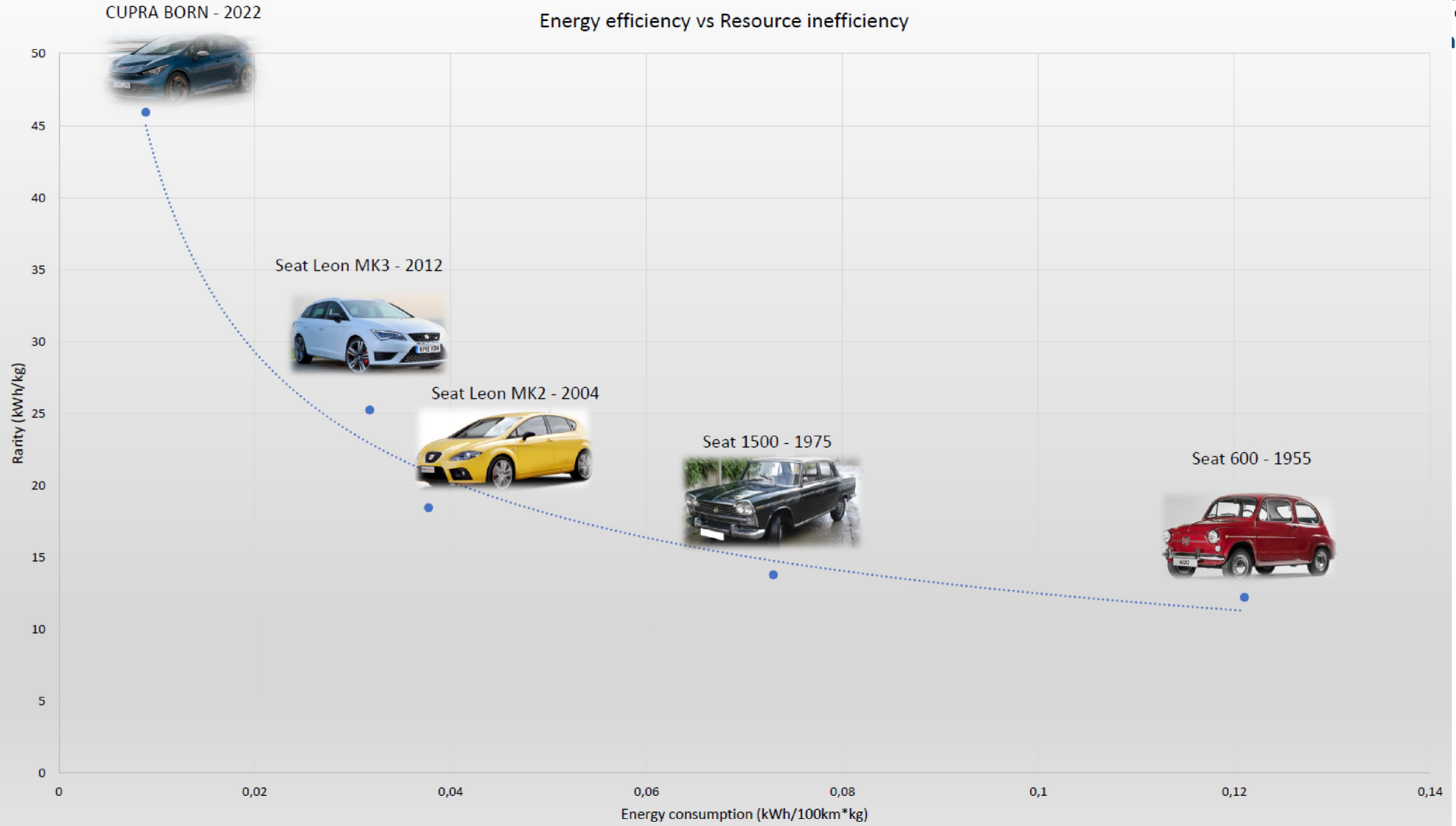


How circular is the circular economy?
53% of Non-renewable exergy is destroyed during recycling

Energetically more efficient, but more sustainable?



Energy efficiency vs Resource inefficiency



Source: authors' own elaboration

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, Thermoeological costs and Thermodynamic rarity.

READ MORE...

Flow Exergy Calculator



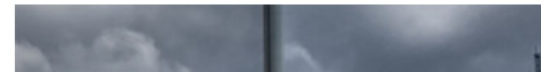
Chemical Exergy Calculator



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

READ MORE...

TaesLAB



Selection

Start with a

Blank Equipment

or Select a Category

PHONES, TABLETS AND NOTEBOOKS

EQUIPMENT ANALYZED:

lphone 6

CATEGORY: PHONES, TABLETS AND NOTEBOOKS



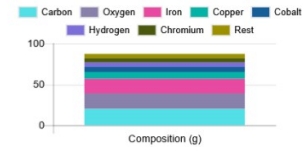
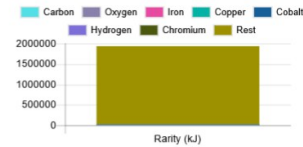
RESULTS

Rarity value

106.34 MJ

Total composition (g)

89.70 g

☐ Zoom ☐ Order rarity by value

Rarity (kJ)

[illegible]

<https://www.exergoecology.com/rarity/>

Bibliography

FRIEDE-GARD-PREIS 2020

TaesLab is a software tool designed for the thermoeconomic analysis of energy systems. It is distributed as a MATLAB/Octave Package.

It is based on the thermoeconomic analysis works developed since 1986 in the University of Zaragoza. Spain.

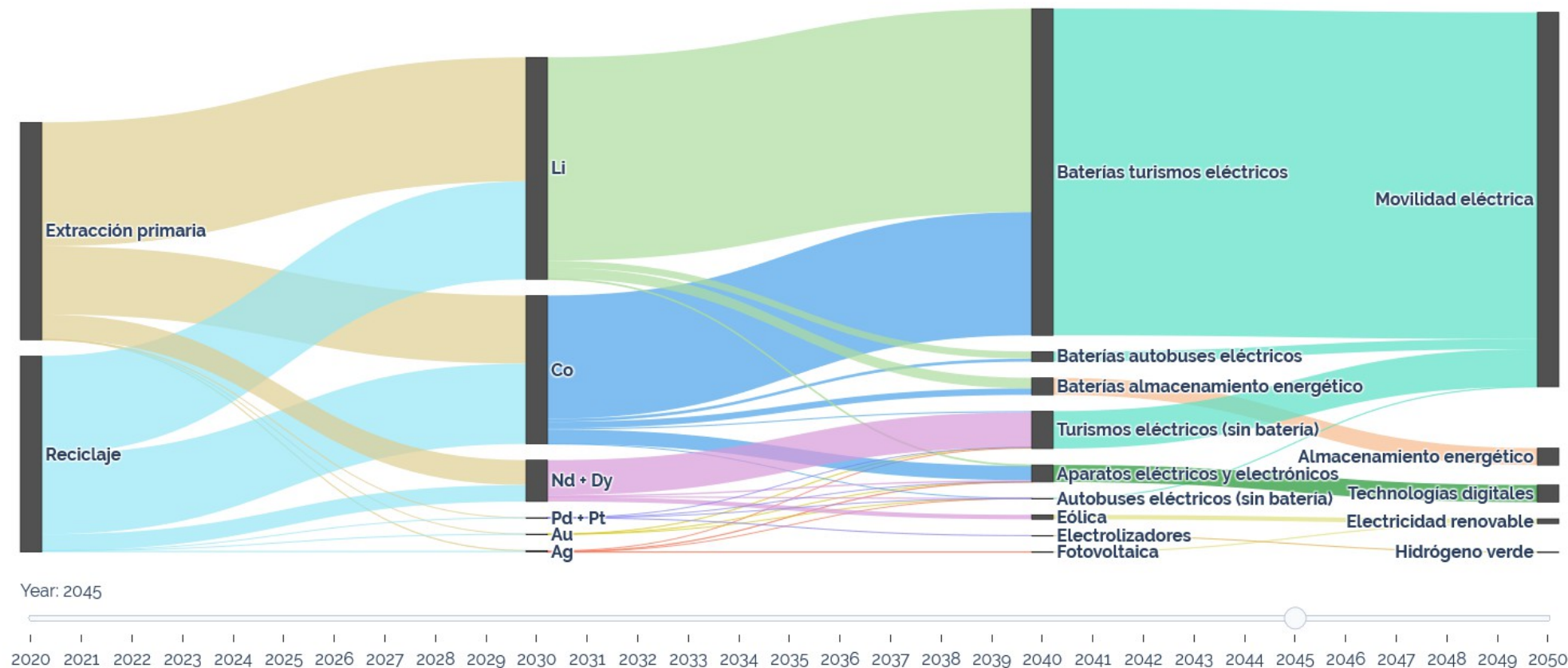


Recycling can substitute mining

Demanda anual [t]

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

**Recycling could
satisfy ~57% of
demand by 2050**



https://www.tierra.org/wp-content/uploads/2023/12/informe_minerales_para_la_Transicion.pdf

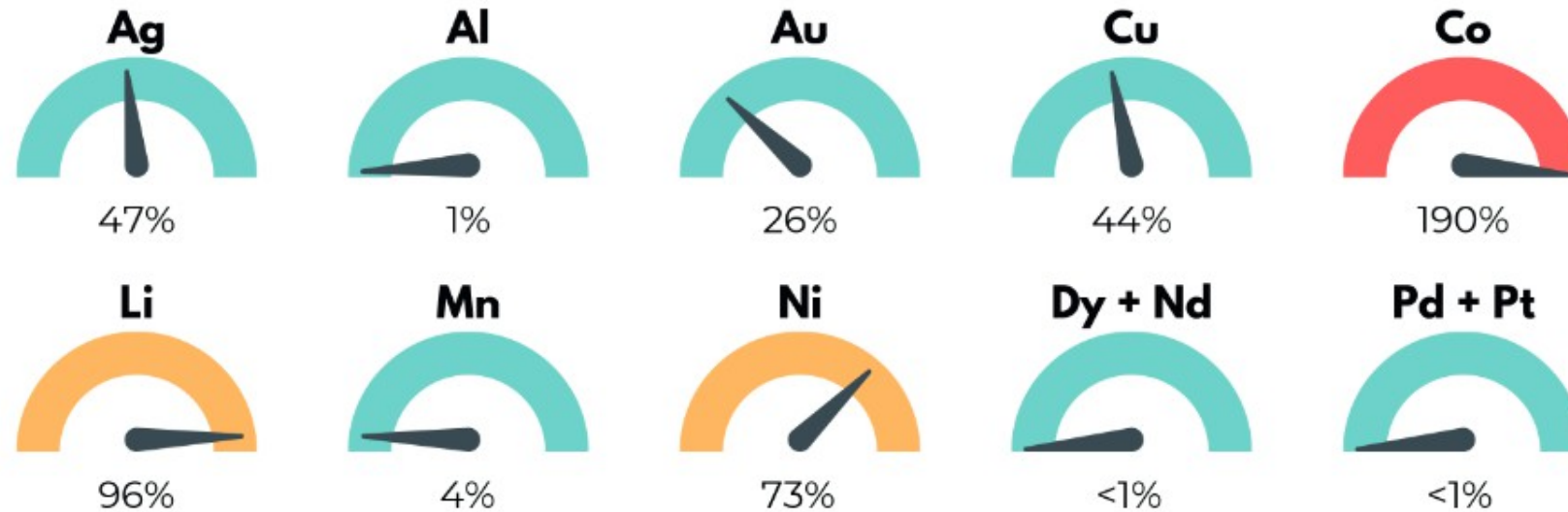
Recycling can substitute mining



Recycling can overcome supply
bottlenecks by 2050

Cumulated metal demand 2020-2050

Escenario de transición



Population Spain:
0,6% world
population→
**Equitable share of
reserves: 0,6% of
reserves (USGS,
2022)**

https://www.tierra.org/wp-content/uploads/2023/12/informe_minerales_para_la_Transicion.pdf

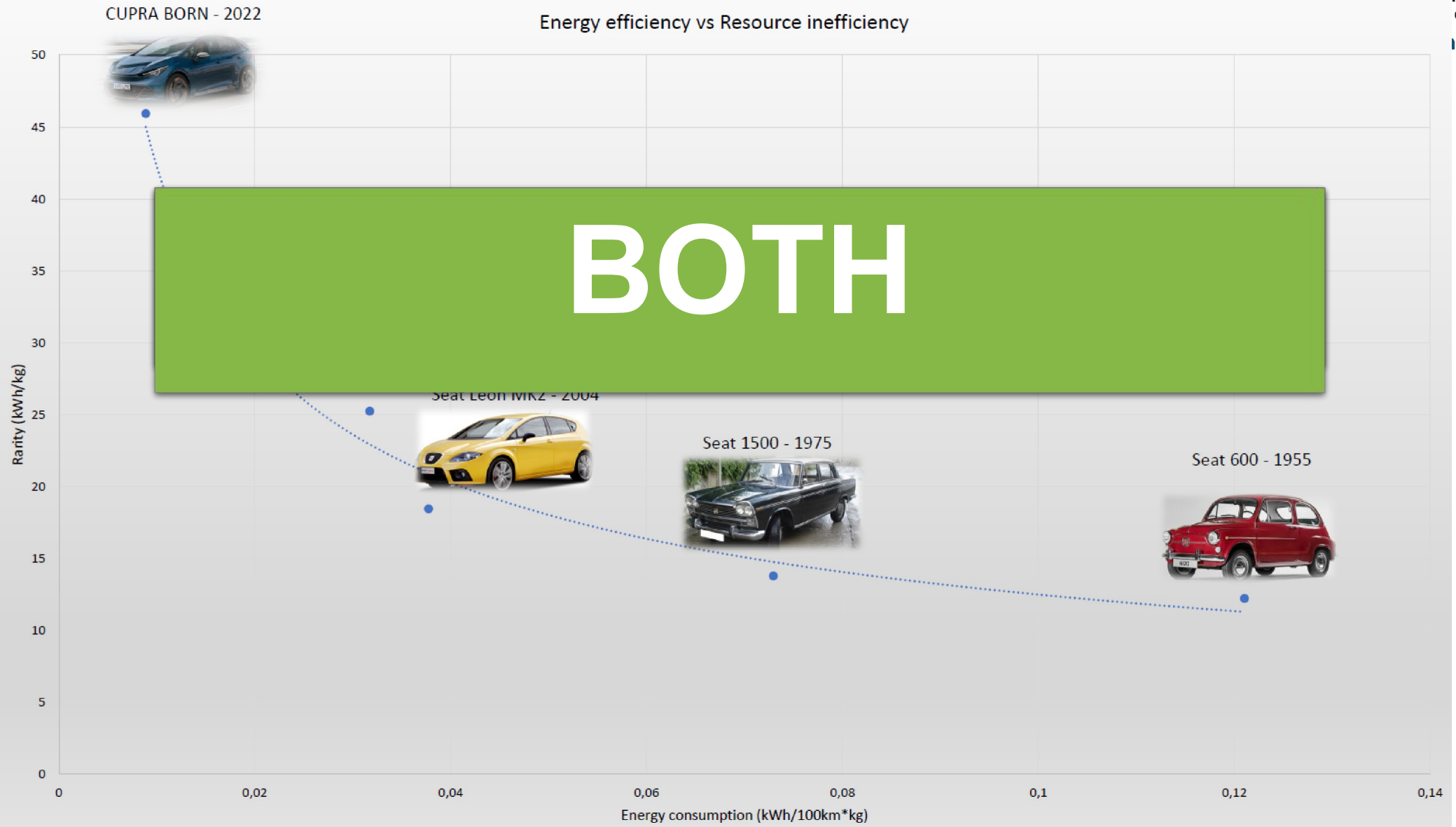
Recycling can overcome supply
bottlenecks by 2050



3. How can we reduce irreversible resource losses?

Are there other options to avoid
exceeding material limits?

Energy efficiency vs Resource inefficiency



Source: authors' own elaboration

BACK TO THE ROOTS, BACK TO THE FUTURE:

Quality in products

“BOTIJO ENGINEERING”



- Keeps water cold (Energy efficient)
- Simple design
- Local and cheap materials
- Robust
- Easy to repair and recycle (only 1 material)
- Creates sense of community

THE “DIS FACTORY”

Quality in processes

- A car factory produces one car every 2 minutes.
- The same factory is unable to disassemble a single vehicle!



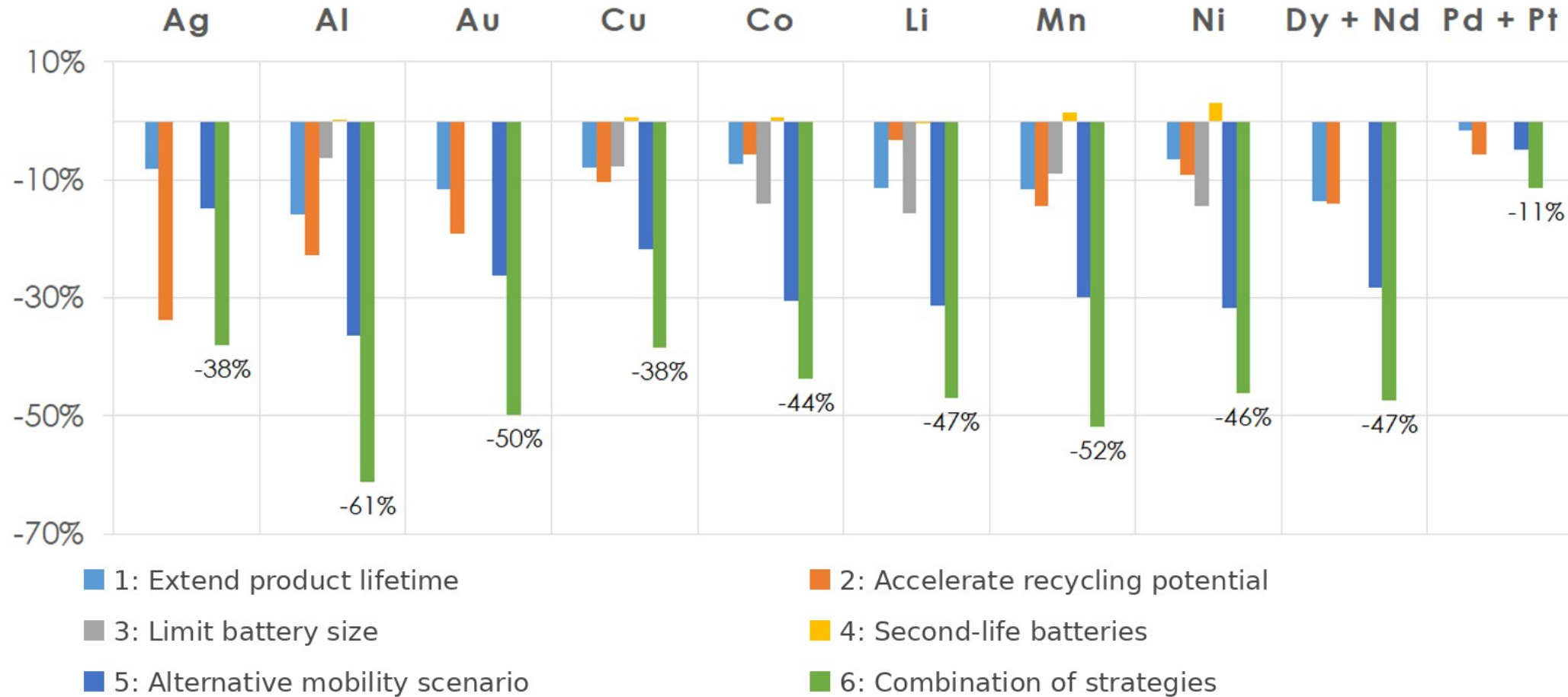
Source: [CC BY-SA](#)

In product design, ensure that they can be easily disassembled.

Piece-by-piece strategy: For a truly circular/spiral economy, products should not become a source of materials, but a source of spare parts!

Sufficiency scenarios for the case of Spain

Cumulated metal demand 2020-2050



SPIRAL ECONOMY-WASHING MACHINES

lb composition: ■ Prior phases (carried IB) ■ Energy and other resources ■ Material resources ■ Material return



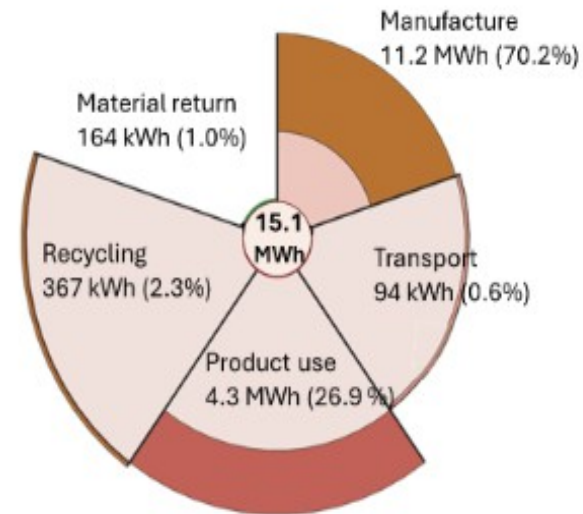
Scenario 1. Frequent Renewal

- Replaced every 5 years based on user behavior
- 3 units are consumed within a 15-year

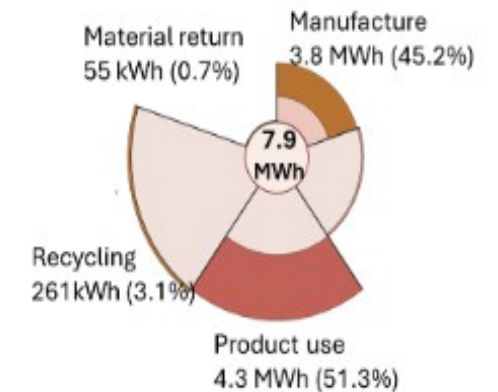
Scenario 2. Lifespan Extension

- Extended lifetime from 5 to 15 years
- Use of one machine

Scenario1



Scenario2



<http://www.tierra.org/wp-content/uploads///la-caracola-de-la-irreversibilidad-como-reducir-el-coste-oculto-de-la-tecnologia.pdf>

SPIRAL ECONOMY- REFRIGERATORS



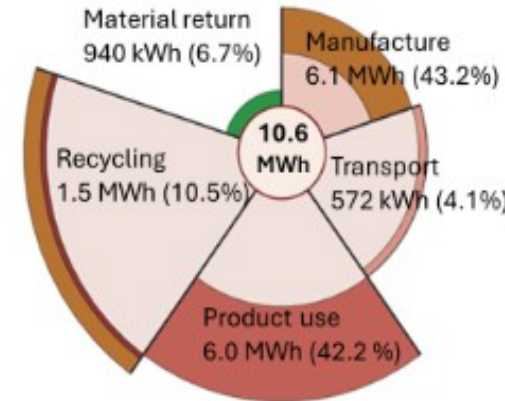
Scenario 1. Efficiency-Driven Replacement

- Type-E refrigerator used for 10 years
- Replaced by a new unit more energy-efficient Class A mode for 10 years

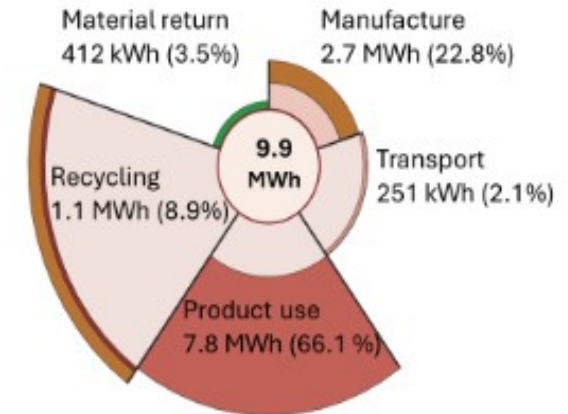
Scenario 2. Lifespan Extension

- Single type-E refrigerator operates stably for 20 years
- No requiring repairs and maintaining a constant energy efficiency.

Scenario1



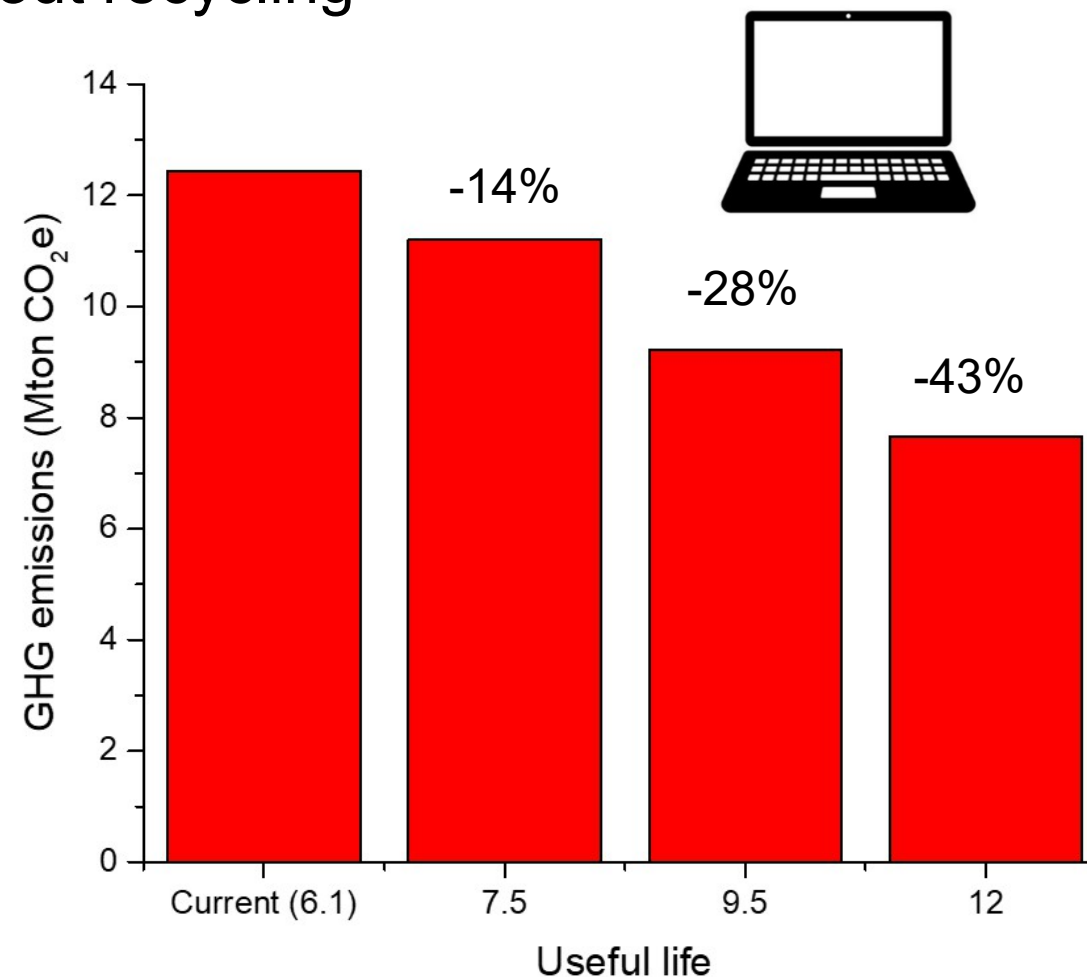
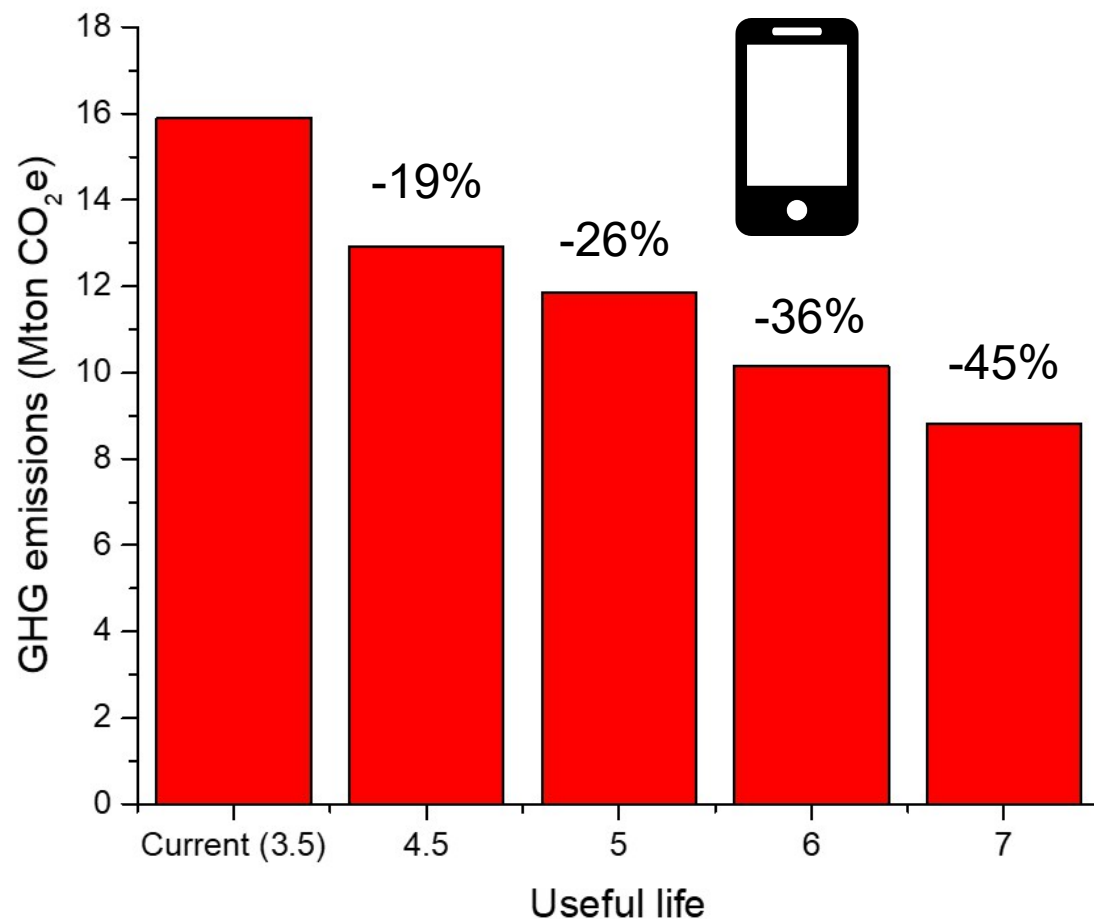
Scenario2



<http://www.tierra.org/wp-content/uploads///la-caracola-de-la-irreversibilidad-como-reducir-el-coste-oculto-de-la-tecnologia.pdf>

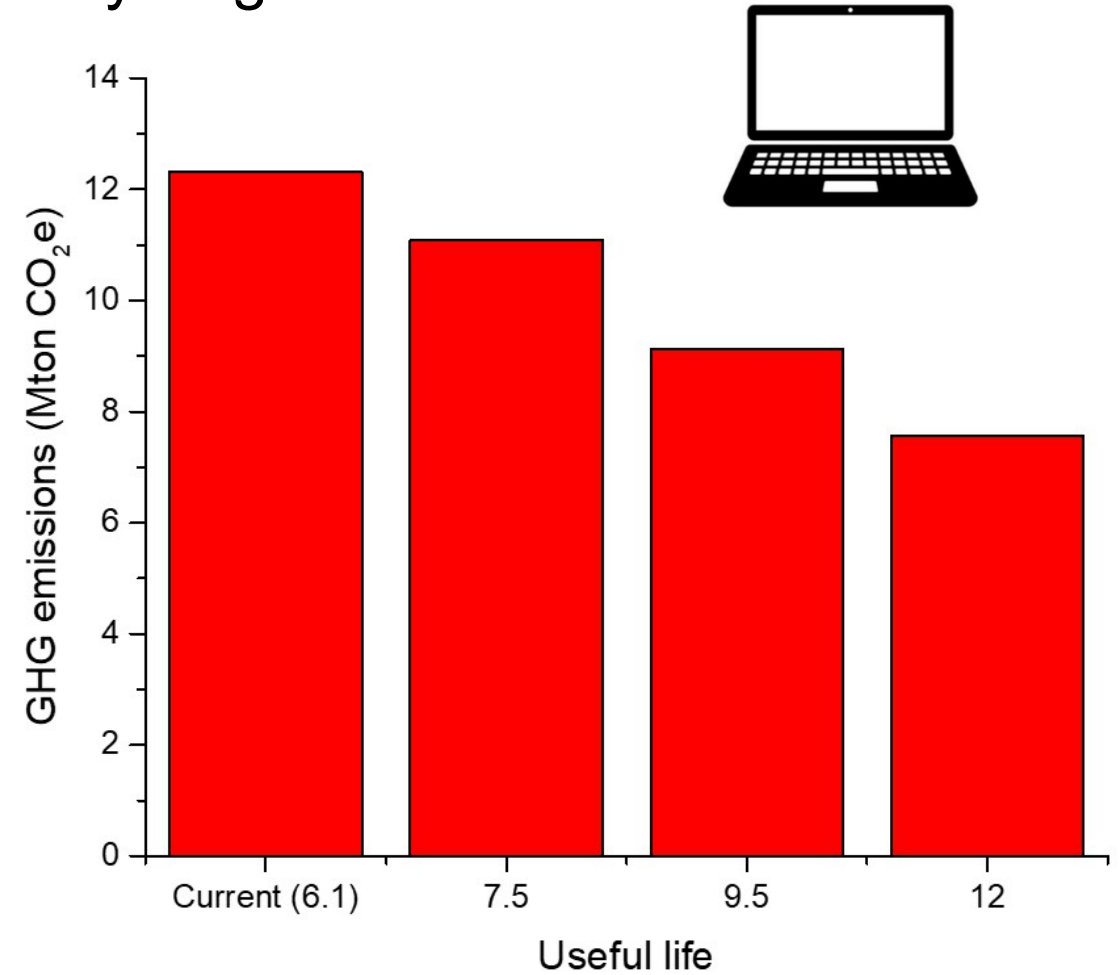
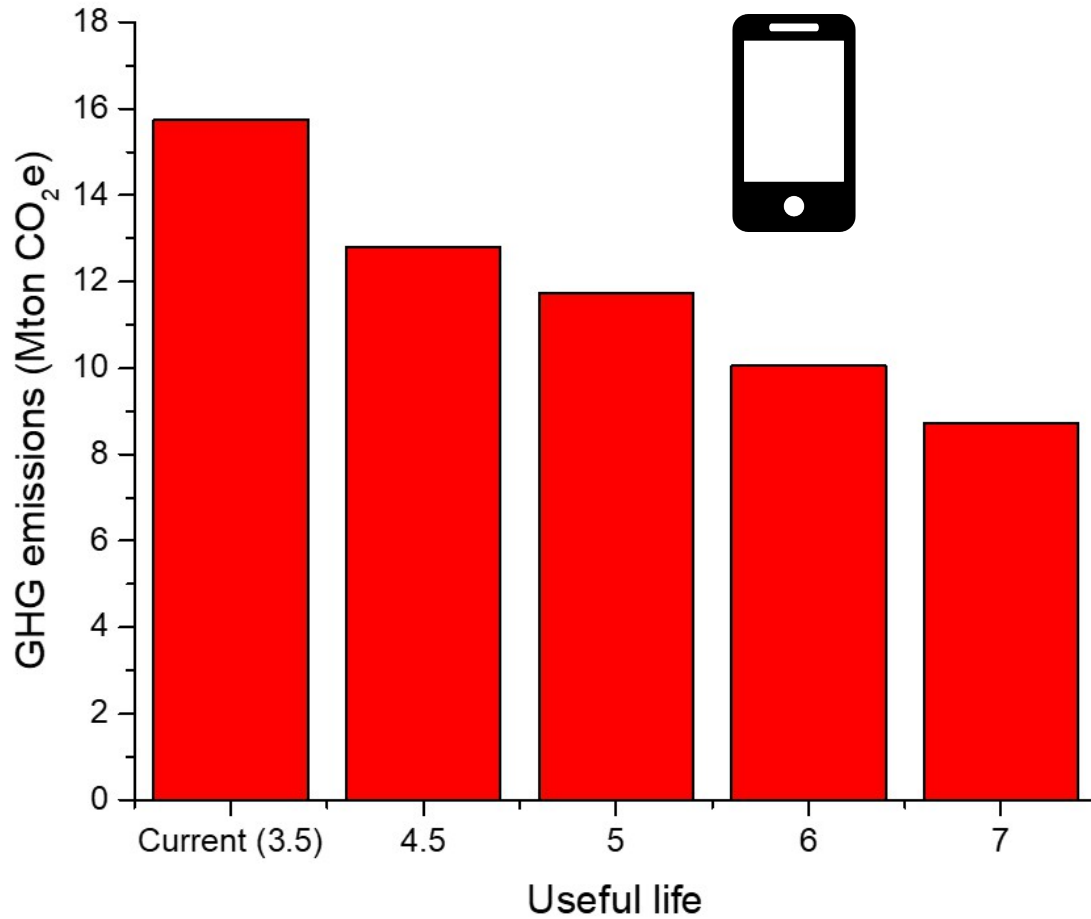
The effect of long-lasting products

Without recycling



The effect of long-lasting products

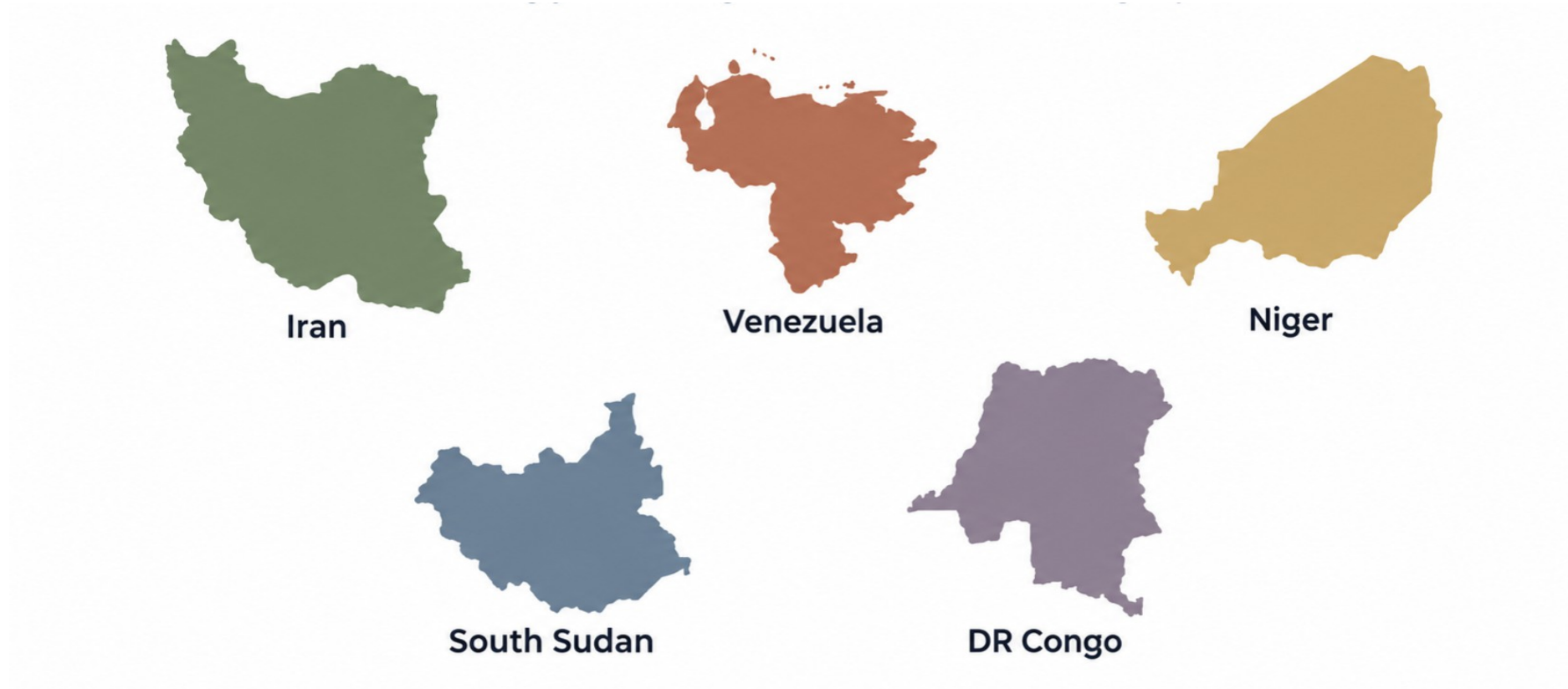
With recycling



Are there other options to avoid
exceeding material limits?



What do these places have in common?



The search for the last resources

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



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

Selling natural cathedrals at the price of bricks

GDP and other economic indicators do not take the effort by Nature to produce resources and future generations into account. The scarcer, the greater the debt to Nature.



Source: wikimedia commons



- Natural capital is a natural heritage of those who live today but also of those who will be born. It must be valued fairly in order to create a true sense of conservation and intergenerational justice!

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

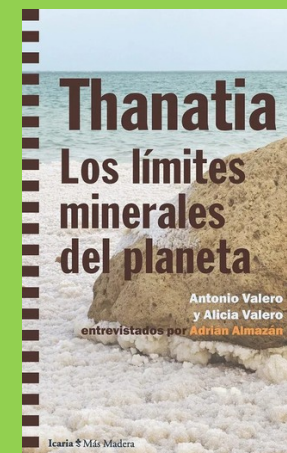
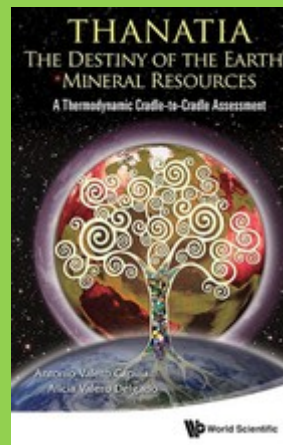
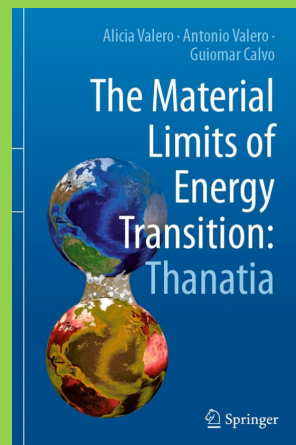
Honesty and Justice in a Finite World



**A SUSTAINABLE ECONOMY MUST
RECOGNIZE PHYSICAL LIMITS.**

**Prosperity is not only what we produce
today, but also the natural wealth and
opportunities we preserve for tomorrow.**

**Let us connect science, economics and
society to make better choices.**



Thank you very much!

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