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GeMMe
Georesources, Minerals Engineering & Extractive Metallurgy

Raw Materials, Criticality & Circular Economy

Eric PIRARD

Raw Materials and Society

… lost in transitions

Renewable times

- *7 metals*
- *100% renewable energies*
- *3-4 manpower/day*

J. Vermeer, 1666

- *91 metals*
- *> 80% non-renewable energies*
- *400 manpower/day*

Anonymous, 2024

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Fuelling energy transitions

- Reduction and smelting of iron ore in the blast furnace
  - > 1450 °C

Charcoal

$$2\ Fe_2O_3 + 3\ C = 4\ Fe + 3\ CO_2$$

Massive Deforestation

> Unsustainable production of pig iron (Buffon, 1783)

Blast furnace in the region of Spa(1612) Jan Brueghel

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Fuelling energy transitions

- Modern steelmaking
  - John Cockerill (1817)

Coking coal

$$2\ Fe_2O_3 + 3\ C = 4\ Fe + 3\ CO_2$$

1,9 tons CO_2 per ton of steel

> 5% of world GHG emissions in 2023

HFB Blast Furnace in Ougrée

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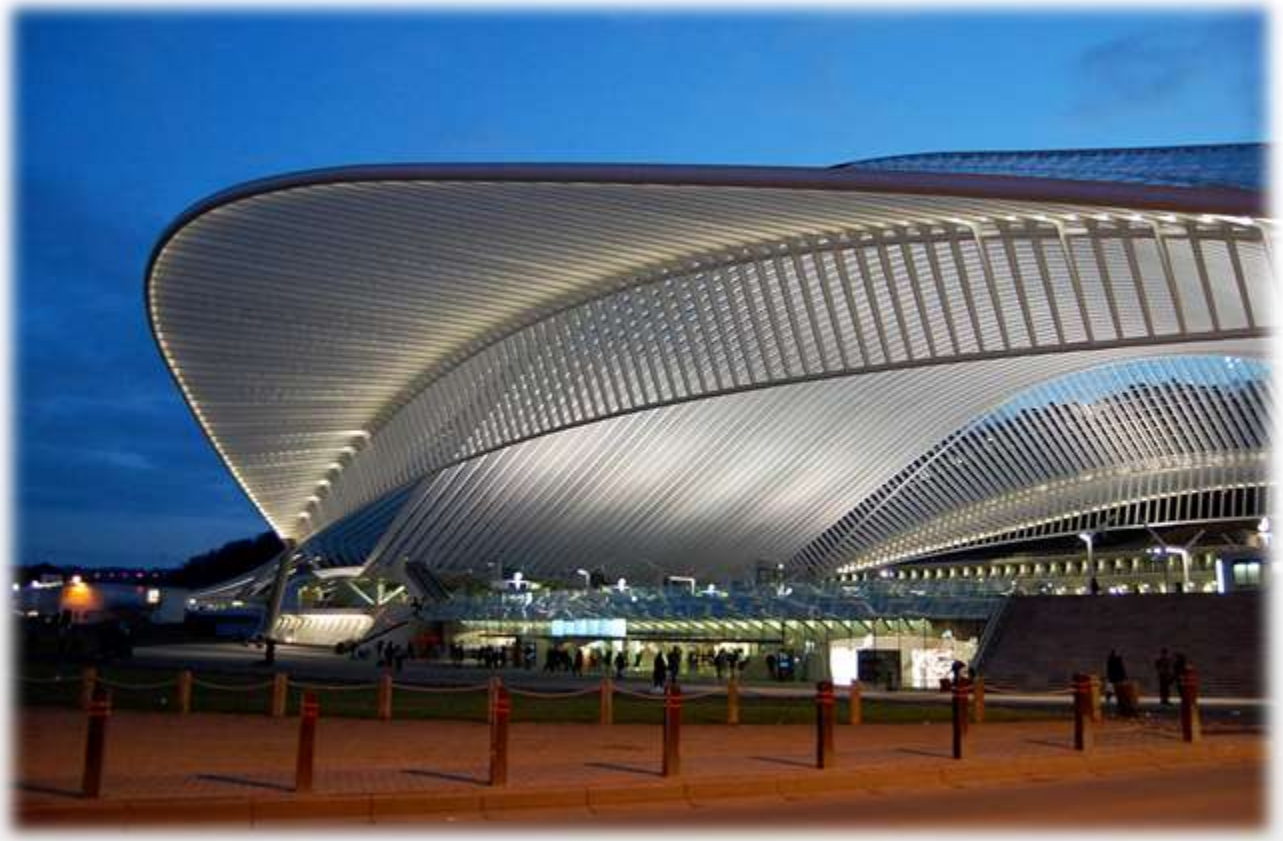
Fuelling energy transitions

- World production of 1,5 Gt steel
  - 450 kg steel/ pers yr (Europe)

Where to find hydrogen?

$$Fe_2O_3 + 3\,H_2 = 2\,Fe + 3\,H_2O$$

Water vapour



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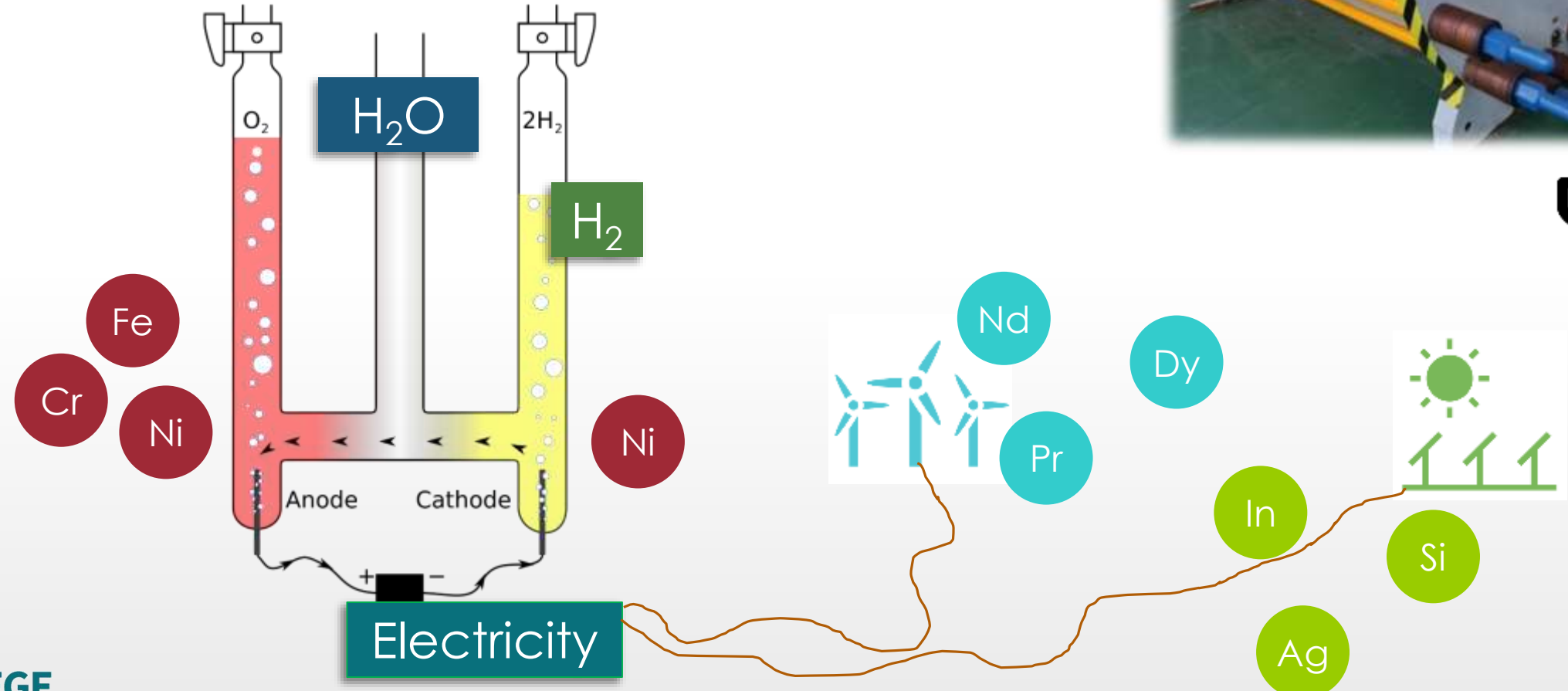
Fuelling energy transitions

- Green Hydrogen
  - We need water and « green » electricity!

John Cockerill



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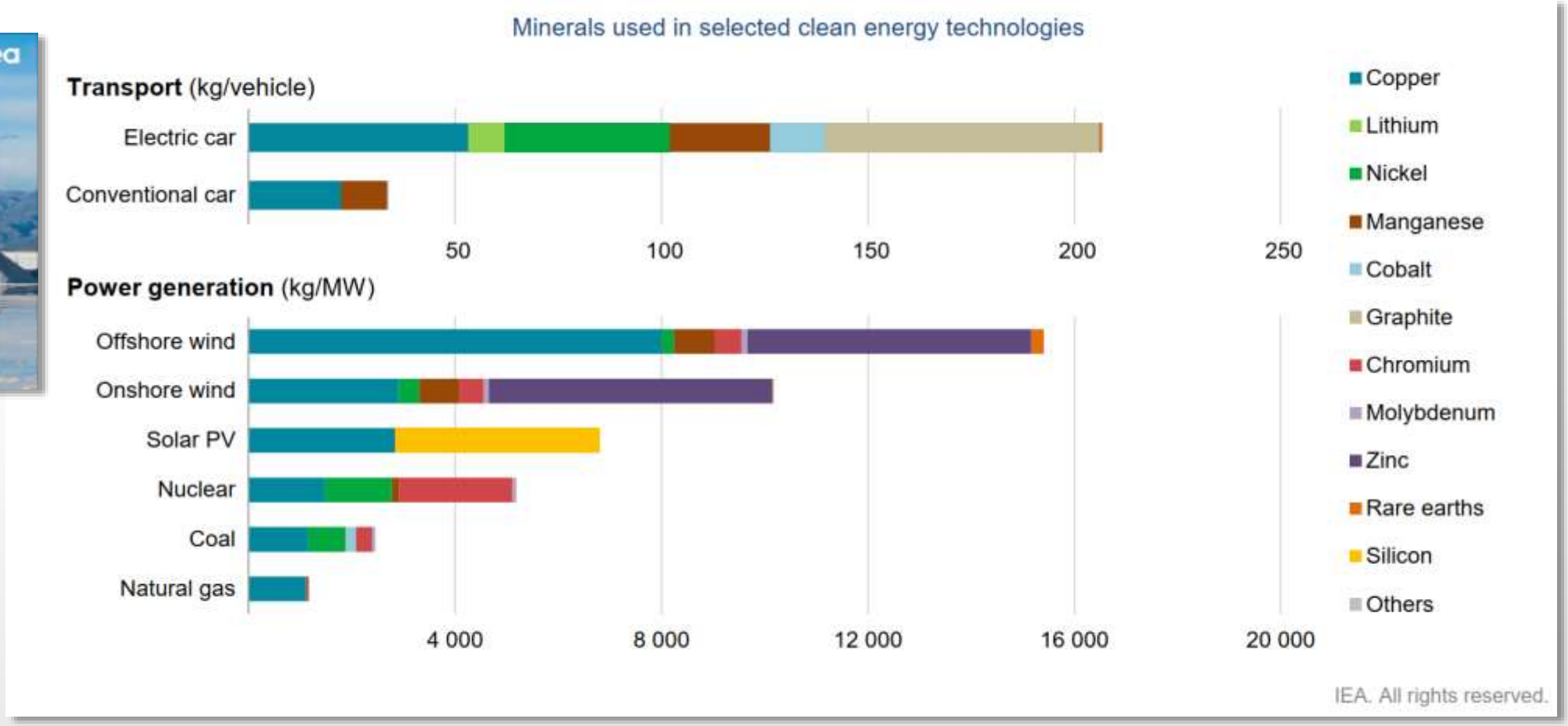
Metals of the Green Deal

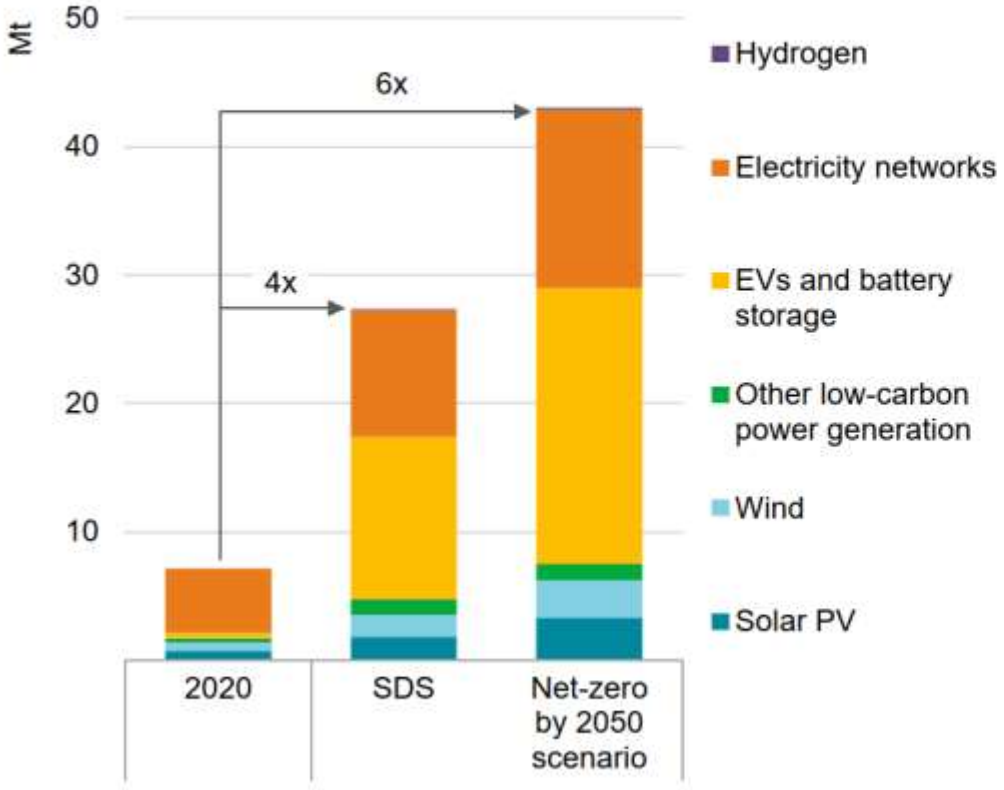
- The role of critical minerals in clean energy transitions
  - IEA (2021)



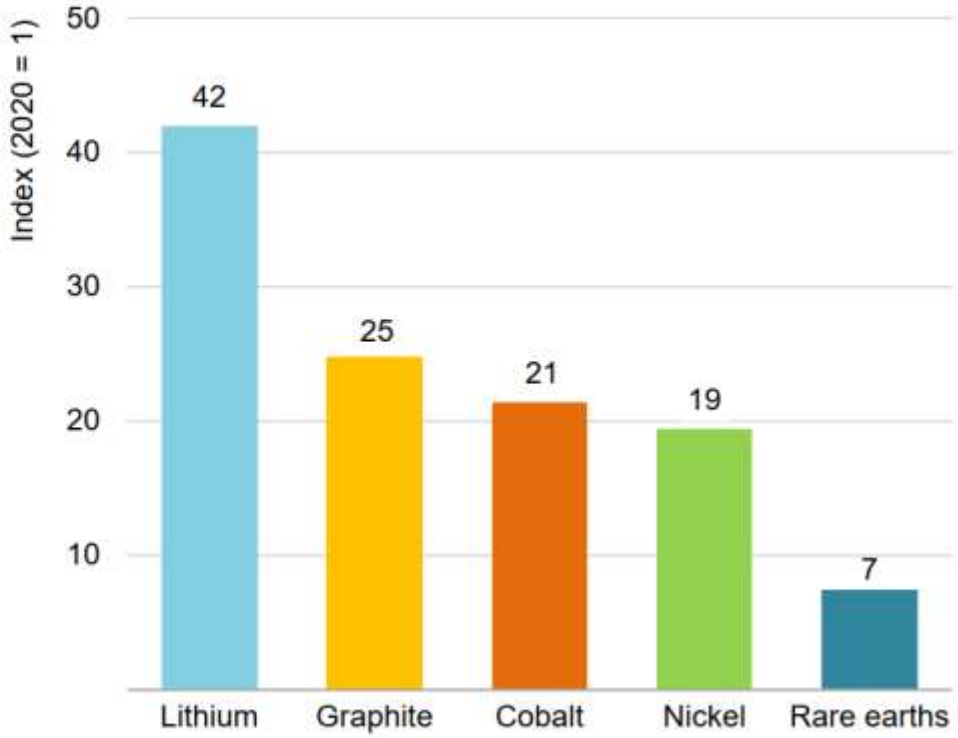
Metals of the Green Deal

Mineral demand for clean energy technologies by scenario

Growth to 2040 by sector

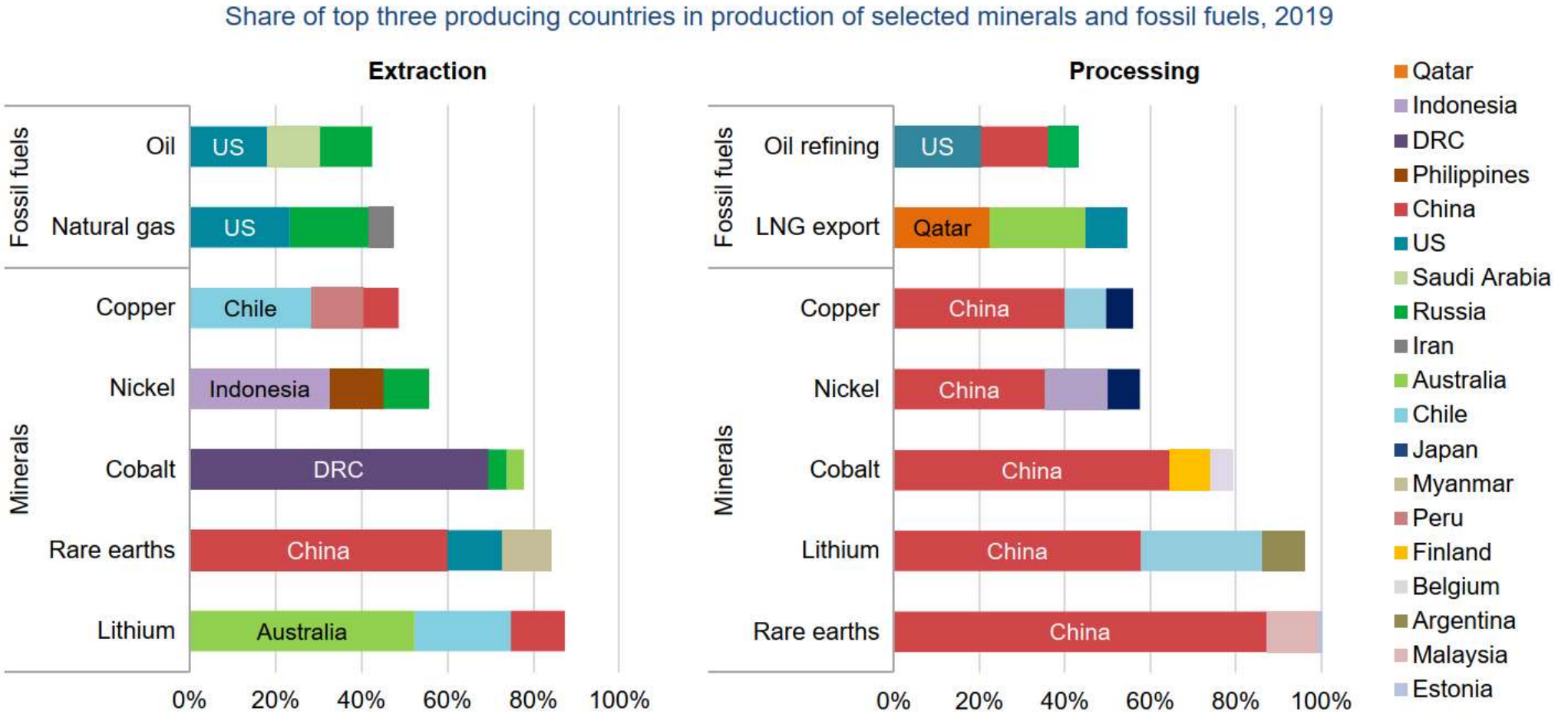


Growth of selected minerals in the SDS, 2040 relative to 2020



Metals of the Green Deal

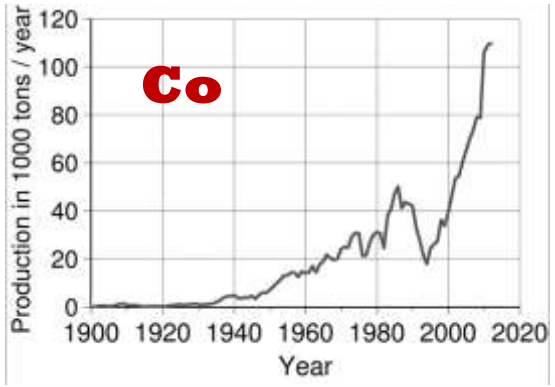
- More concentrated than fossil fuels, especially down the value chain

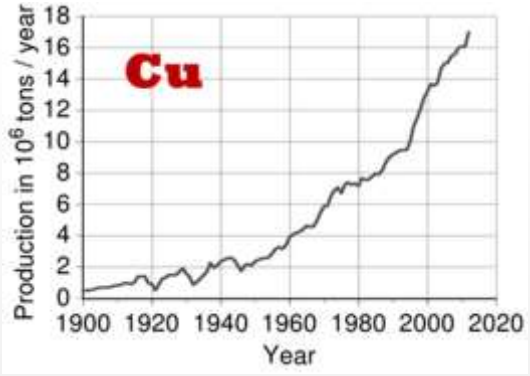


Sustained or Sustainable Development

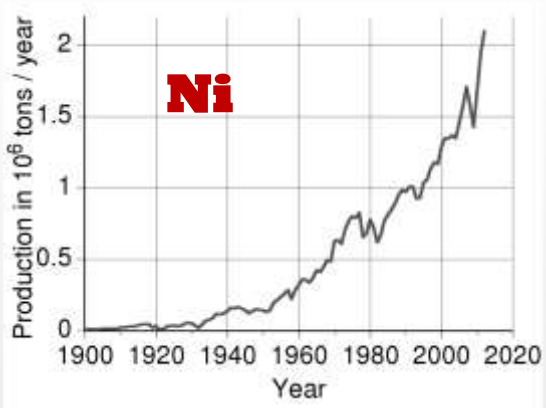
… squaring the circle

Exponential Growth

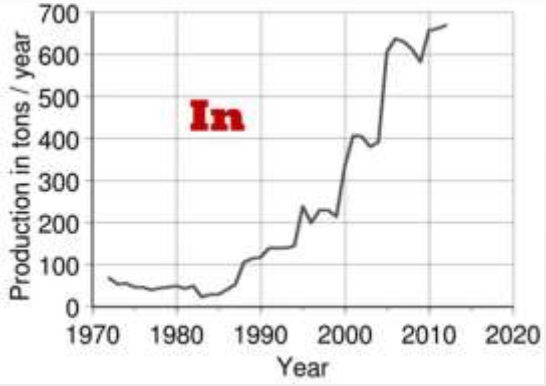




Base Metals



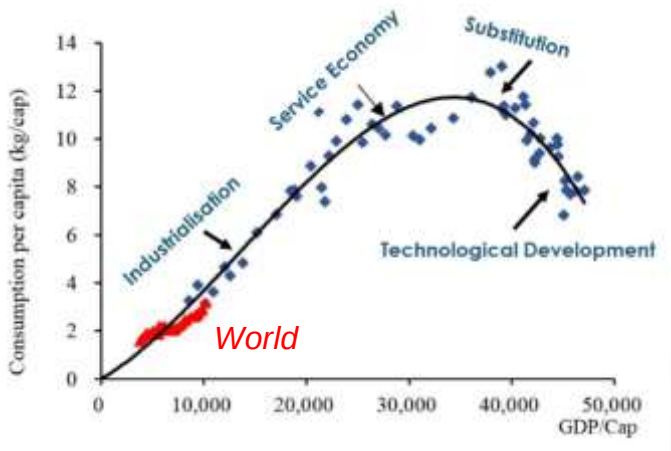
Tech Metals



E-metals

Decoupling?

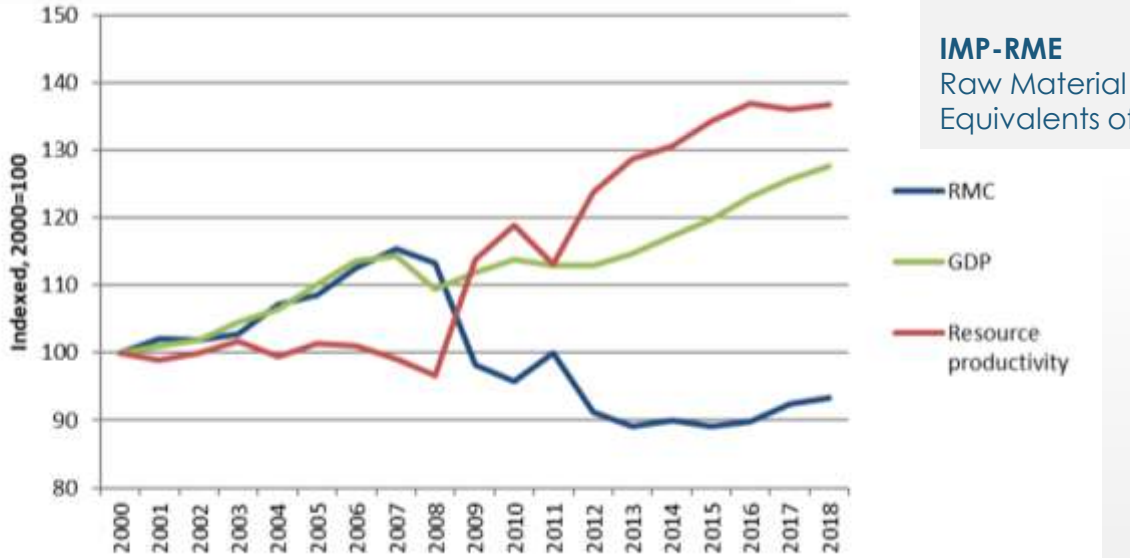
GDP vs Cu consumption per capita
for Japan (after Watari et al., 2018)



Aluminium consumption per capita

21 kg/pers Corea
9 kg/pers Belgium
2,4 kg/pers India

GDP and Raw Material Consumption in EU27



http://www.materialflows.net/decoupling-material-use-and-economic-performance/

RMC
Raw Materials Consumption

vs.

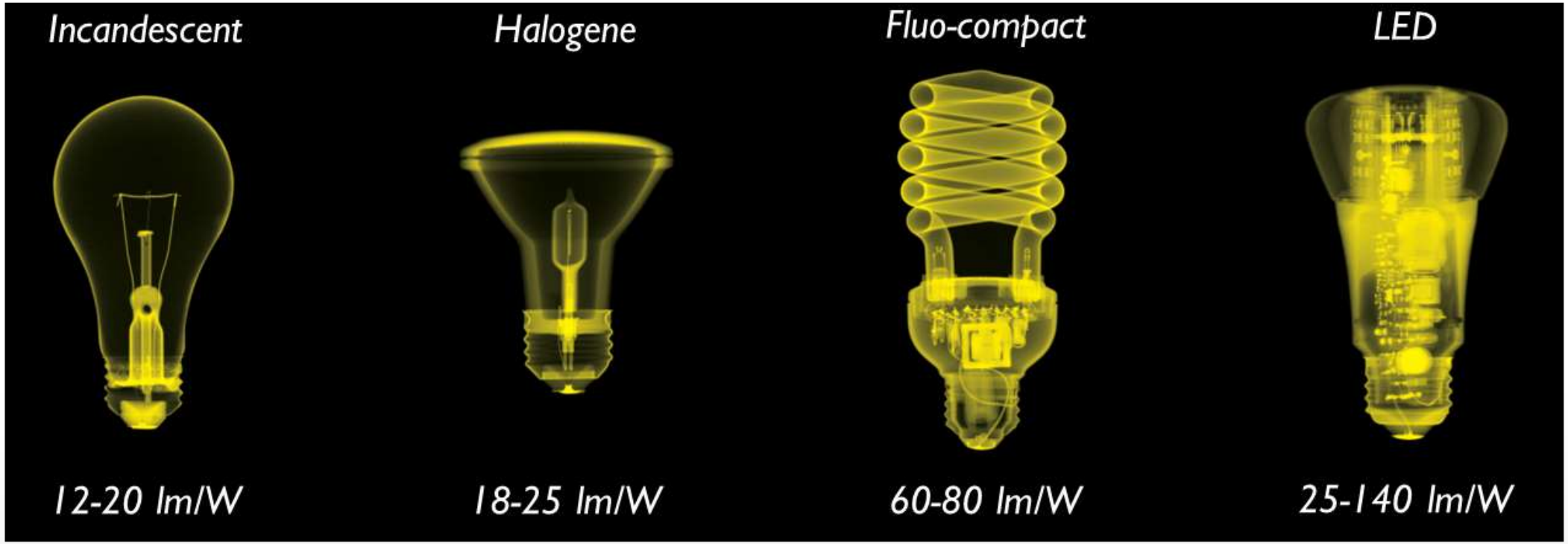
IMP-RME
Raw Material Equivalents of Imports

Dematerialisation?

Mini means 600kg in 1960

Mini SE means 1440 kg in 2023

Optimization through HYPERmaterialisation



Tungsten	Tungsten	Tungsten	Gallium
Glass,…	Iodine, Bromine, …	Mercury, Rare Earths,… Glass,	Indium, Cerium, Yttrium,
	Glass,…	Plastics,…	Copper, Silver, Silicium, …
			Plastics, …

We have optimized functionality (and lowered in-use GHG emissions) at the expense of resource extraction and recyclability

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Objective Earth!

Objective Earth!

- Spherical Economy

The art of administering an asset (a planet!) by prudent and wise management in order to obtain (for all and for future generations) the best return by using the least resources.

Atmosphere

Geosphere
Georesources

Biosphere
Bioresources

***NOT** a single reference to **metals** and minerals in the thousand pages on **Sustainable Development Goals (SDG)**!*

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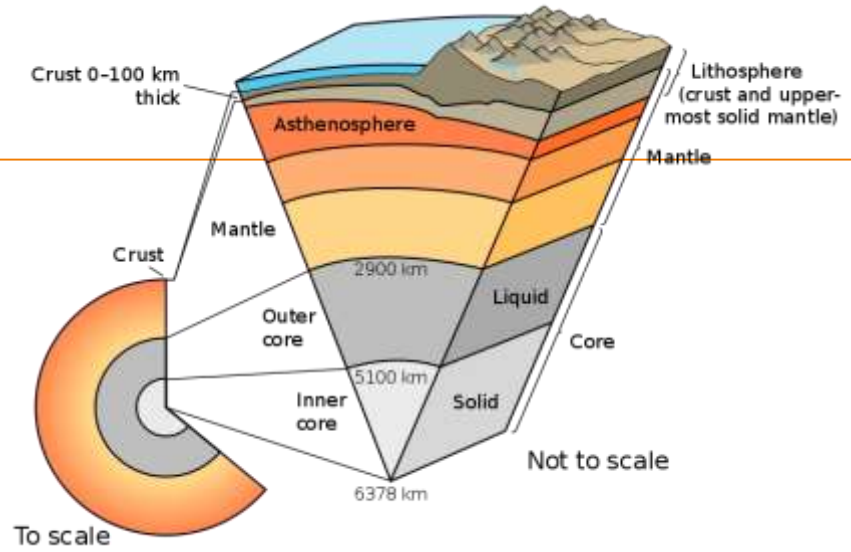
Objective Earth!

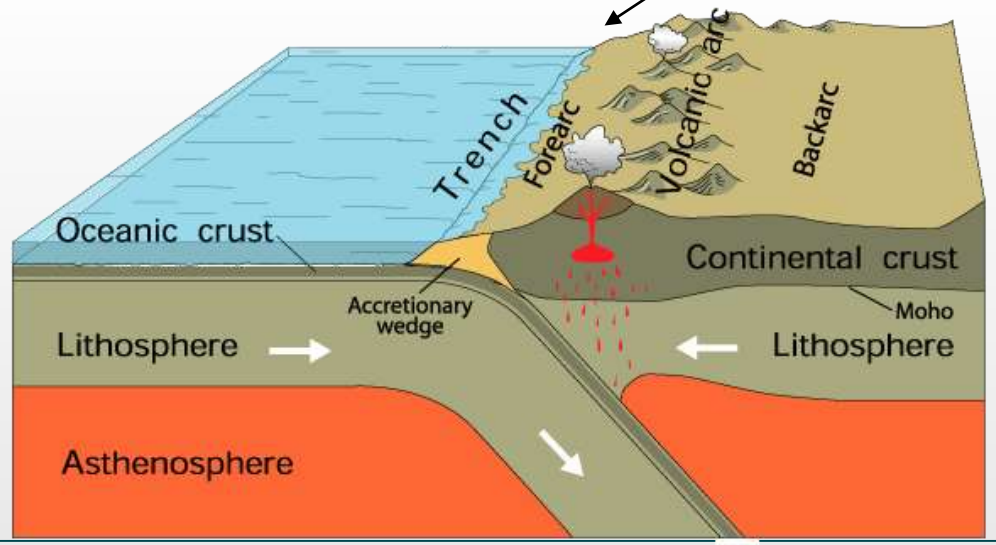
- Fossil Energy Resources
  - Petroleum, Gaz, Coal, Lignite,…
  - Uranium
    - *Non-renewable*
- Water Resources
    - *Vital, Purifiable*
- Industrial Minerals
  - Sand, aggregates, gypsum, …
  - Kaolin, talc, diatomea,…
  - Gems
    - *Non-recyclable, Synthetisable*
- Metallic Resources
  - Base Metals
  - Critical Metals ?
  - Precious Metals
    - *Recyclable*

Objective Earth!

- Geology of the earth
  - **Oceanic** Crust 300 Mkm² (60%)
    - Very well known (homogeneous, young)
    - Limited potential (nodules, crust) *Ni, Co, Cr, Cu…*
  - **Continental** Crust 210 Mkm² (40%)
    - Only superficially known (300m)
    - Hosts most metal deposits (strong diversity)



Active tectonic margin
Intense metal remobilisation and deposition



Newly formed oceanic crust
Ocean floor (- 5000m)

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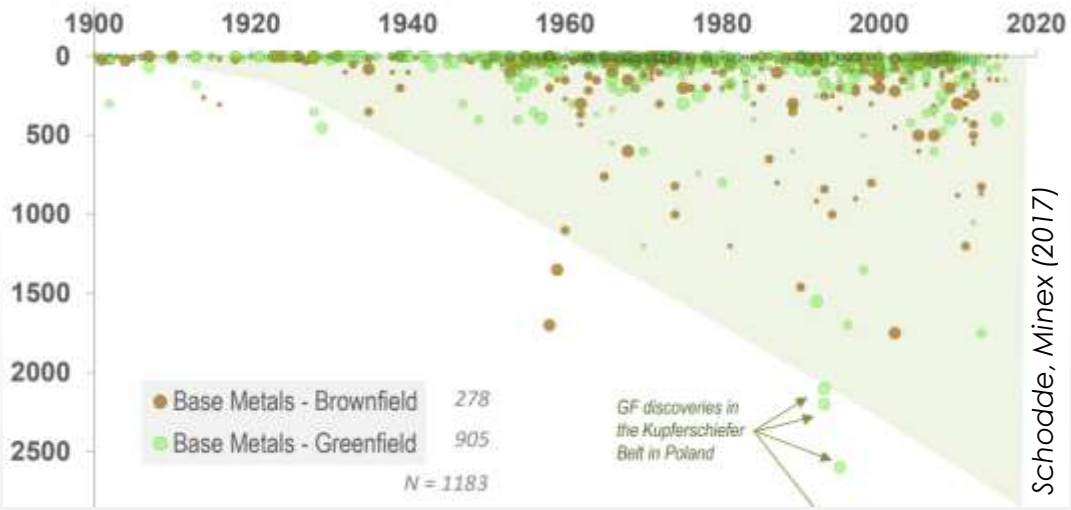
Objective Earth!

- Geology of the Earth is only superficially (2D) known
  - Unknown under heavy cover (vegetation, ice, sand,…)
  - Very limited deep exploration techniques (geophysics, drilling,…) (< 300 m)

Deposits discovered by laymen in Finland © GTK



Most deposits currently mined were discovered by laymen and are within the first 300 m of the crust

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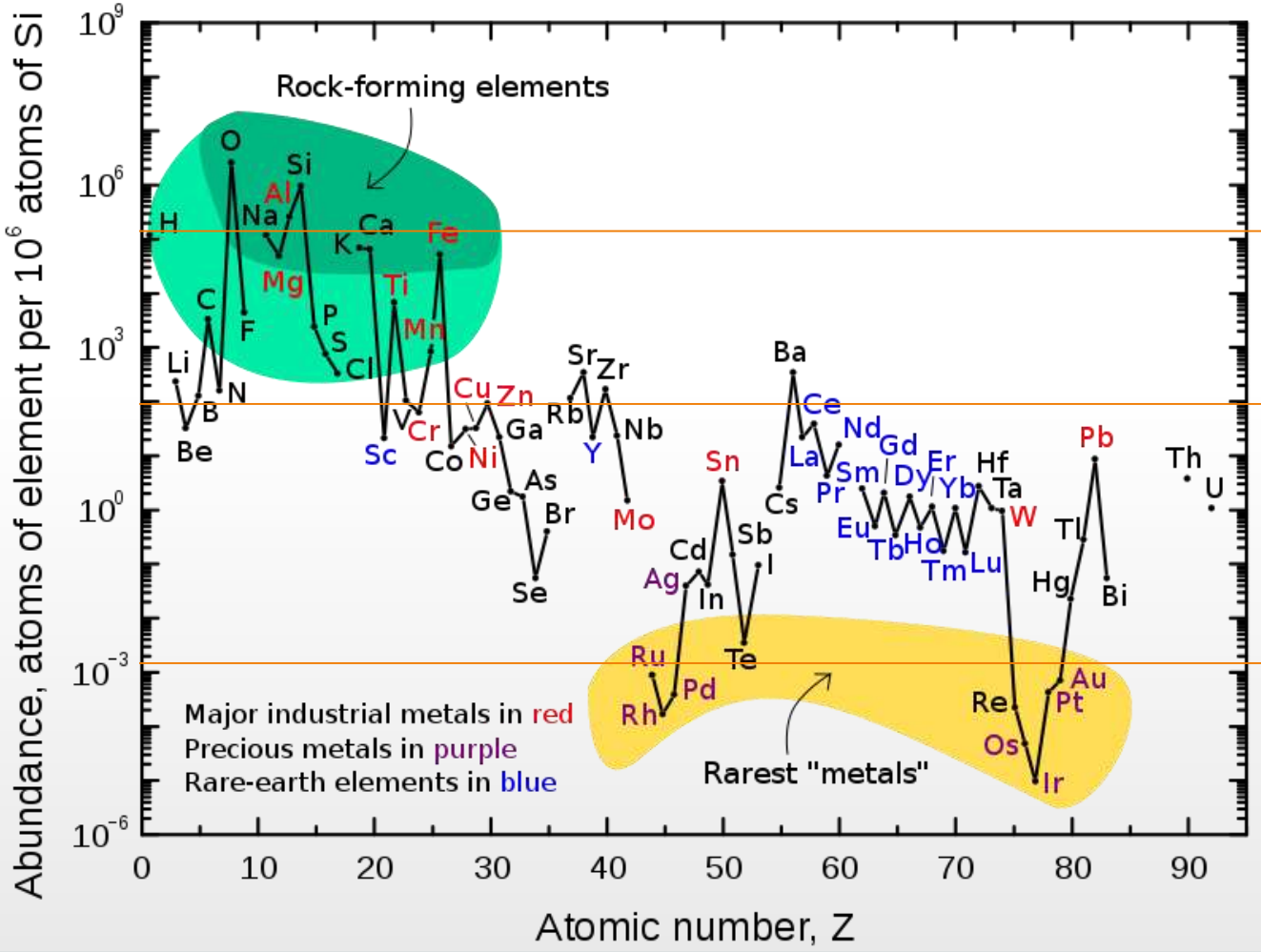
Objective Earth!

- Relative abundance of elements in the Upper Continental crust

Important to remember:

1 % = 10 000 ppm

1 ppm = 1000 ppb



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The science of reporting resources

From occurrence to reserve

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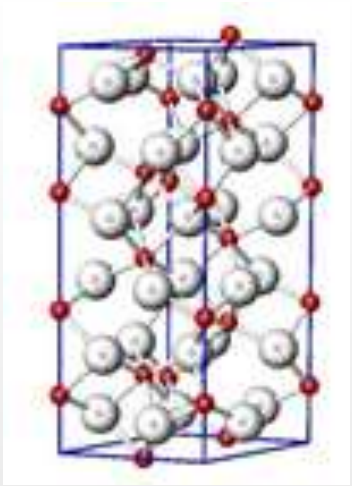
Mineral

- Definition

> *"…a mineral is an element or chemical compound that is normally crystalline and which has been formed as a result of geological processes…"*
>
> *Nickel, E. (1995) Definition of a mineral*
> *Commission for New Minerals and Mineral Names*

HEMATITE
Fe_2O_3
Its name makes reference to the blood (hema) red colour from its powder.



Fe_2O_3
Two (2) iron atoms (red) for three (3) oxygen atoms.
Notice the relative size of the atoms!

Rock

- A rock is a natural composite material.
- It is made up of an aggregate of grains which are most often of varying kinds (mineralogy).

http://lithotheque.ens-lyon.fr

LHERZOLITE

A common rock of the oceanic crust.

Ore

- Ore *(erts – minerai)*
  - An **ORE** is a rock that allows the industrial valorisation of its content in terms of economic profitability.
    - **DYNAMIC** notion which changes with regard to the value of metals, cost of energy, transportation, etc.

58 % Fe

5 % Zn

0,5 % Cu

0,0001 % Au

Ore = Valuable Minerals + Gangue (waste)

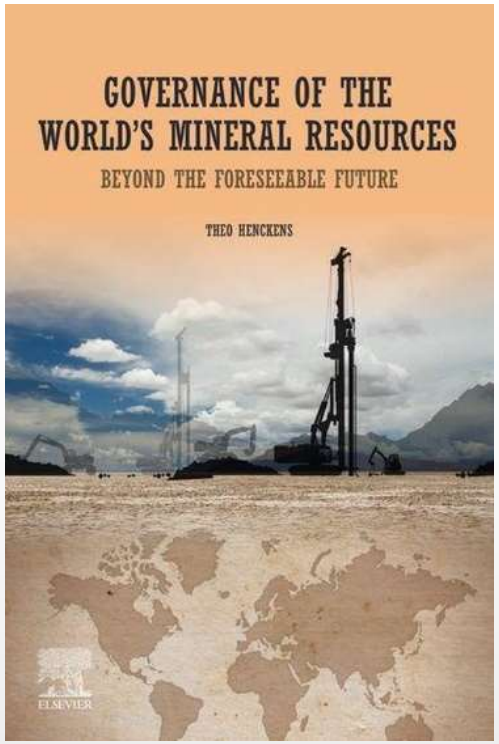
Deposit

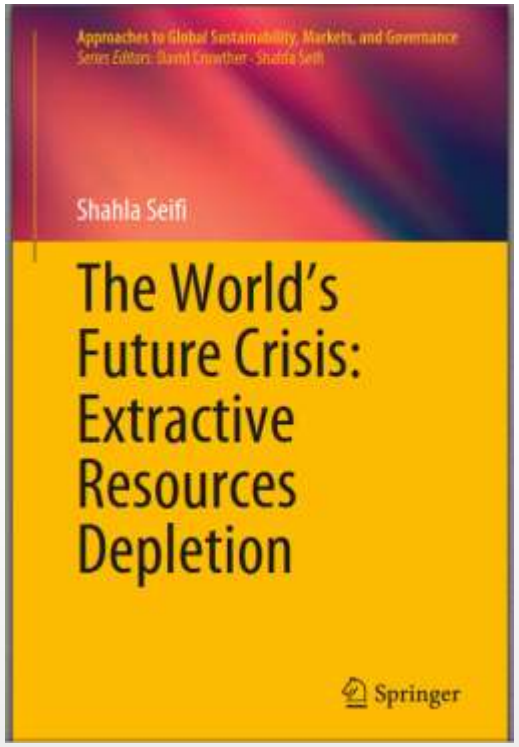
- A deposit is a geological site which contains a sufficient amount in quantity and quality of rocks (ores) for potential economic exploitation.

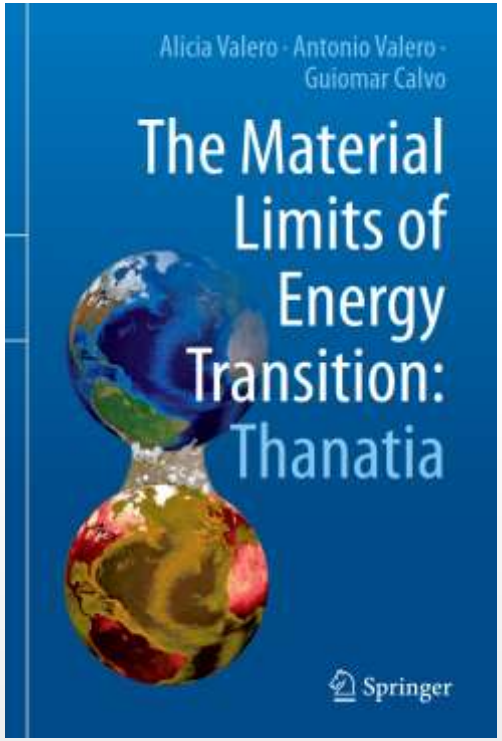
Greenbushes (W Australia)
Orebody (pegmatite) containing economic amounts of Lithium (1% Li) and Tantalum (Ta) as by-product

The science of reporting resources

- Abundance of alarming messages about resource depletion
  - … written (mostly) by non-geologists!?

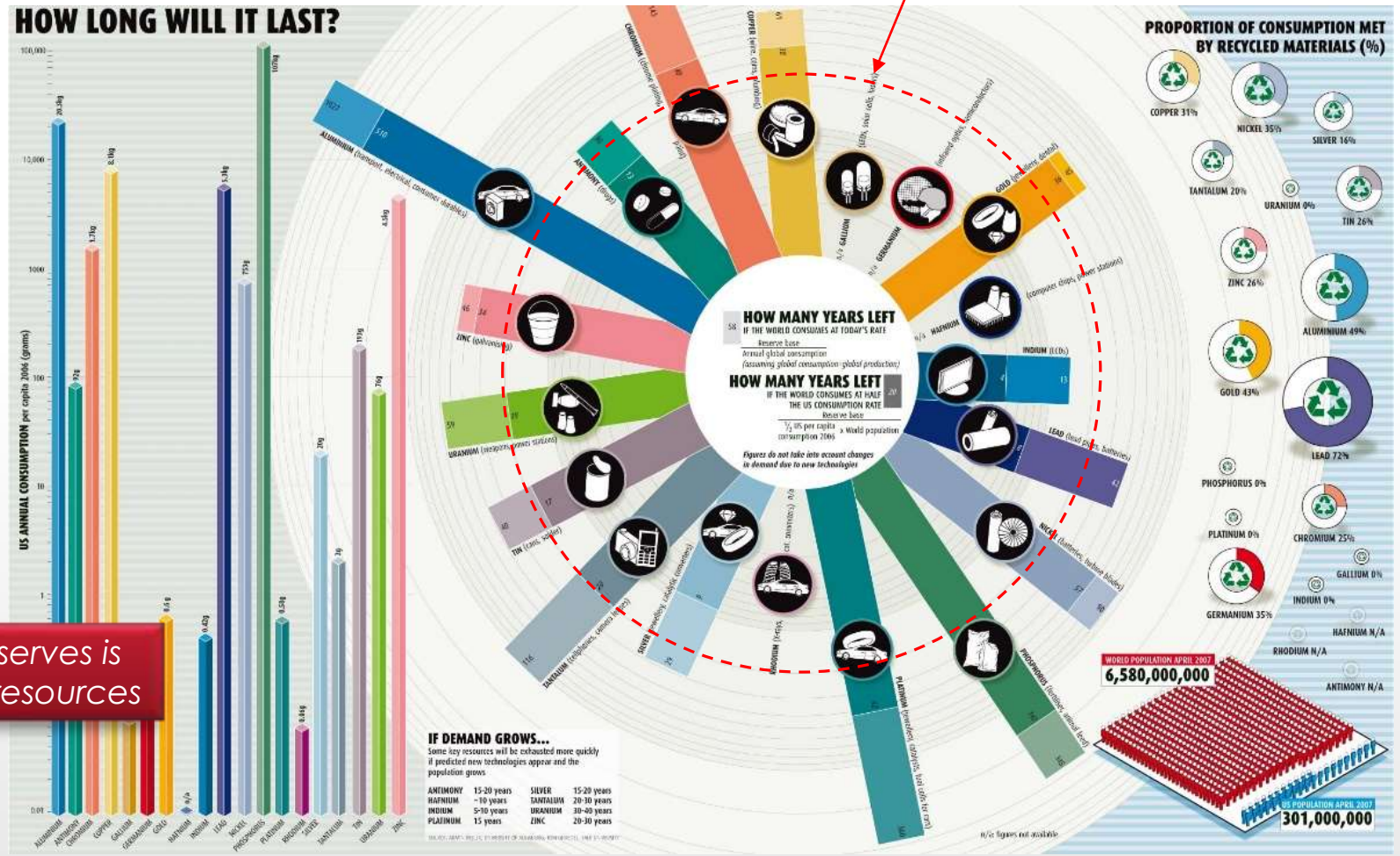






The science of reporting resources

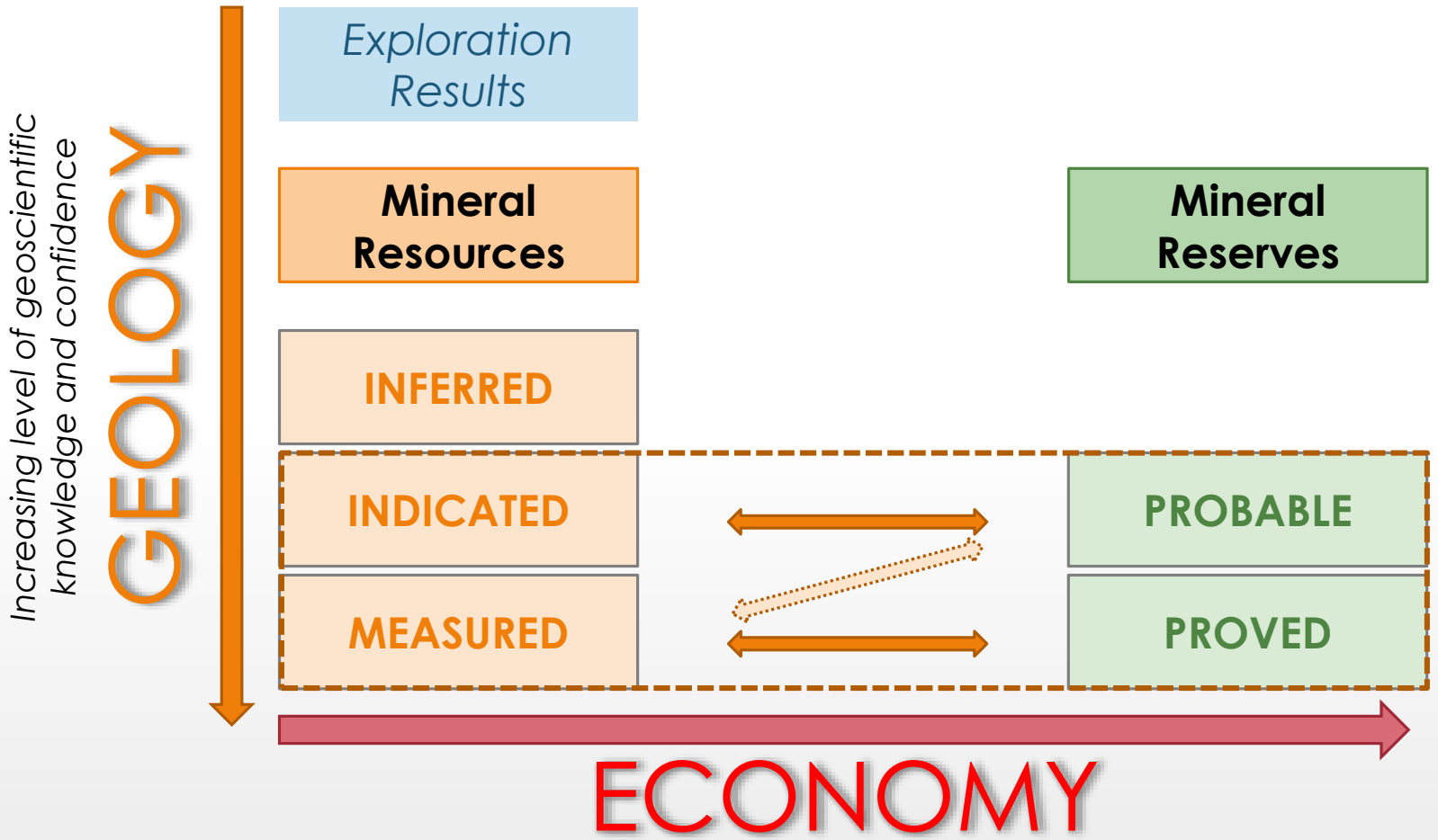
- Poor understanding of resource dynamics



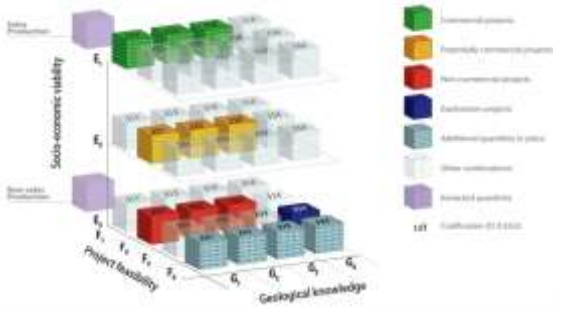
Annual production vs. world reserves is not a good metric of available resources

A. Reller & T. Graedel, 2007

The science of reporting resources



UNFC
UN Framework Classification for Fossil Energy and Mineral Reserves and Resources



CRIRSCO
Committee for Mineral Reserves International Reporting Standards

Consideration of mining, metallurgical, economic, market, legal, environmental, social, governemental … factors

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The science of reporting resources

- Static vision of mineral reserves
  - With different consumption growth scenarios

Commodity	Reserves 1999	Annual Production 2000	Lifetime +5% Scenario
Zinc	190 Mt	7,75 Mt	16 yrs
Aluminium	25 Gt	123 Mt	48 yrs
Indium	?? t	200 t	?? Yrs
Nickel	46 Mt	1,1 Mt	22 yrs
Tin	8 Mt	207 kt	21 yrs

*After « **Breaking New Ground** »*
Report of the Mining, Minerals & Sustainable Development Project
Int. Institute for Environment and Development (IIED), 2002

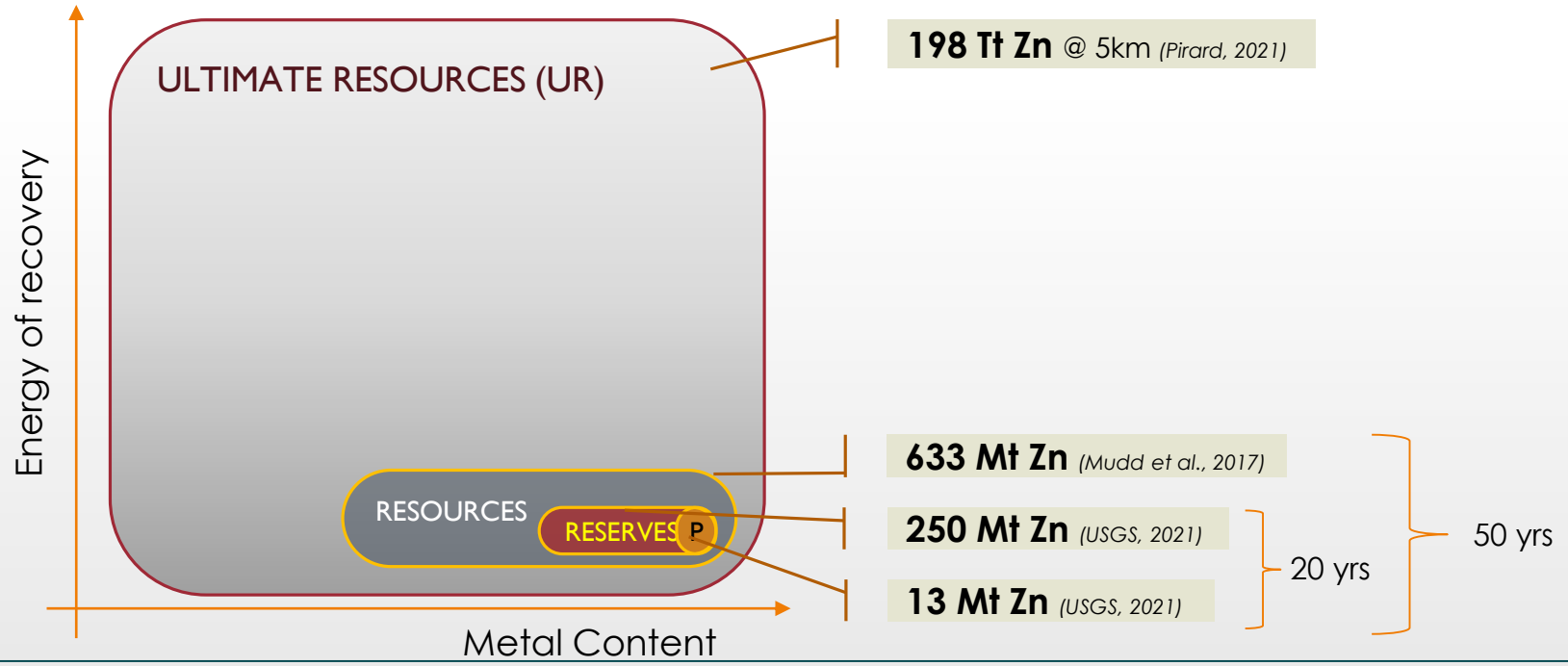
Zinc in 2021

250 Mt (world reserves)
13 Mt (world annual production)

… another 19 years left!

The science of reporting resources

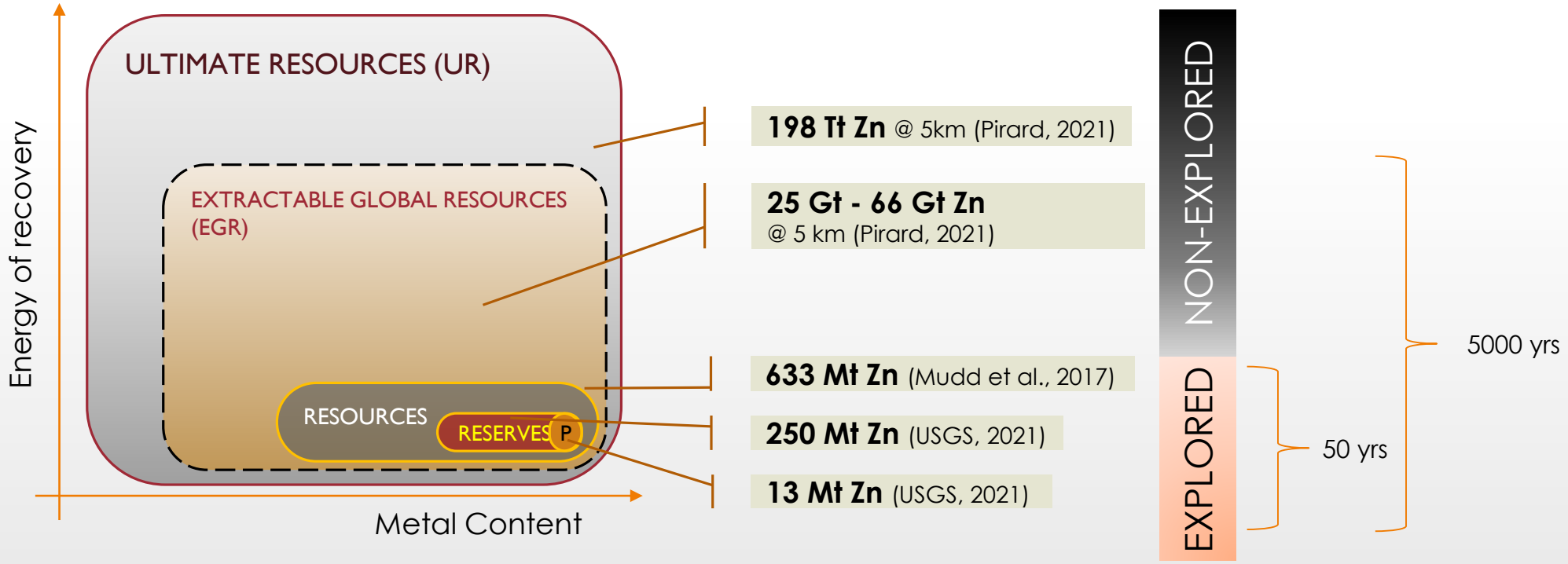
- **ULTIMATE RESOURCES (UR)**
  - Total tonnage of metal <u>available</u> in the <u>mineable</u> part of the crust (5 km)
- **RESOURCES**
  - Total amount of ore reported by exploration geologists with ≠ levels of confidence (inferred, indicated, measured).
- **RESERVES**
  - Subset of resources which have undergone a full feasibility study.
- **PRODUCTION**



The science of reporting resources

- Extractable Global Resources (EGR)
  - Very long term perspective
  - Relying on technical innovation (robotics, deep exploration tools, …)
  - Based on US discovery factors
    - US-type exploration coverage (1/3 world)

***Thousands of years left** for mining similar deposits at similar grades (but greater depth)*



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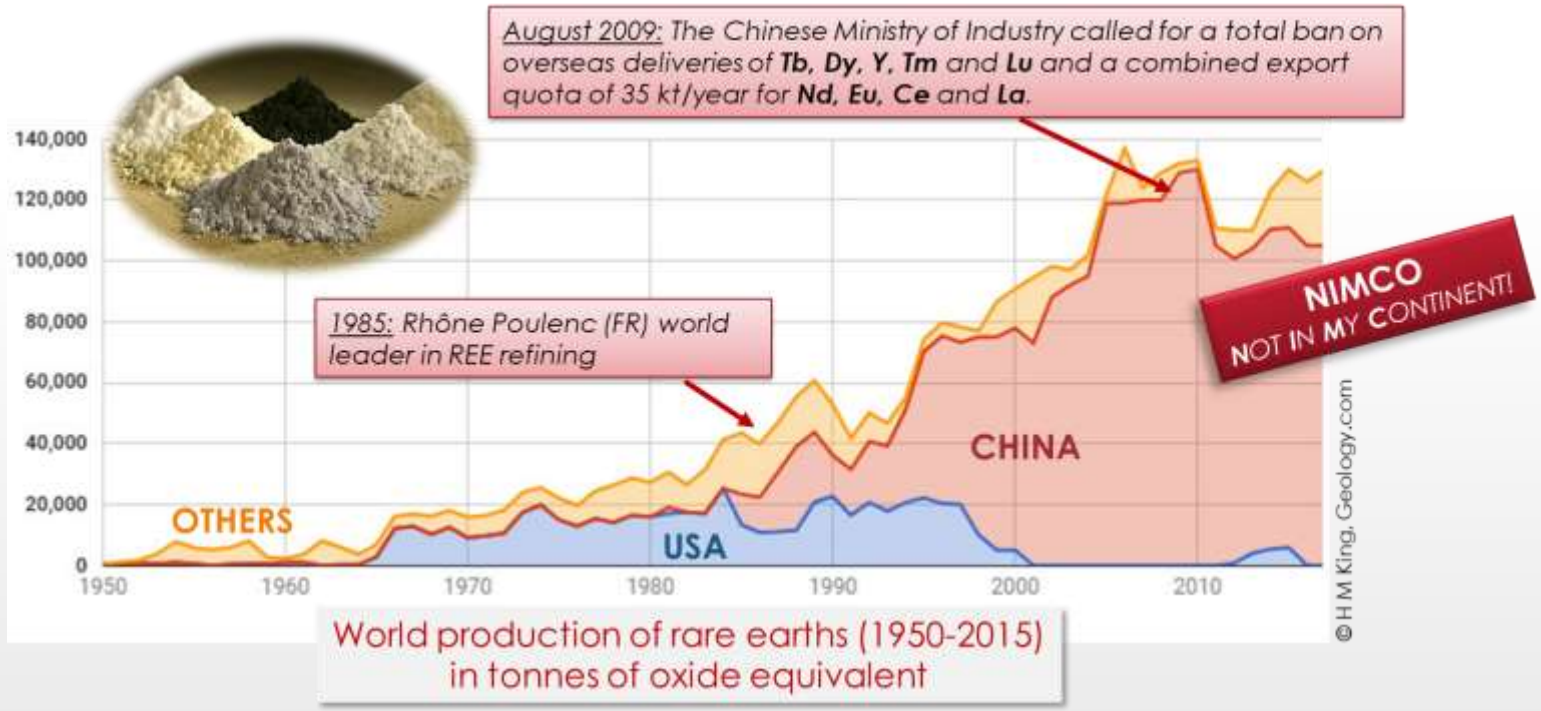
Why metals suddenly became critical?

Time to Act

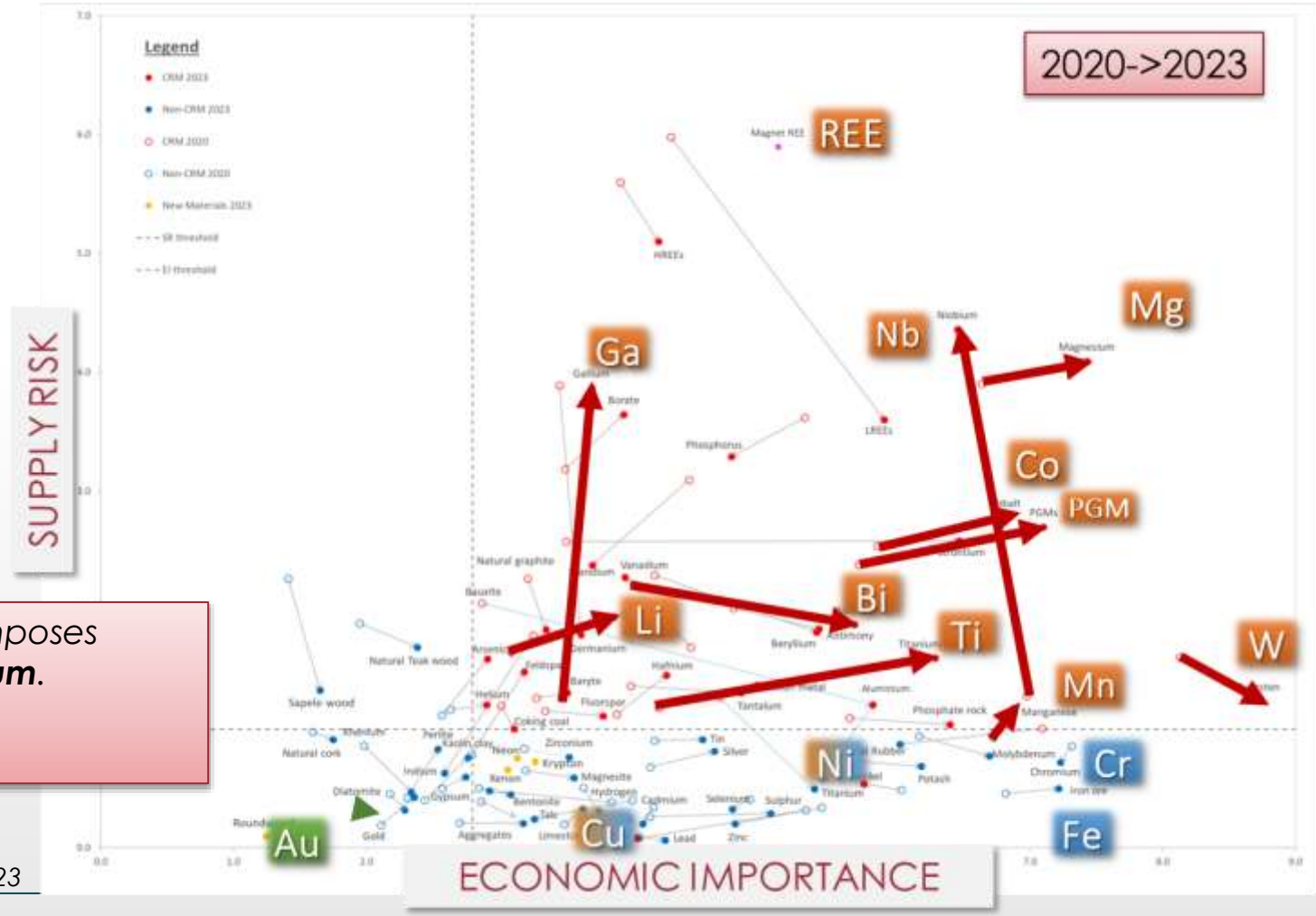
Why metals suddenly became critical?

- Criticality is a geopolitical question
  - **NIMCO** - *NOT IN MY CONTINENT*
  - China's monopoly on Rare Earth mining and processing is exactly what we wanted…
  - 1985
    - **US** is a significant player in mining
    - **FR** has unique know-how in refining
  - 2000 – today
    - Mining is in **China**
    - Processing is in **China**



Why metals suddenly became critical?

- 30+ critical and strategic elements for the EU in 2023 … and counting
  - Supply risk
    - concentration within a few hands
  - Economic importance
    - limited diversity of uses



Aug 2023: *The Chinese Ministry of Industry imposes export restrictions on* ***Gallium*** *and* ***Germanium****.*

Dec 2023: *… adding high-grade* ***Graphite****.*

after JRC, 2023

Why metals suddenly became critical?

- So what ?
  - Critical Raw Materials **ACT** (Effective May 23rd 2024)
    - Recycling and Mining = **REINDUSTRIALISATION**

SETTING 2030 BENCHMARKS FOR STRATEGIC RAW MATERIALS

EU EXTRACTION

At least **10%** of the EU's annual consumption for extraction

EU PROCESSING

At least **40%** of the EU's annual consumption for processing

EU RECYCLING

25%

At least **15%** of the EU's annual consumption for recycling

EXTERNAL SOURCES

Not more than **65%** of the EU's annual consumption of **each strategic raw material at any relevant stage of processing** from a single third country

Brownfields in EU

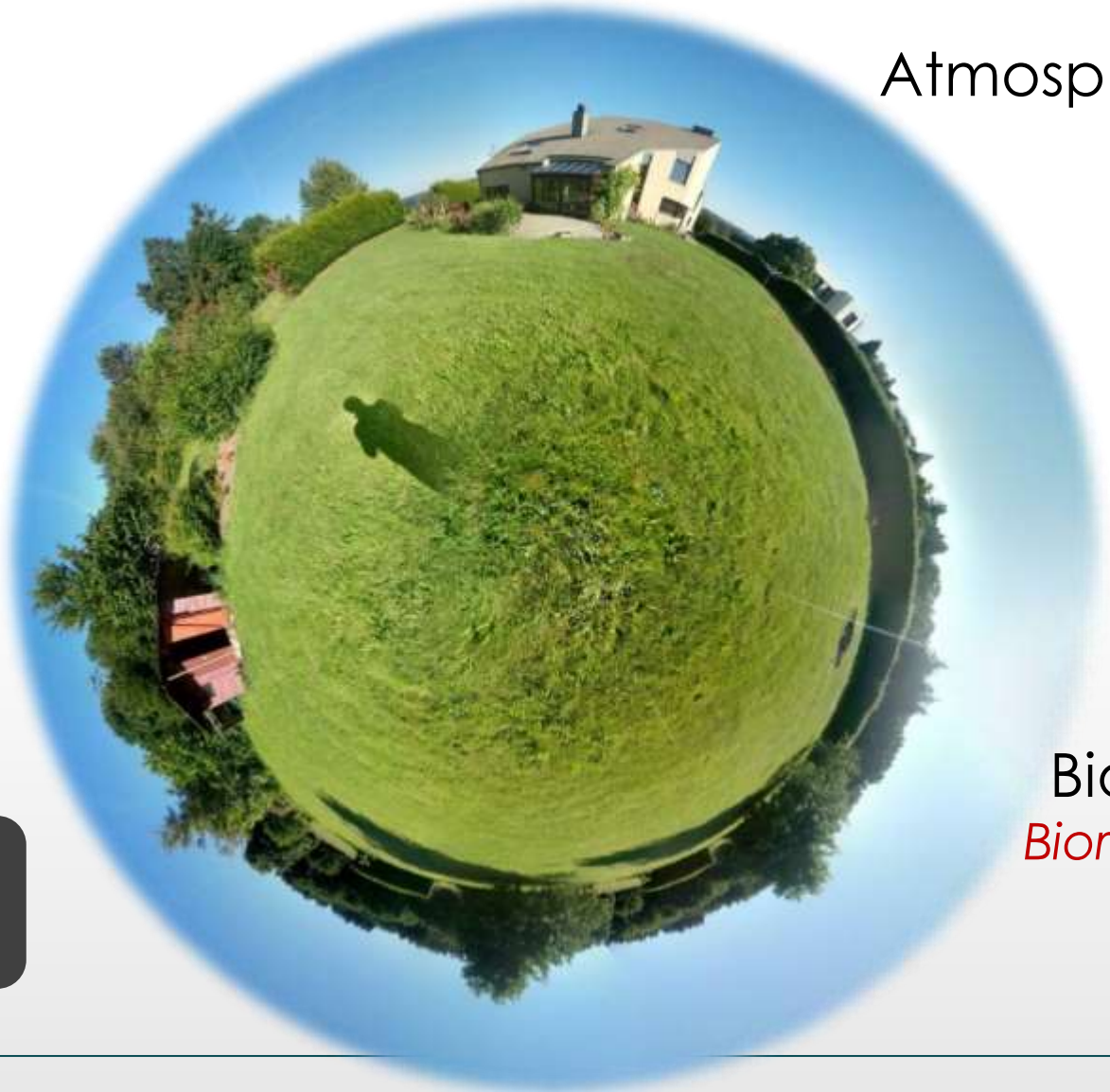
Unique opportunity for a ***circular reindustrialisation***

Sustainable Resource Availability

Think Circular

Spherical Economy

- The art of administering an asset (a planet!) by prudent and wise management in order to obtain (for all and for future generations) the best return by using the least resources



Atmosphere

Geosphere
Georesources

If you can't grow it…
you'll have to dig it!

Biosphere
Bioreesources

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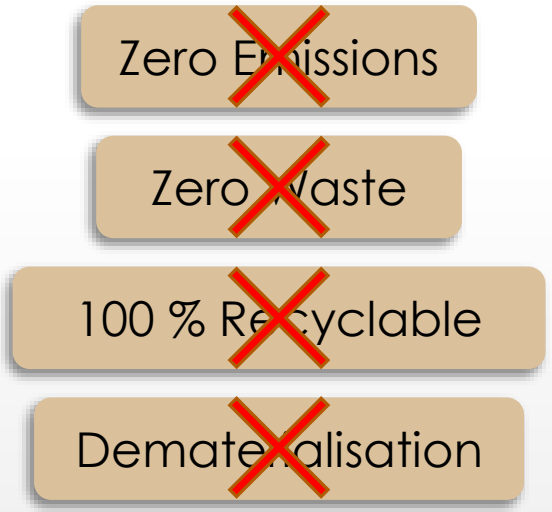
There is no Circular Economy (yet!)

- Stimulating paradigm to rethink the entire lifecycle
  - Biomimicry, Geomimicry



Source:
P. Huovila, Buildings as Materials Banks (BAMB – H2020)

There is no Circular Economy (yet!)

- Developing a holistic vision

  - (Re)thinking the life cycle
    - "Material stewardship »
    - Sustainable availability of materials
  - Encouraging industrial symbiosis
    - Re-industrialisation
    - Short circuits
  - Measuring Circularity
    - Indicators

There is no Circular Economy (yet!)

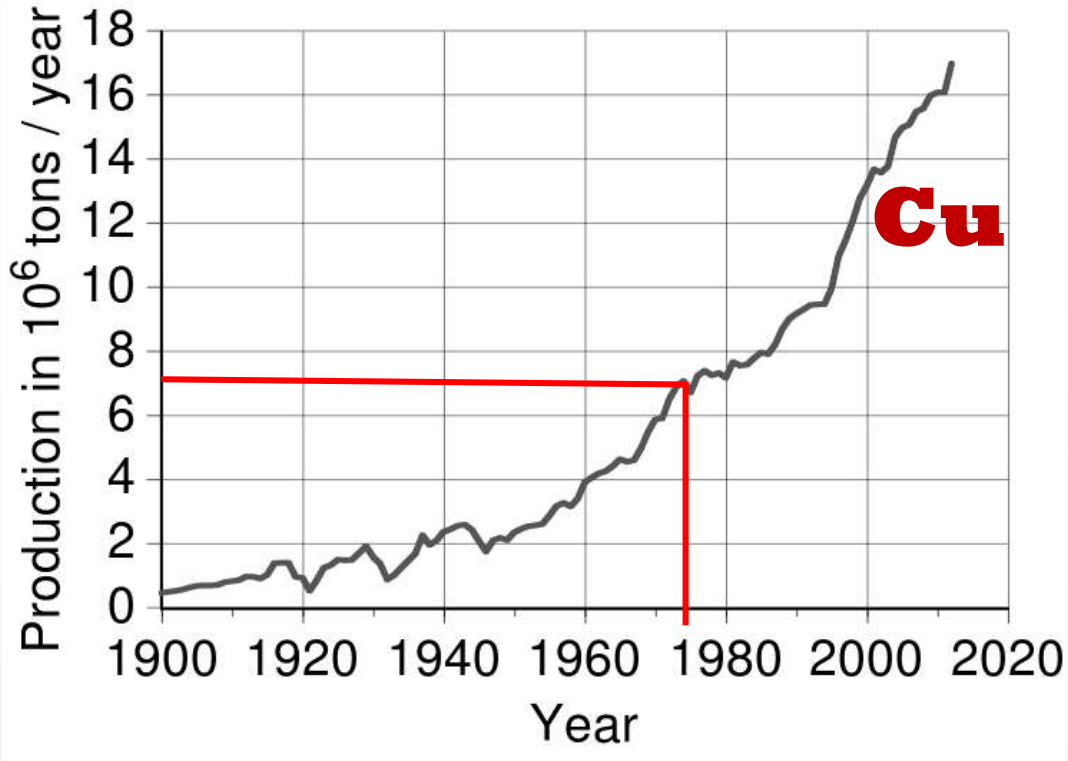
- The 4 challenges of a more circular economy

Four Challenges

For a more circular economy

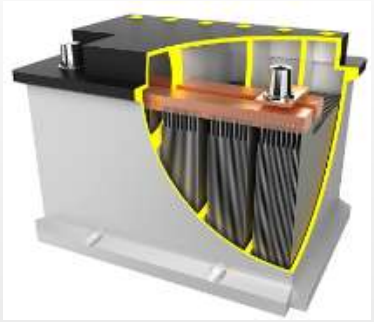
Challenge n°1 : FEED the loop

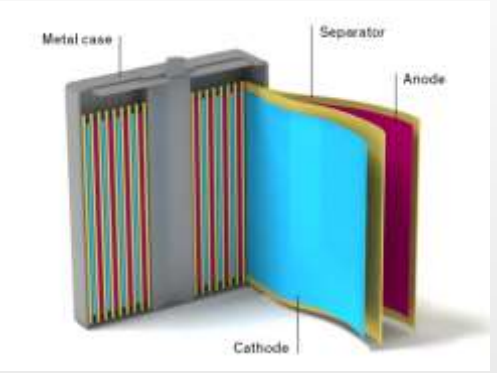
- Recycling does not suffice to satisfy growing needs
- The future is mining!



Challenge n°2 : DESIGN the loop

- Recent technologies have made significant progress in terms of functionality
  - … but a highly questionable progress in terms of RESOURCE USE and RECYCLABILITY





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Challenge n°3 : SLOW DOWN the loop

- Lifetime of most products is much too short
  - Consumer education
  - Sharing economy

Challenge n°4 : CLOSE the loop

- The urban mine
  - Revival of metallurgical know how
  - Reindustrialisation (short circuits)

  - Educate engineers!

Spiral economy
dissipation !

$81\%^{3} = 53\ \%$

WEEE sculpture (Eden Project, UK)

The art of exploiting urban mines

Closing the Loop

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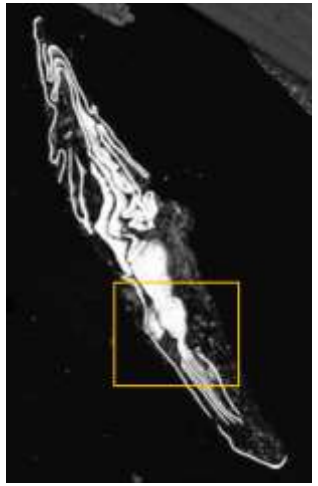
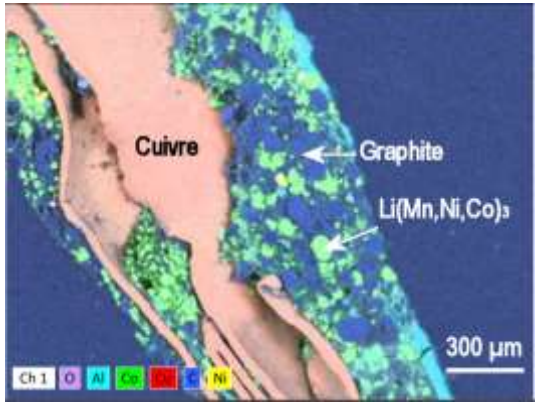
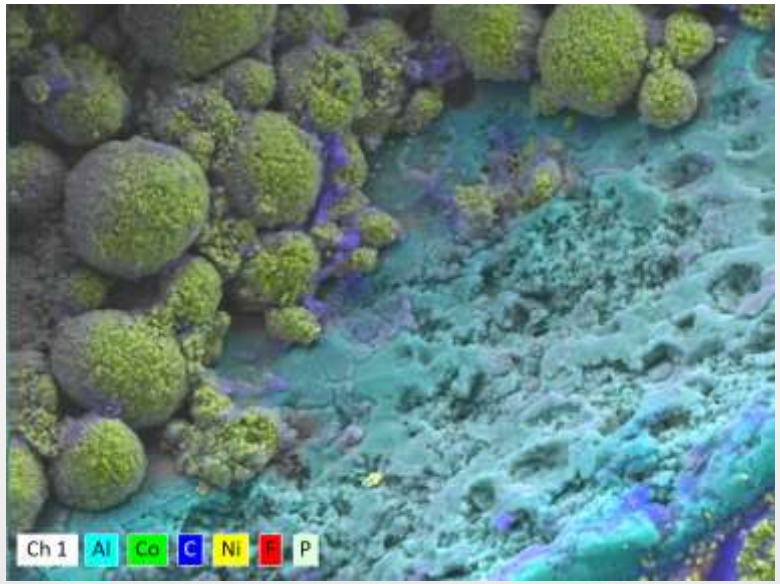
The art of exploiting urban mines

- Dismantling of e-scooter
- Electrodynamic fragmentation of Li-ion batteries
  - Black mass binder (PVDF); Adhesion to Cathode;…







The art of exploiting urban mines

- Dismantling and Shredding of end-of-life hybrid plug-in vehicles
  - 7 000 CV (5 cars/min)

The art of exploiting urban mines

- Pre-Processing

Technical sand

Plastic

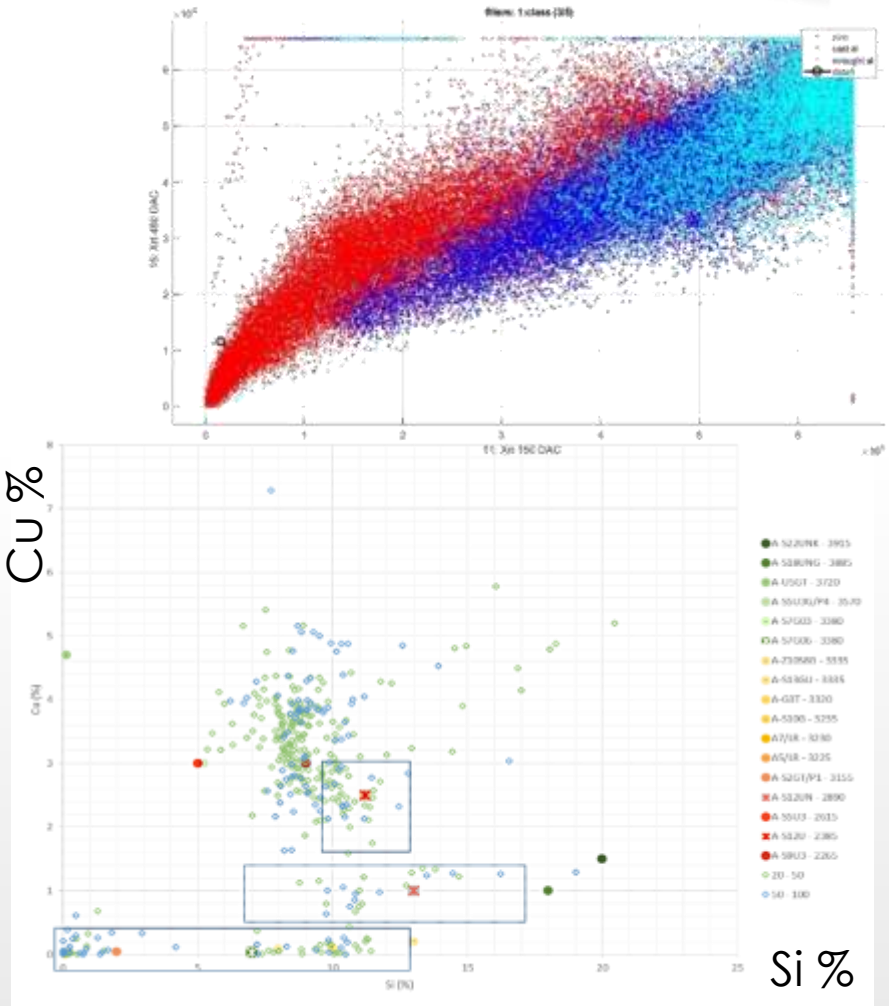
Ferrous

Non-Ferrous Scraps

PICK-IT Smart Sorting of Al-Alloys

- Real-time identification of scraps (10^9 pcs/yr)
  - Multiple **sensing** (3D, VNIR, XRT, LIBS,…)
  - **Deep learning** algorithms
- Functional recycling (6 t/h)
  - Grouping specific alloys into **multiple bins**
  - Delta **robots**

Transportable sorting plant – 5 robots



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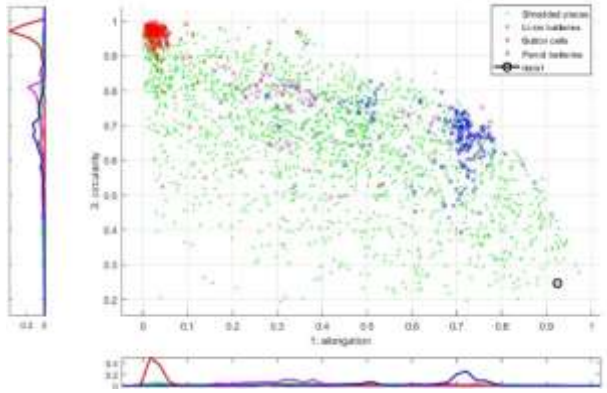
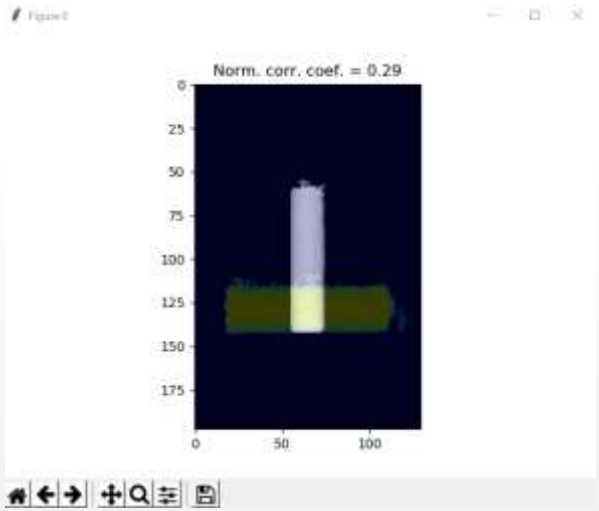
PICK-IT Smart Sorting of Batteries

- Real-time sorting of batteries recovered from shredded WEEE
  - Using shape descriptors: low precision in concentrate
  - Using template matching: acceptable results, but room for improvement





	Masse (Kg)	Pourcentages	
Déchets	6.87		
Piles dans déchets	0.215	**3.0%**	**% piles éch. dans déchets**
Concentré piles	6.46	**91.1%**	**% piles éch. dans concentré**
Déchets dans concentré	0.41	**6.0%**	**pollution du concentré**
Déchets dans: trier à la main	1.54	**5.9%**	**% piles éch. dans classe 4**
Piles dans: trier à la main	0.415		
Total masse échantillon	15.91		

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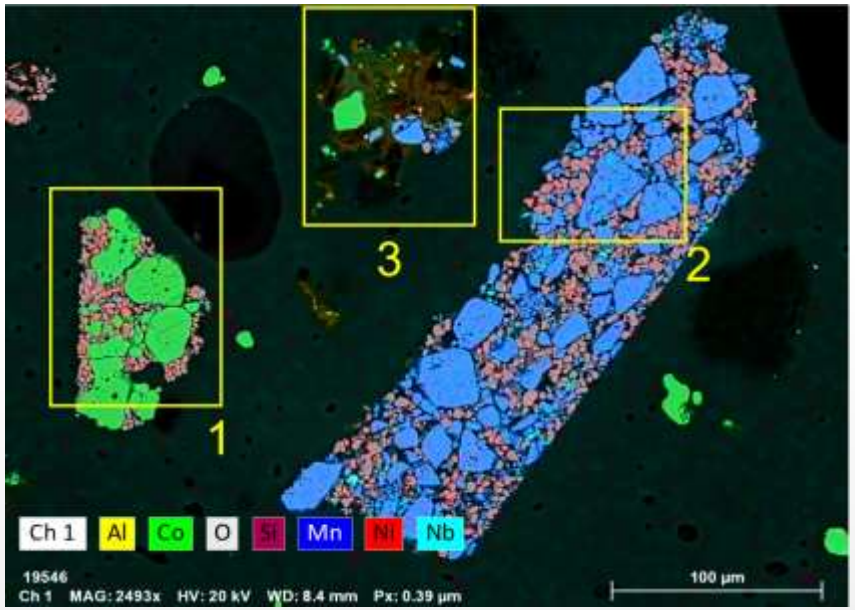
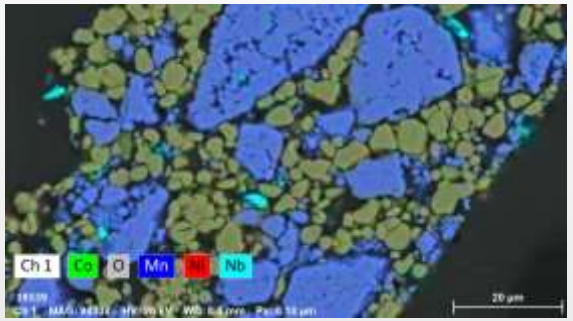
- Exploring metal deportment in WEEE
  - Phase mapping using SEM-EDX automated microscopy



Exploring the Black Mass in LIBs



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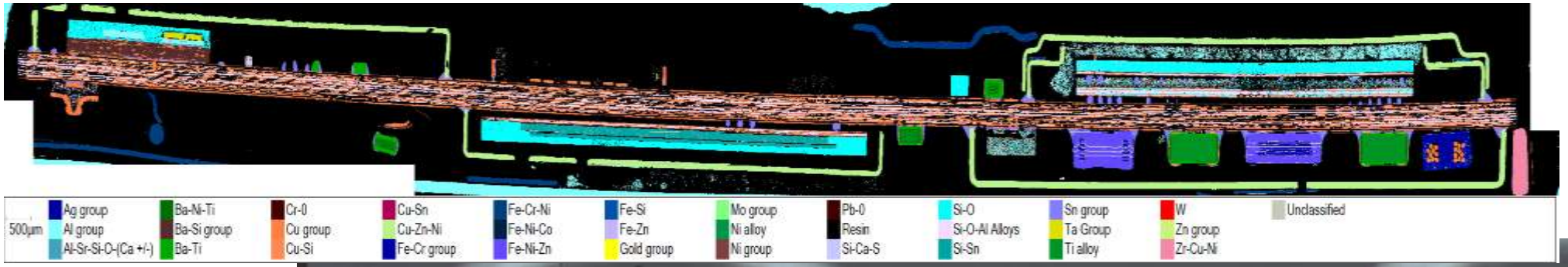
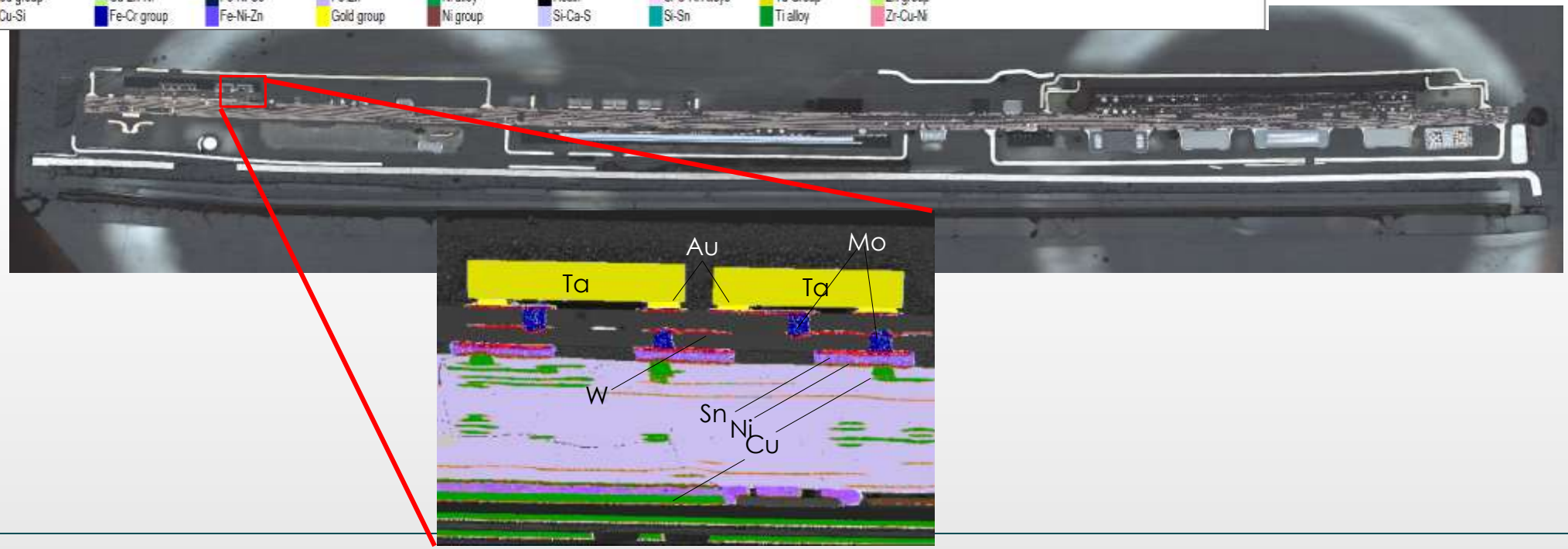
- Exploring metal deportment in Smartphones





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- Recovering copper by dissolution of complex copper-bearing phases

Hydrometallurgical pilot facilities @ULiege

BIOLIX

Leaching, solvent extraction and electrolysis to obtain a 99,98% Cu cathode @ULiege

3D model of the solvent extraction facility

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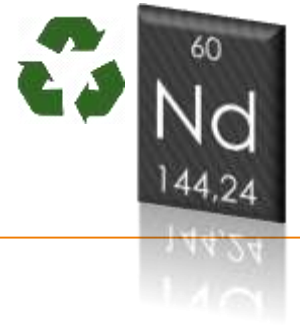
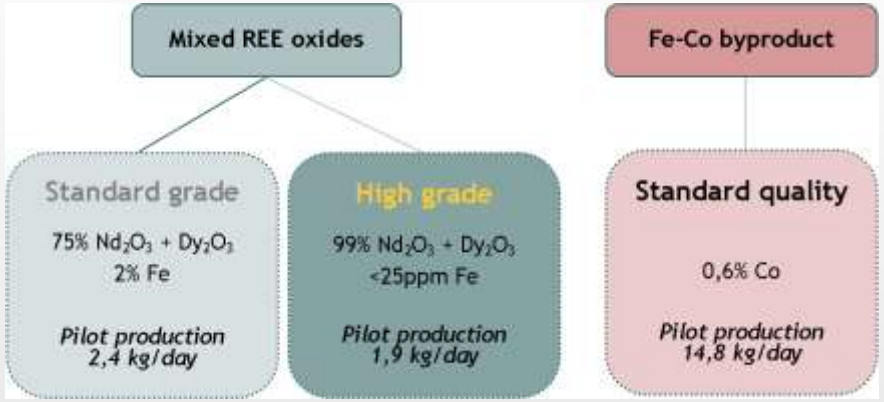


- Manual dismantling of supermagnets
  - 1,2 kg of REE in the rotor segments of the electrical engine

Manual dismantling and recovery of NdFeB magnets after thermal demagnetization

REEFINE

- Extractive metallurgy of Nd
  - 4 stage low T° (< 80°)
  - 95 % recovery
  - Mixed REO & Fe-Co byproduct



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WEEE sculpture (Eden Project, UK)

A Circular Economy Finally ?

Still a long way to go

A Circular Economy Finally ?

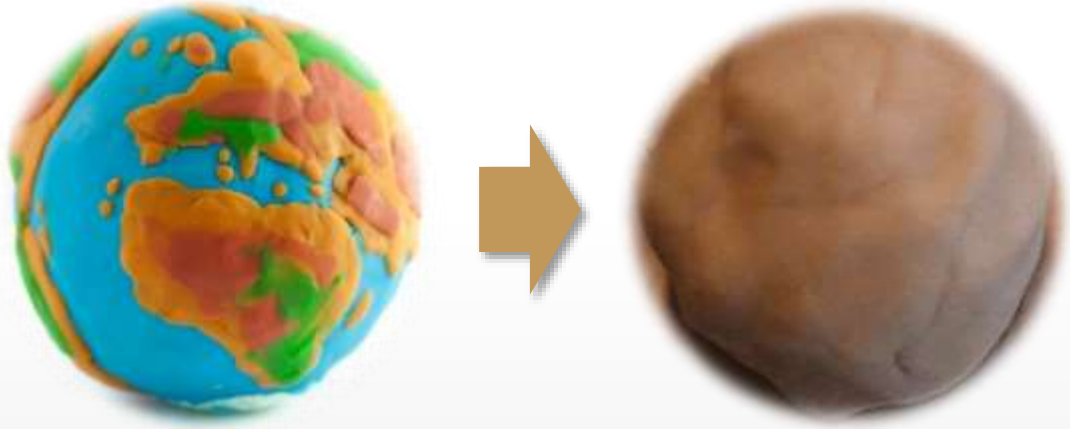
- Tonnage
  - Limited physical dispersion - Capacity to transport and collect back

- Grade
  - Privilege massive materials vs. composites. Limit dispersive use (filler, coating, …).

- Metal deportment
  - Stable and mature technologies. Identification for sorting/grouping
- Liberation
  - Limit electronics, sensors, nano-microassemblages. Facilitate dismantling. Removable binders

Anthropy or Entropy

- Let's join forces to postpone the end!



What is **critical** is not so much the long-term availability of raw materials as the short-term **use** we make of it!