LIÈGE université

GeMMe Resourceful Engineers

Metal Resources Indicators in LCA

from depletion of the geosphere
to recoverability from the anthroposphere

Eric PIRARD

Sandra BELBOOM

LIÈGE université

GeMMe

Géoressources, Génie Minéral & Recyclage

EMERALD
ERASMUS MUNDUS MASTER IN GEORESOURCES ENGINEERING

eit RawMaterials
Connecting matters

GeMMe operates on the characterization, beneficiation, transformation, use and recycling of mineral materials at any stage of their life cycle.

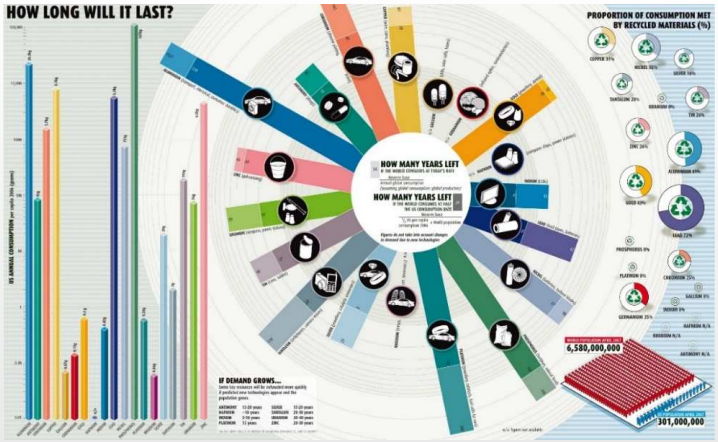
LIÈGE université

Metals : An « Area of Protection » ?

- UNEP - Report of the International Resource Panel (Oberle et al., 2019)

Extraction processes contribute 50% to the global carbon emissions and even 80% to biodiversity losses

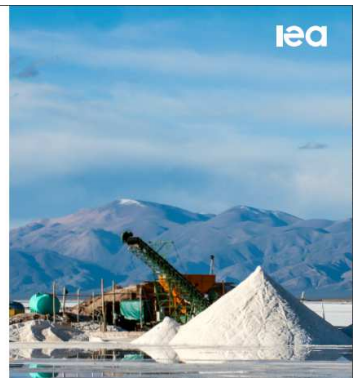
- How long will it last?
  - A. Reller & T. Graedel, 2007



LIÈGE université

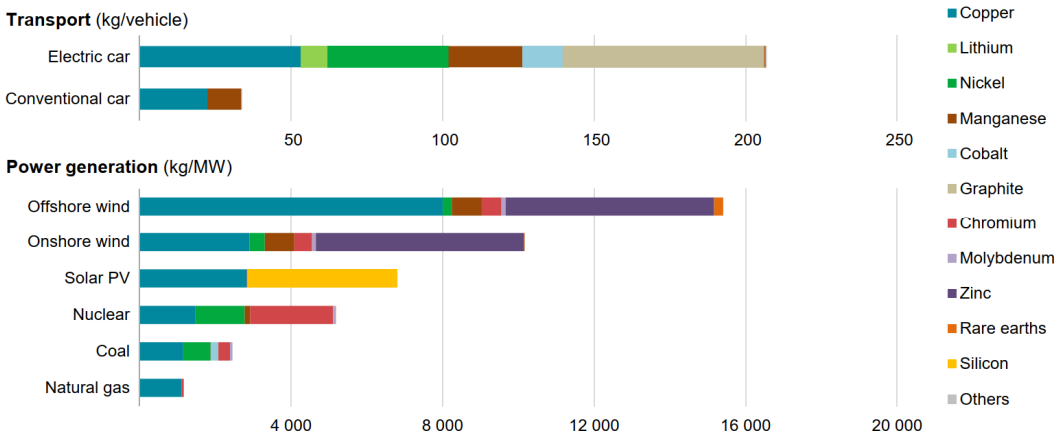
Green Deal : A bright future for metals

The Role of Critical Minerals in Clean Energy Transitions

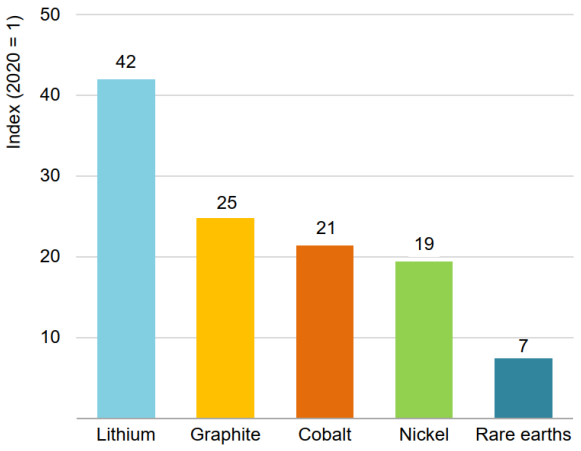


World Energy Outlook Special Report

Minerals used in selected clean energy technologies



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



LIÈGE université

Metal Resources

Limited Horizons

Impact Assessment of Metal Depletion

- Abiotic Depletion Potential (ADP)
  - ✓ Guinée and Heijungs, 1995

  - P_i : world **annual production** of element i (kg/yr)
    - Well documented (USGS, BGS,…)

  - R_i : estimated **ultimate global reserve** of element i (kg)
    - Based on USGS Reserve Base (discontinued in 2010)

  - Normalized to a **reference** commodity
    - Antimony (Sb) was taken arbitrarily

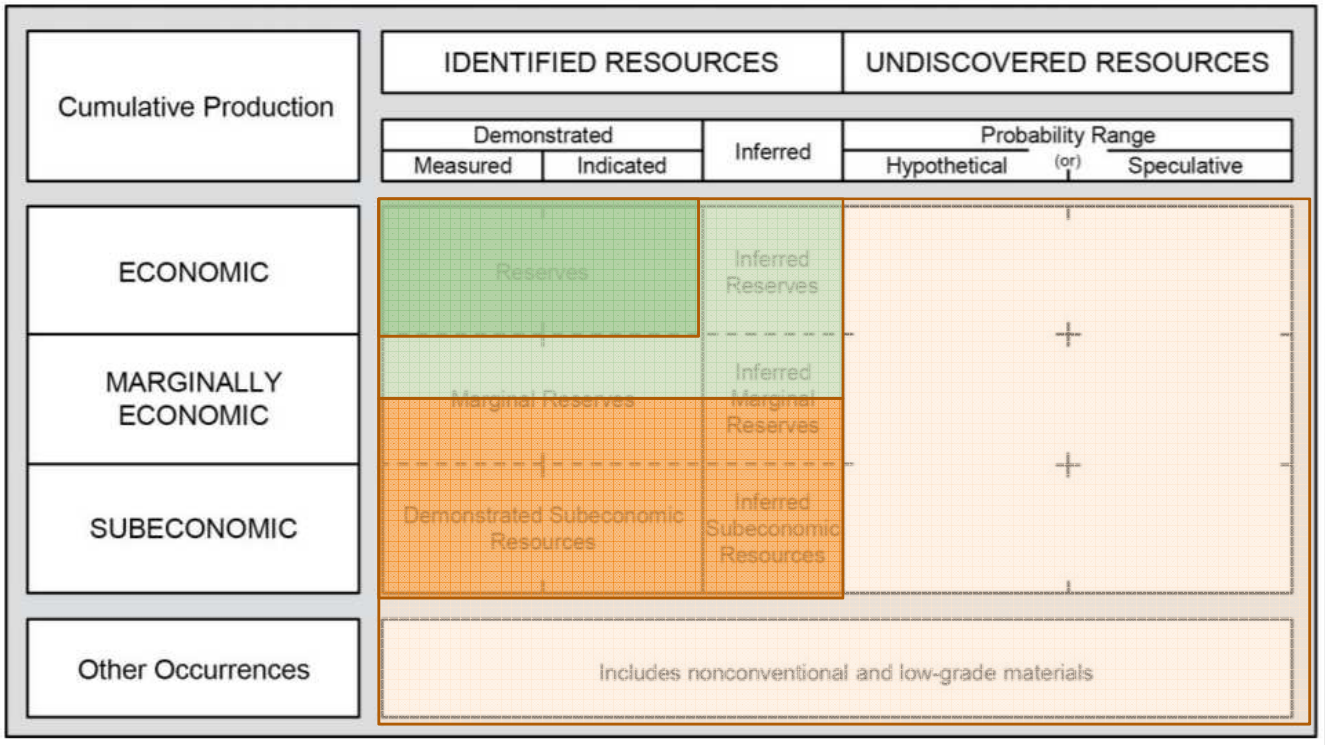
$$ADP_i = \frac{\frac{P_i}{R_i^2}}{\frac{P_{ref}}{R_{ref}^2}} = \frac{P_i R_{ref}^2}{R_i^2 P_{ref}}$$

Van Oers and Guinée (2016) : *Reserve estimates are relatively certain as they are based on present practice, but they are also highly unstable and continuously change over time*

Van Oers et al. (2020) : *Abiotic resource depletion potentials (ADPs) for elements revisited (update of extraction rates and five year average)*

Impact Assessment of Metal Depletion

- Reserves & Resources (UN, CRIRSCO, JORC, 43-101,...)

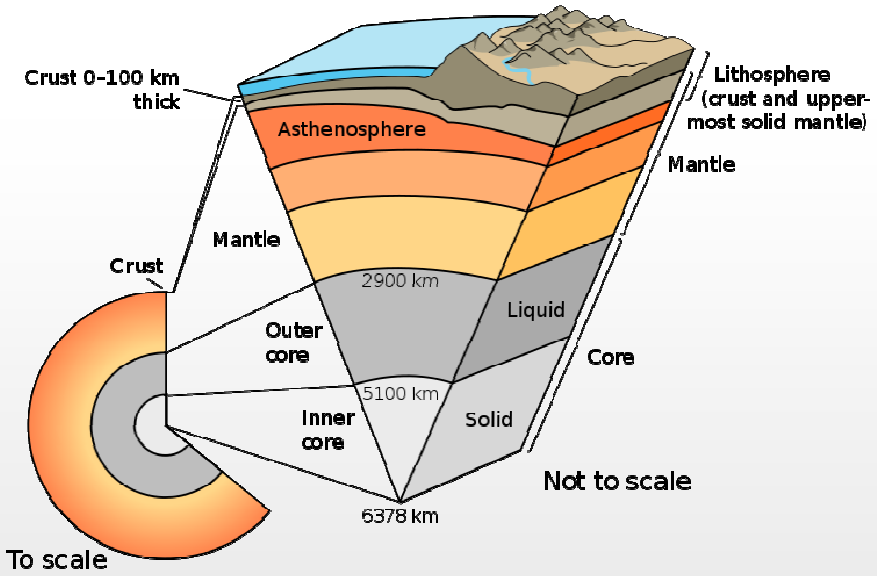


Impact Assessment of Metal Depletion

- Ultimate Resources (ULTR)
  - Estimate based on crustal content

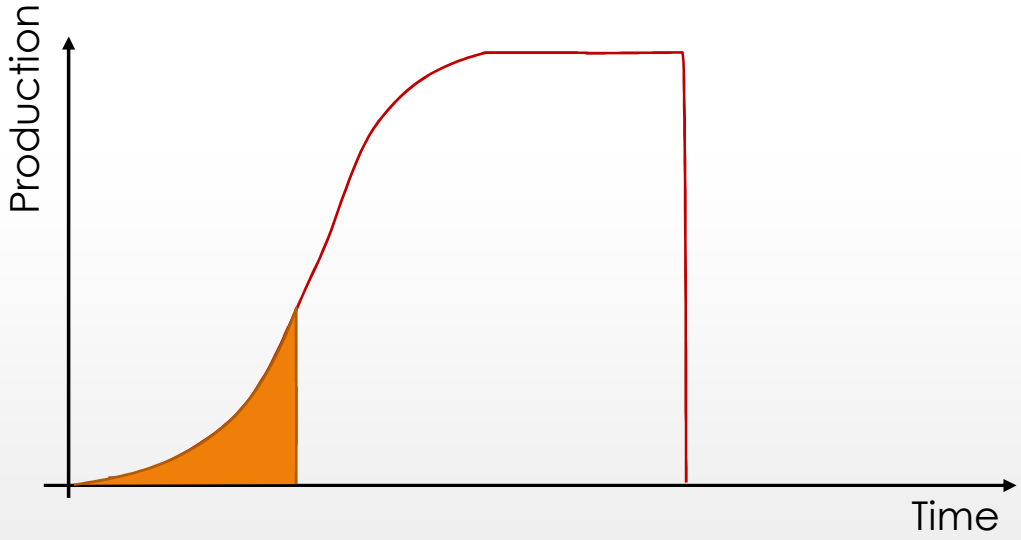
  - Geochemical background
    - 70 ppm Zn
  - How deep?
    - 1 km ? (UNEP, 2011)
    - 3 km ?
    - 15 km (450° C)
  - Metal in continental crust only
    - 596 exagrams of Zn (15 km)
    - 596 000 000 Mt Zn
    - **596 Tt Zn**

Van Oers et al. (2020) : *crustal content gives a better and more robust indicator of what the Earth offers us than a technology and market-dependent metric.*



Impact Assessment of Metal Depletion

- How long can we crunch the apple?
  - Fixed stock paradigm



Impact Assessment of Metal Depletion

- Top 20 elements contributing to ADP
  - Van Oers et al., 2020

  - 72,4 % to … gold!
    - Most useless and less critical element!

  - 7,9% to … copper!
    - Re, Mo and Te are typical by-products
      Windfall effect!

Element	Share in category total for 2015 (in %)
Gold	72.4
Copper	7.9
Silver	3.8
Palladium	3.5
Platinum	3.3
Antimony	2.1
Lead	1.4
Cadmium	1.1
Rhenium	1.1
Molybdenum	0.8
Zinc	0.6
Boron	0.4
Tin	0.3
Sulfur	0.3
Chromium	0.2
Tellurium	0.2
Bismuth	0.1
Ruthenium	0.1
Mercury	0.1
Phosphorus	< 0.05

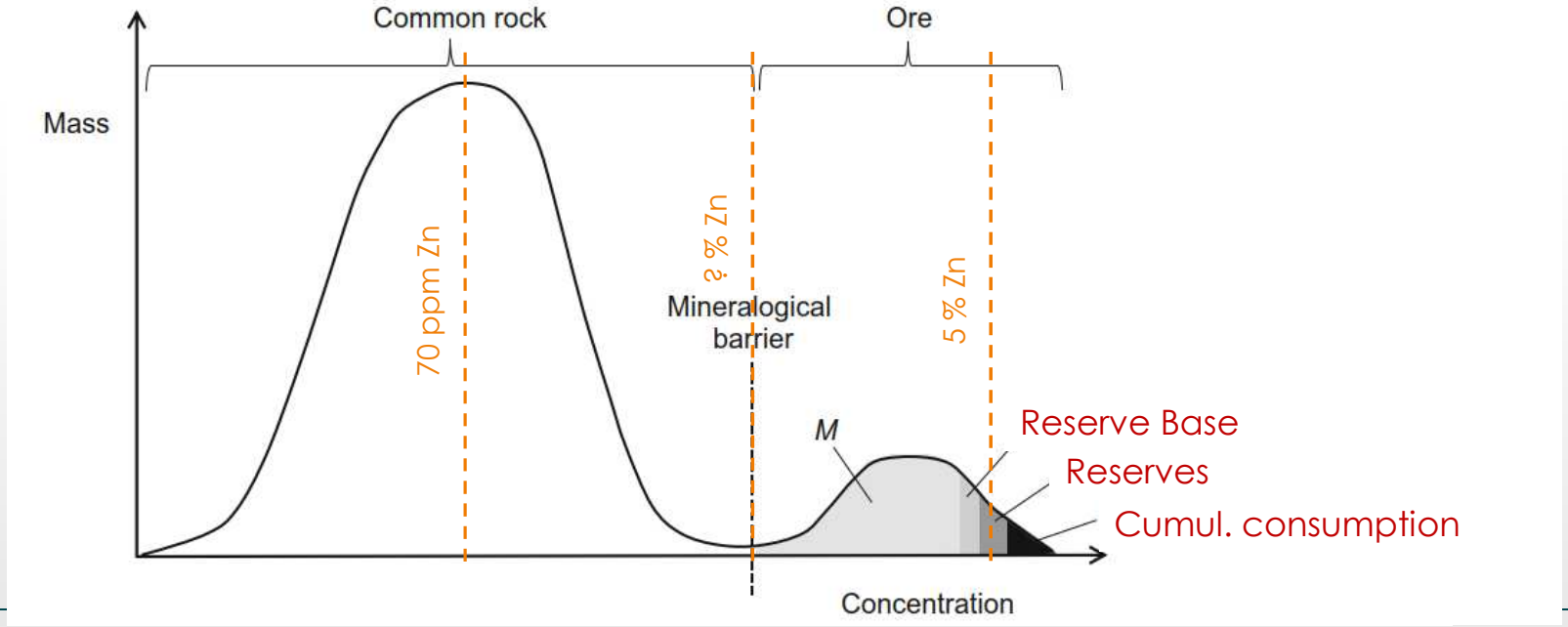
Extractable Global Resources

Mineralogical Barriers

LIÈGE université

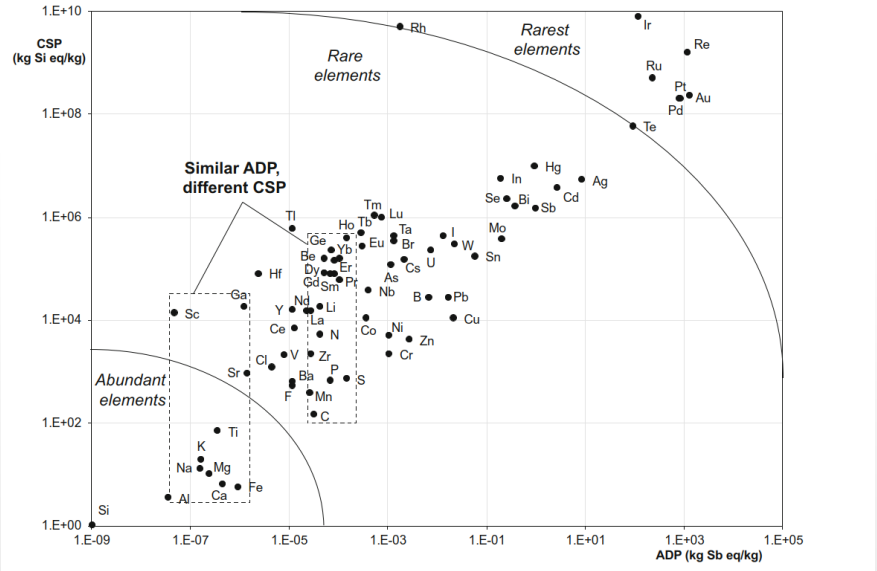
Extractable Global Resources

- What fraction of ultimate resources is extractable (mineable) ?
  - Possible existence of a thermodynamic limit
    - « mineralogical barrier »
  - UNEP(2011) sets Extractable Global Resource EGR to 0,01% ULTR



Extractable Global Resources

- Use of EGR in LCIA
  - Arvidsson et al. 2020, A crustal scarcity indicator for long-term global elemental resource assessment in LCA
  - Normalize to Silicon
  - Consider Crustal Scarcity Potential (CSP) with EGR being proportional to ULTR



Int J Life Cycle Assess (2020) 25:1805–1817

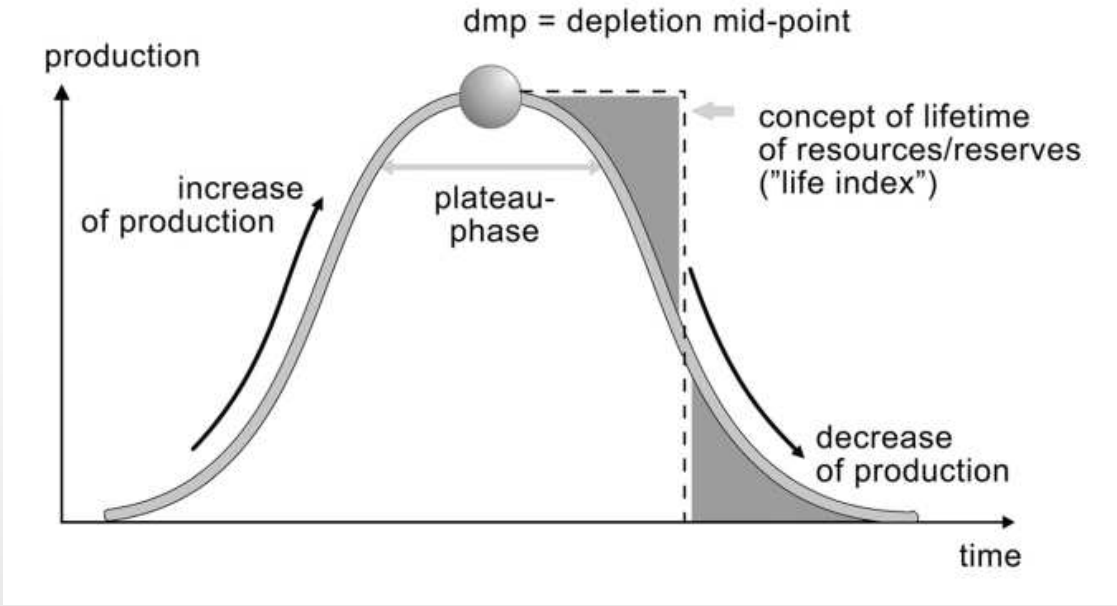
Element	CSP (kg Si eq/kg)	Element	CSP (kg Si eq/kg)	Element	CSP (kg Si eq/kg)	Element	CSP (kg Si eq/kg)
Ir	7,600,000,000	Tb	470,000	Th	51,000	Cr	2100
Os	6,900,000,000	I	400,000	Nb	35,000	Zr	2100
Rh	4,700,000,000	Ta	400,000	B	26,000	V	2000
Re	1,500,000,000	Ho	370,000	Pb	26,000	Cl	1200
Ru	470,000,000	Mo	350,000	Ge	22,000	Sr	880
Au	220,000,000	Br	320,000	Ga	18,000	S	700
Pd	190,000,000	W	280,000	Li	18,000	P	650
Pt	190,000,000	Eu	260,000	Y	15,000	Ba	620
Te	57,000,000	U	220,000	La	14,000	F	510
Hg	9,400,000	Sn	170,000	Nd	14,000	Mn	370
In	5,400,000	Be	150,000	Sc	13,000	C	140
Ag	5,100,000	Yb	150,000	Co	11,000	Ti	67
Cd	3,500,000	Cs	140,000	Cu	10,000	K	19
Se	2,200,000	Er	130,000	Ce	6600	Na	12
Bi	1,600,000	As	110,000	Pr	5800	Mg	10
Sb	1,400,000	Dy	79,000	Rb	5800	Ca	6.2
Tm	1,000,000	Gd	76,000	N	5100	Fe	5.4
Lu	940,000	Hf	76,000	Ni	4800	Al	3.4
Tl	570,000	Sm	74,000	Zn	3900	Si	1

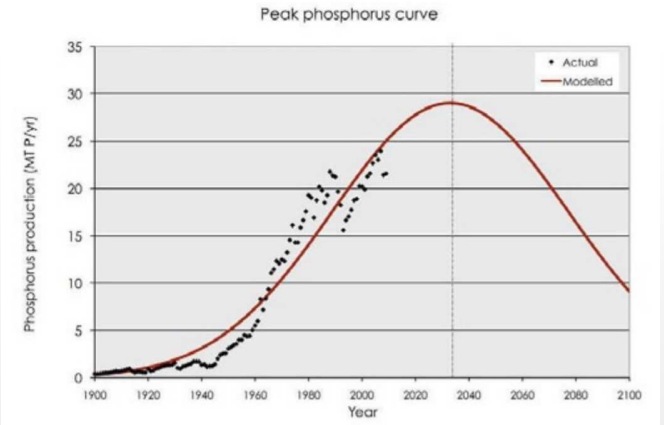
Peak Metal

Surplus Energy

Peak Metal

- The end is coming closer…
  - Discovery rate is slowing down
  - Future deposits will have lower grades / be at higher depth
  - Increased energy per kg metal extracted

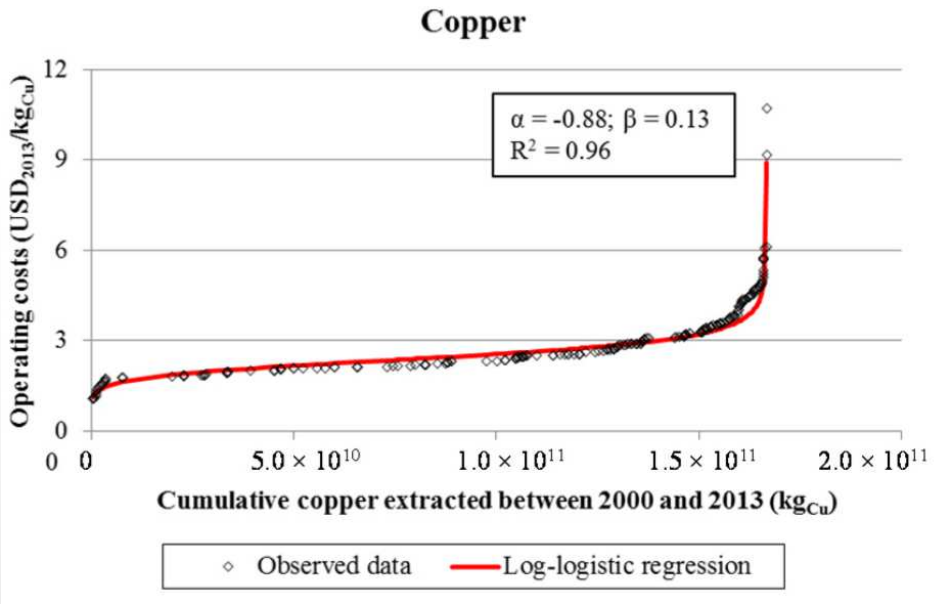




Global Phosphorus Research Initiative

Peak Metal

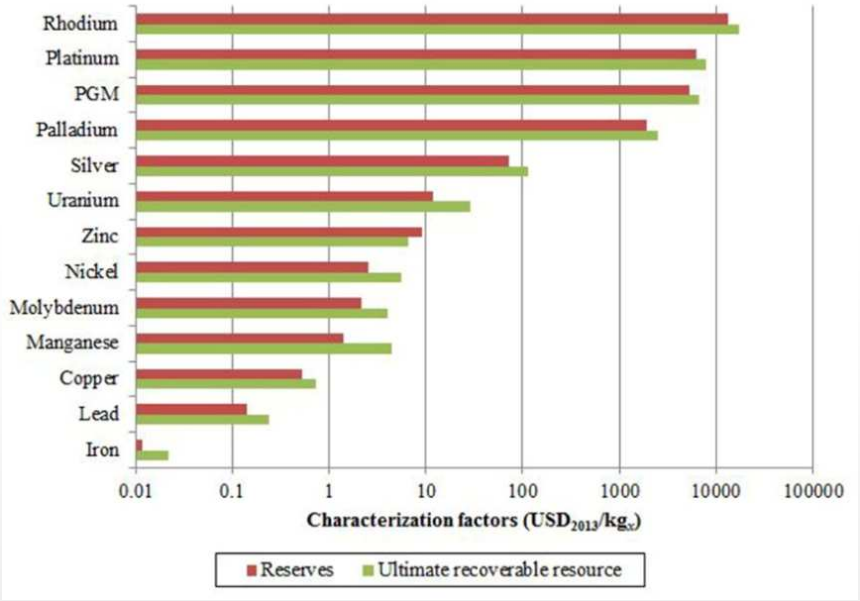
- Impact Assessment Based on Surplus Energy (SOP/RECIPE)
  - Vieira et al. 2012, Swart and DeWulf, 2013, Vieira et al. 2016
  - SOP : surplus ore potential - extra amount of ore mined per additional unit of resource extracted
  - SCP : surplus cost potential



Vieira et al. 2016

Peak Metal

- Impact Assessment Based on Surplus Energy (SOP/RECIPE)
  - Critical analysis
    - Drielsma et al., 2016; Ericsson et al., 2019
  - Grades (SOP) or Costs (SCP) do not tell the full story
    - Geometallurgy
    - Energy and logistics
    - …
  - Not only highest grades are mined
  - Deposits are not discovered in the « right » order
  - No reason to think grades will go down with depth
  - Costs and energy will increase in the future
    - … but not modelled through grades



Vieira et al. 2016

  - Normalized to Fe is not better than Sb
    - Completely different story with even increasing grades over last century ;-)

Recycling a Plug-In Hybrid Car

Case study

LCA data from
Belboom et al. (2016) Waste Management Vol. 50, pp.184-193

LIÈGE université

Recycling a Plug-In Hybrid Car

- Real size test
  - 156 cars processed at Comet Traitements

COLLECTION

COMMINUTION

Ferrous *Plastic* *Ultimate*

Polymetallic Non-Ferrous

PHYSICAL PROCESSING

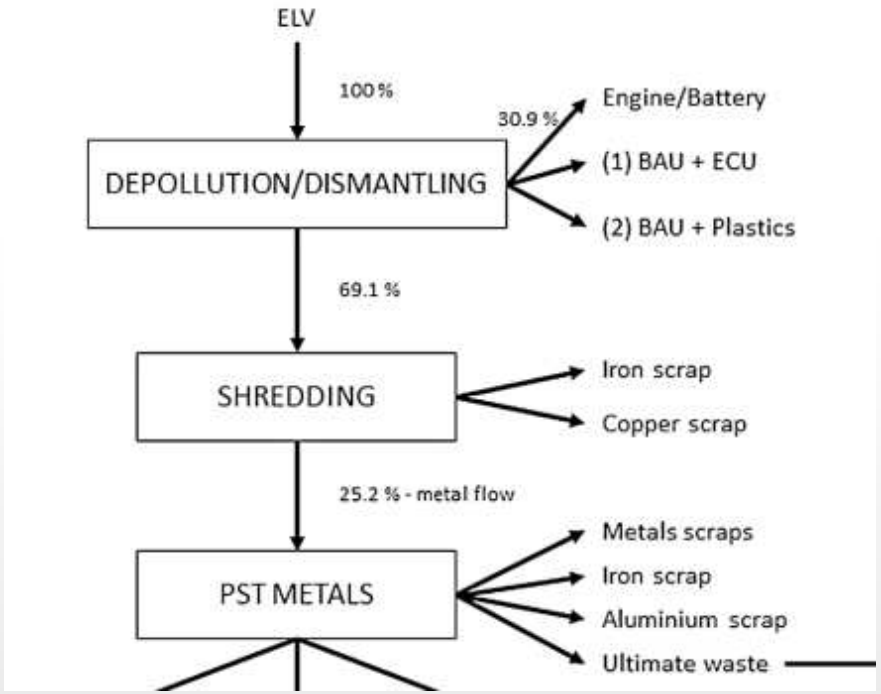
density-conductivity-…

Comparison of three recycling routes in
Belboom et al. (2016) Waste Management Vol. 50, pp.184-193

LIÈGE université

Recycling a Plug-In Hybrid Car

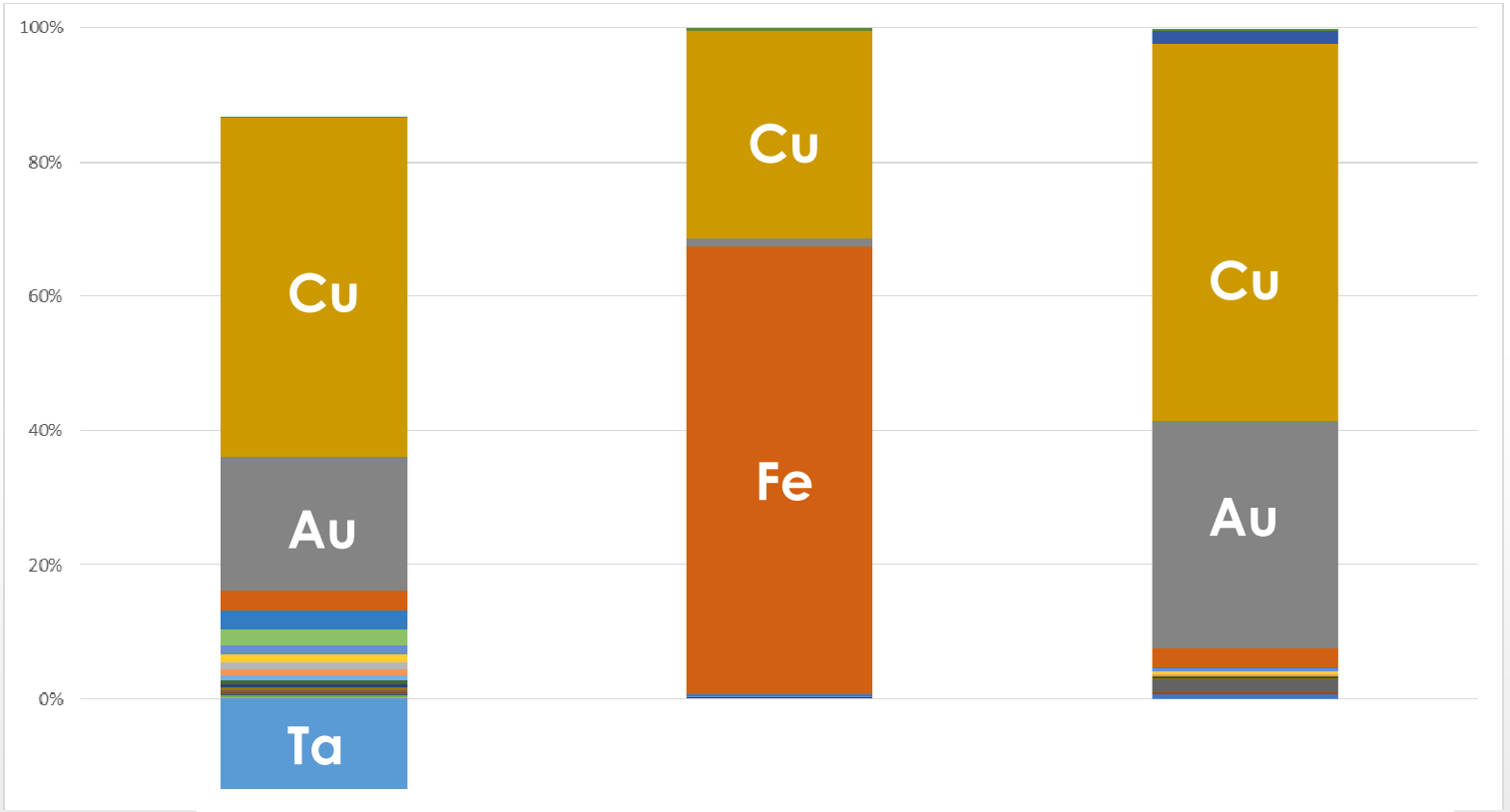
- Inventory data



	Steps	Unit
Consumption		
Electricity	(1)–(6)	kW h/ELV
Fuel	(3)–(6)	MJ/ELV
Magnetite	(3)	kg/ELV
Salted solution	(5)	kg/ELV
Production/recovery		
Iron scrap	(2)–(3)	kg/ELV
Copper scrap	(2), (3), (6)	kg/ELV
Aluminium scrap	(1), (3)	kg/ELV
Ultimate waste	(3), (4), (6)	kg/ELV
Sand	(4)	kg/ELV
Magnetite	(3)–(4)	kg/ELV
Plastics scrap	(1)–(5)	kg/ELV
Electricity production	(6)	kW h/ELV
Heat production	(6)	MJ/ELV
Carbon black	(6)	kg/ELV
Wiring board	(3)	kg/ELV

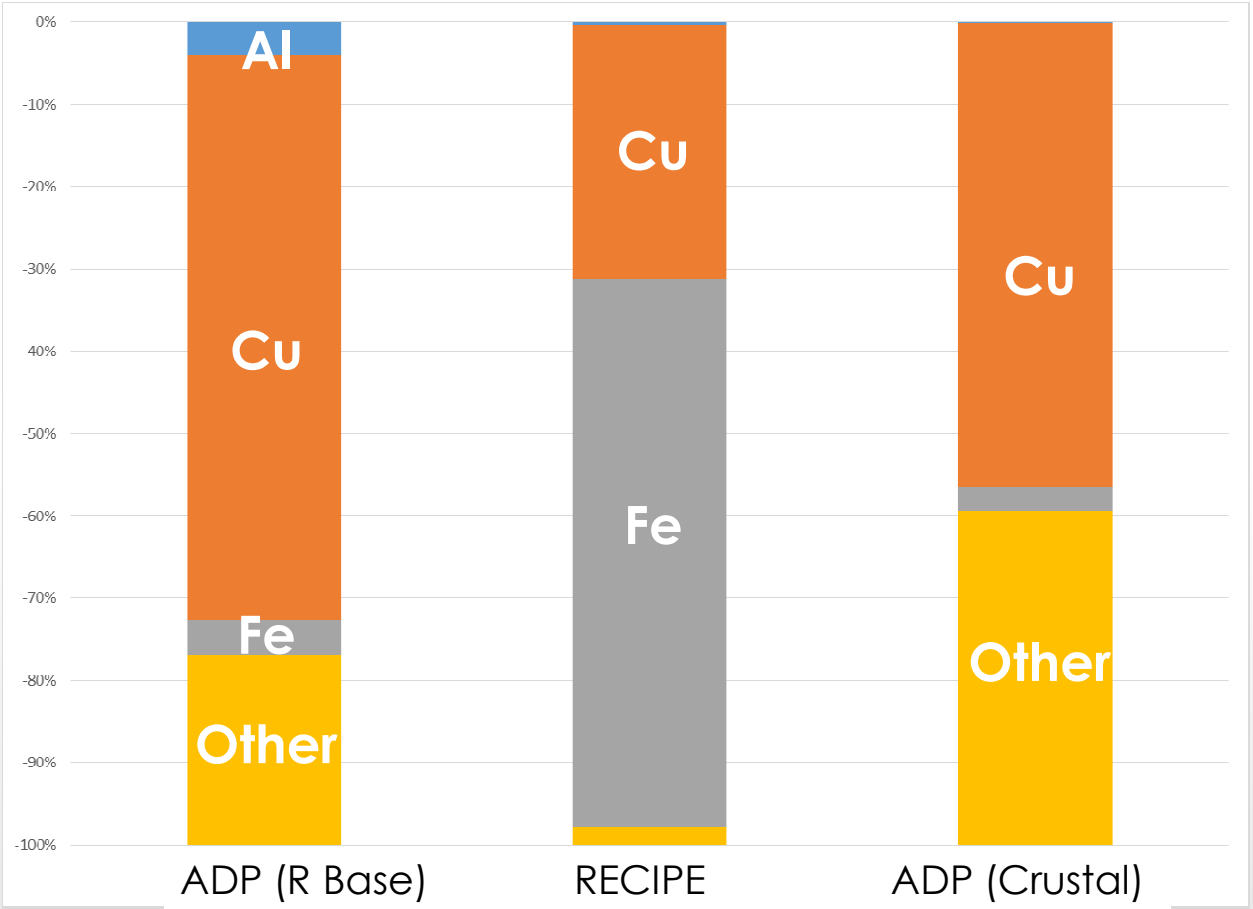
Recycling a Plug-In Hybrid Car

- Metal Depletion



Recycling a Plug-In Hybrid Car

- Metal Depletion (Al, Cu, Fe)

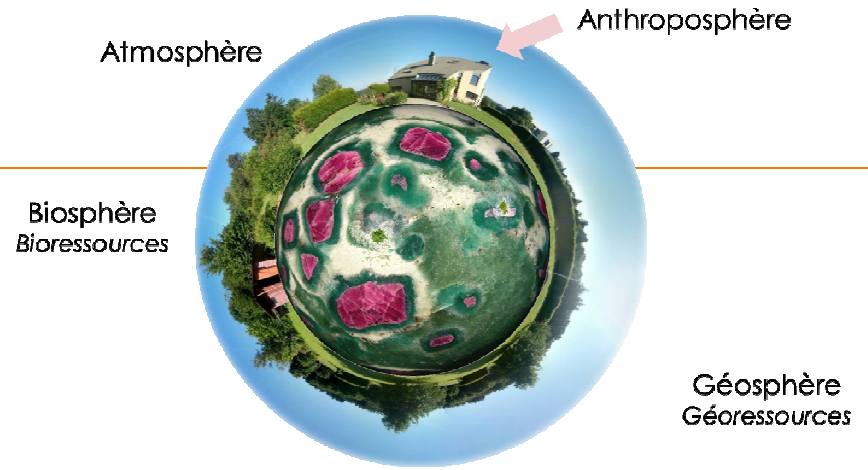


LIÈGE université

Sustainable Availability

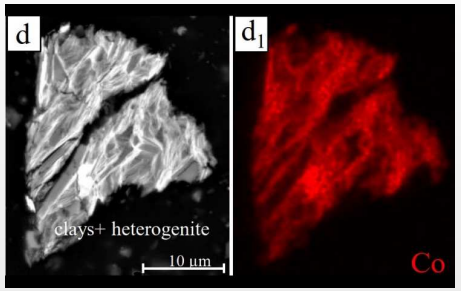
Accessibility, Recoverability,…

Sustainable Availability



- Mining provides metals to mankind
  - Transfer from Geosphere to Anthroposphere
  - Compromising actions (Van Oers et al, 2020)
    - Dissipation (cf. *Environmental Dissipation Potential*)
    - Hibernation : landfills, tailings, abandoned products,…
    - Occupation in use
    - …
  - Dewulf et al., 2021 *Identification and quantification of human actions that compromise the accessibility of metal resources*
    - Dispersed in environment
    - Landfills
    - Tailings
    - Abandoned in anthroposphere
    - Hoarded stock
    - Dispersed in anthroposphere

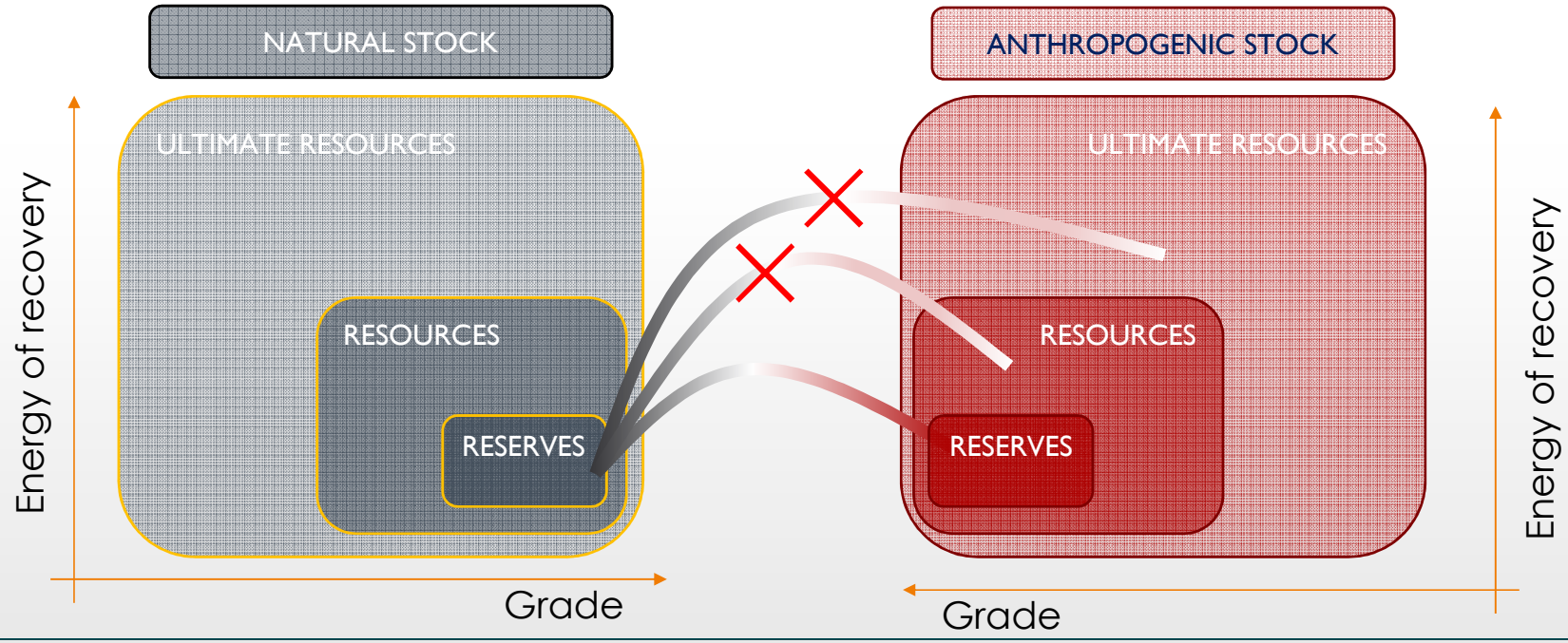
⇨ 30% of Co is « lost » in tailings !?



Santoro et al. (2019) Minerals Engineering

Sustainable Availability

- Need to identify changes in accessibility
- Geomimetism – Building the urban mine of the future
  - Grade – Tonnage – Recovery

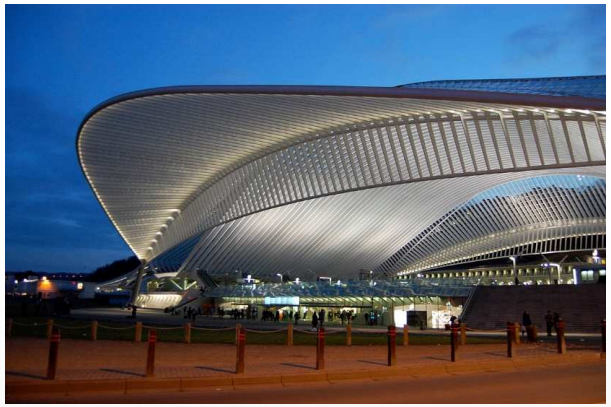


Sustainable Availability

- Mining provides metals to mankind but what does he do with it ?
  - **NAFS** : Net Addition to Functional Stock (Dewulf et al., 2021)

  - IRON
    - Deposits @ 60% Fe

    - Steel beams @ 99% Fe



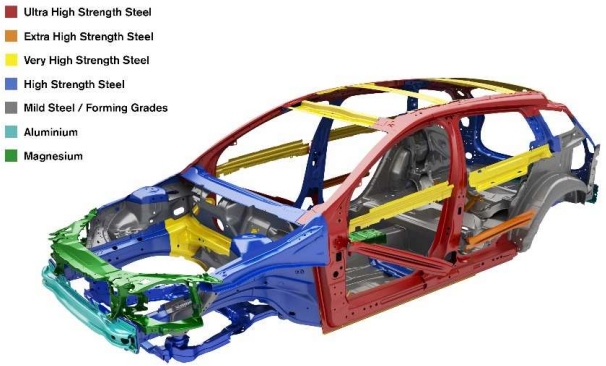
  - LEAD
    - Deposits @ 5% Pb

    - Battery @ 60% Pb

Sustainable Availability

- Mining provides metals to mankind but what does he do with it ?
  - **NAFS** : Net Addition to Functional Stock (Dewulf et al., 2021)

  - NIOBIUM
    - Deposits @ 1% Nb
      - ✓ Araxa, Brasil
    - Microalloyed steel @ 0,1% Nb



  - GALLIUM
    - Deposits @ 45 g/t Ga
      - ✓ Byproduct of Al (Bauxite)
    - Smartphone @ 15 g/t Ga
      - ✓ Polymetallic and submicronic assembly