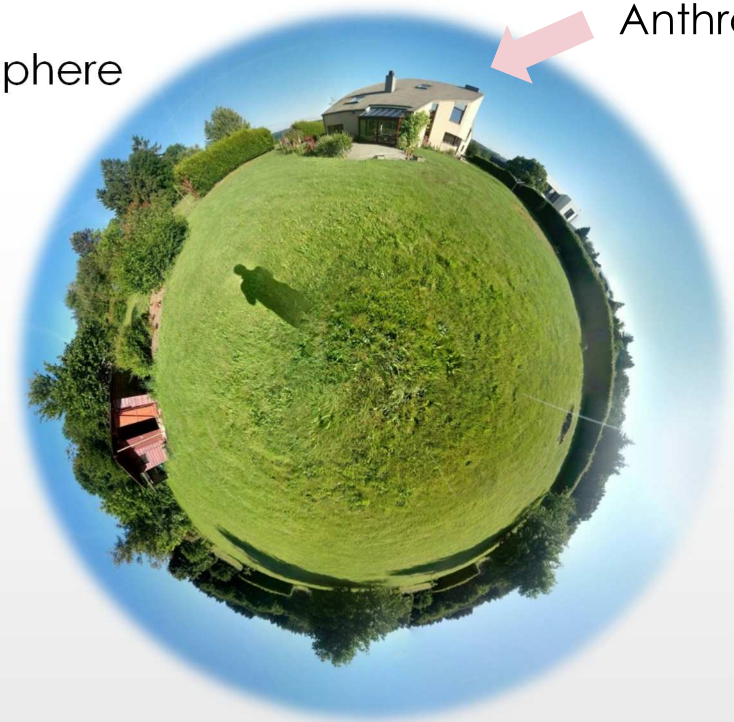
Renewable Energies
&
Raw Materials Availability

Prof. Dr. Ir. Eric PIRARD

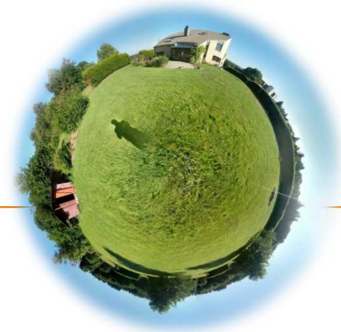
A Spherical Economy

- 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.



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

A World of Georesources



- Energetic resources
  - Oil, Gas, Coal, Lignite,…
  - Uranium
- Water resources
  - Underground
  - Superficial
- Industrial Minerals
  - Sand, aggregates, gypsum, …
  - Carbonates, phosphates, borates,…
  - Kaolin, talc, diatomea,…
  - Gems,…
- Metallic Resources
  - Base Metals ($/kg)
  - Precious Metals ($/g)
  - Critical Metals?

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Fuelling energy transitions

...and the environment

Fuelling energy transitions

Unsustainable pressure on the BIOSPHERE

- XVIIIth - Charcoal and unsustainable deforestation

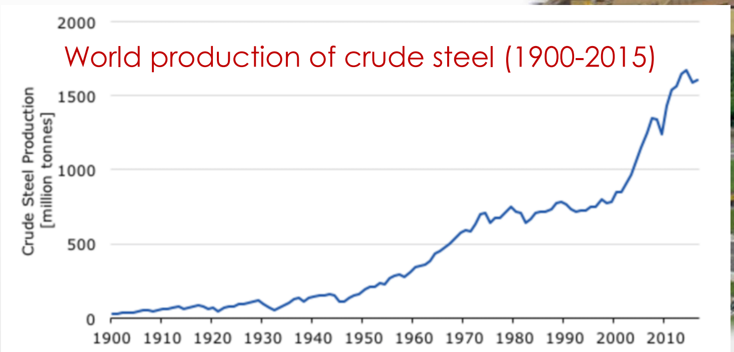
Blast furnace in the region of Spa(1612) Jan Brueghel

Fuelling energy transitions

Unsustainable pressure on the ATMOSPHERE

- XXth - Coal and unsustainable greenhouse gas emissions

HFB Blast Furnace Liège (Ougrée)



1,9 tons CO_2 / ton steel

5% of world's GHG emissions

Fuelling energy transitions

Unsustainable long-term management of radioactivity ?

- XXth – Nuclear energy

Tihange Nuclear Power Plant (Liege, BE)

11630 kWh can be obtained from :

- **6,8 m³ wood**
- **1,62 tons coal**
- **1 ton oil**

- …or 14 grams U (enriched @ 4% U^{235})

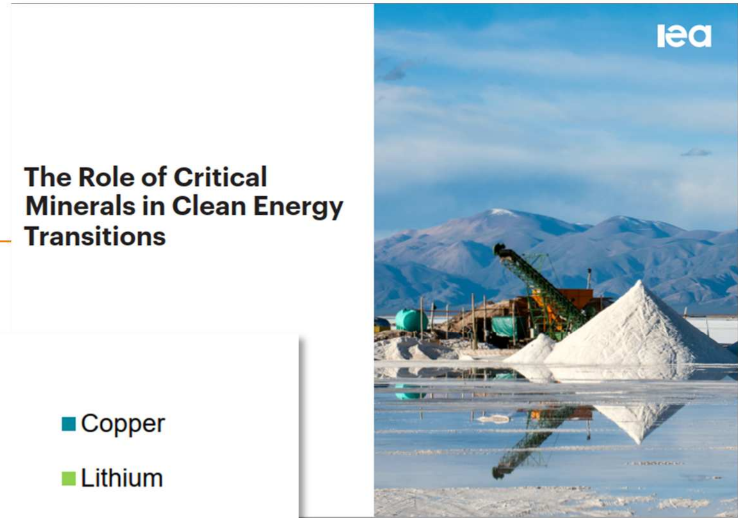
Fuelling energy transitions

Unsustainable pressure on the GEOSPHERE ?

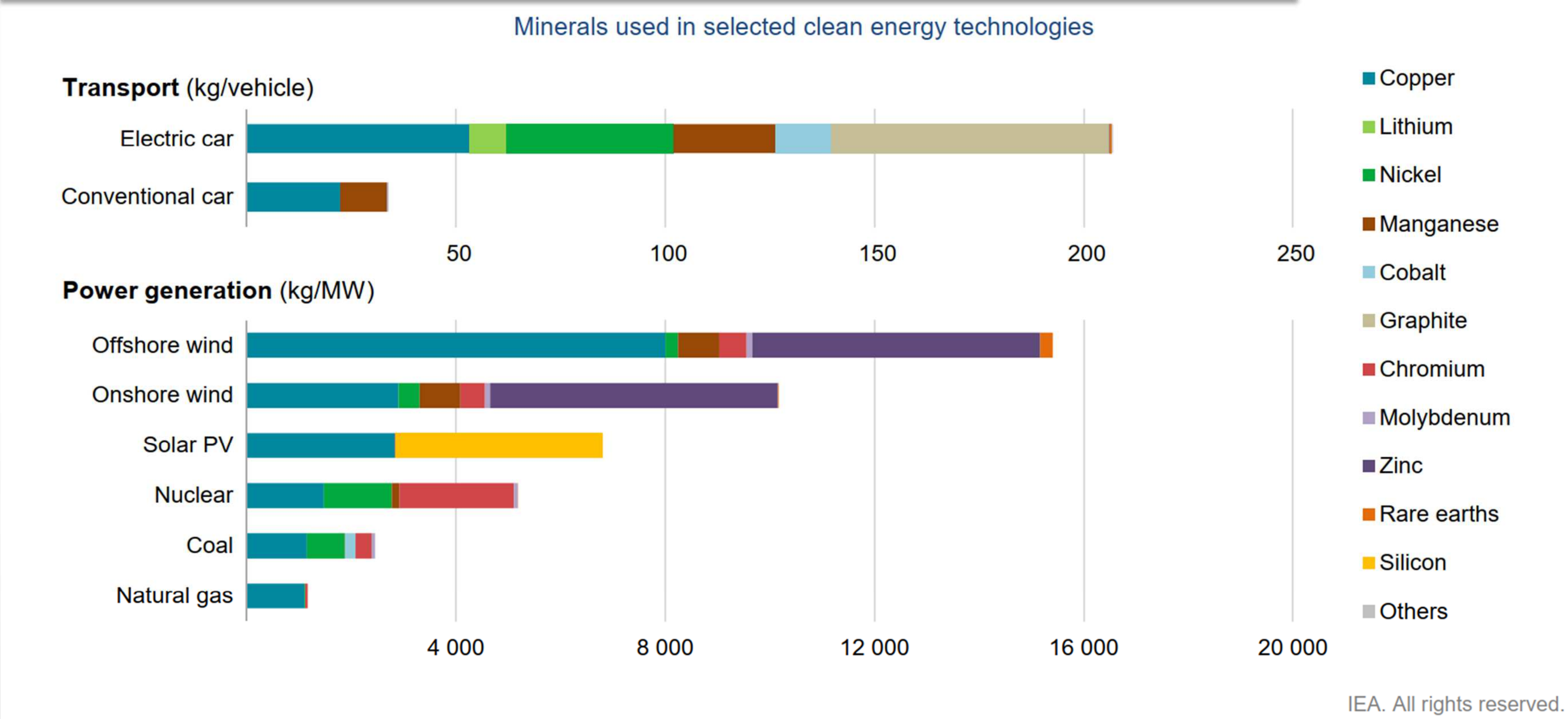
- XXIst – EU Green Deal - Boosting renewable energies

Renewable energy is useful energy that is **collected** from renewable resources, which are naturally replenished on a human timescale

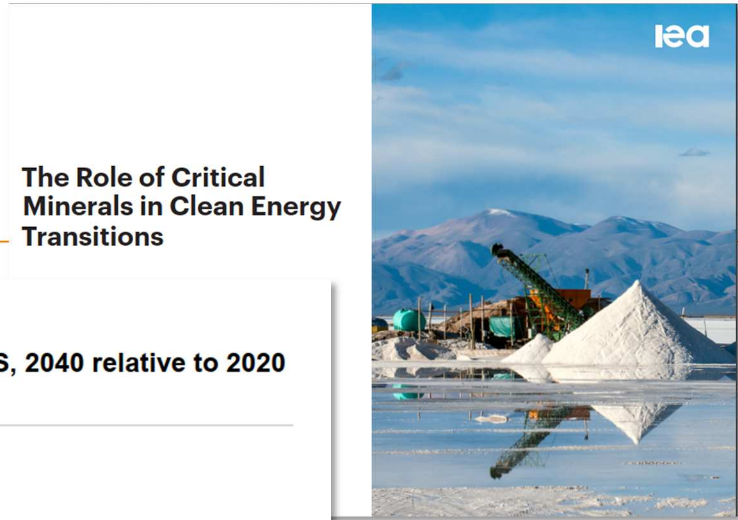
Fuelling energy transitions

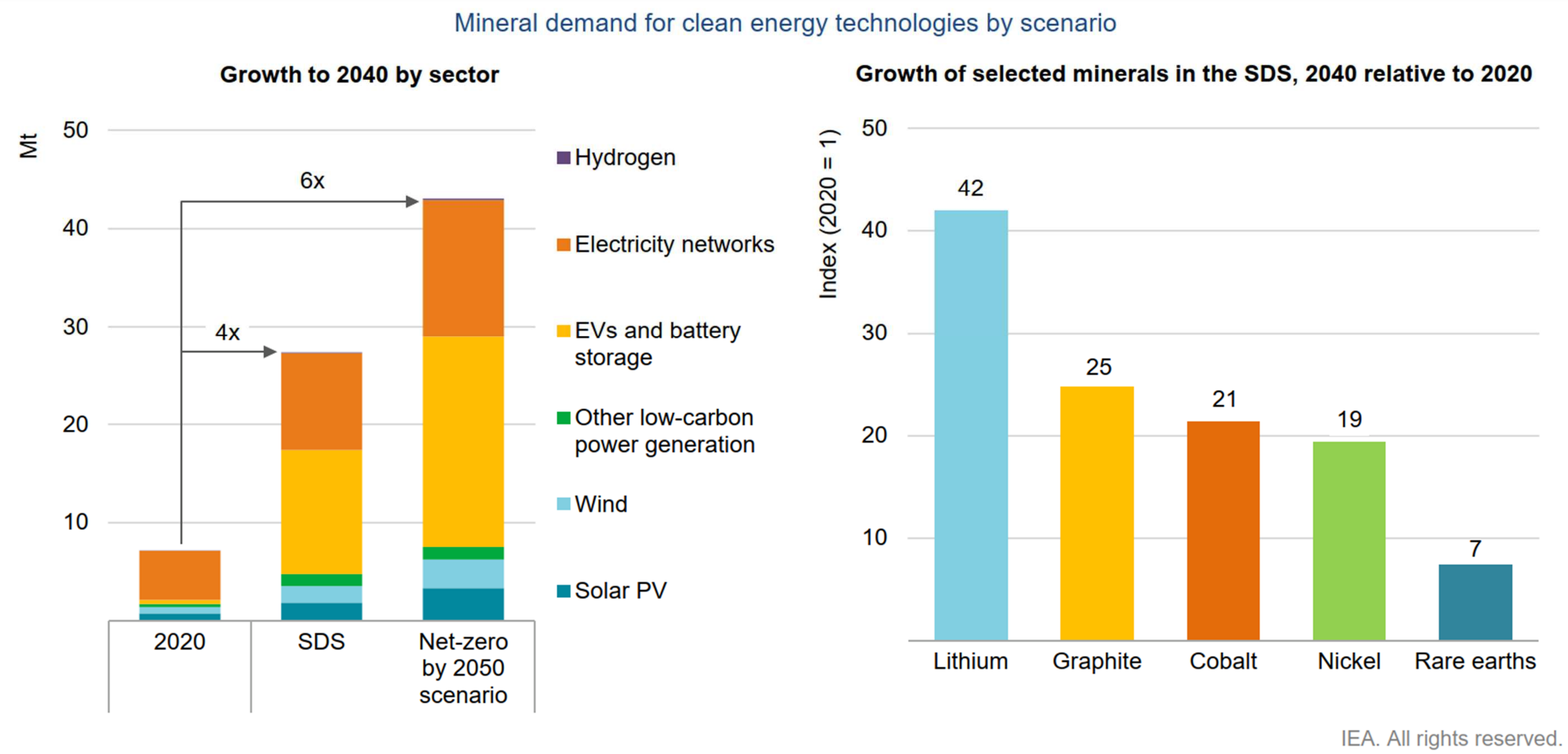


***International Energy Agency**(IEA.ORG), 2021, The Role of Critical Minerals in Clean Energy Transitions*
World Energy Outlook Special Report



Fuelling energy transitions





Solar & Wind Power Generation

Metal intensive solutions

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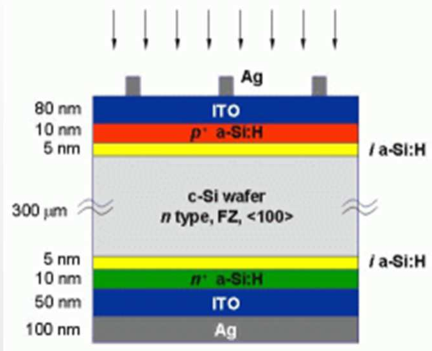
Solar Power Generation Technologies

- Dominant technology is Silicon based

364000 solar modules over 155 ha in North of France (Meuse Dpt). 152 MWp capacity (23 000 hab)

- Monocristalline Si
  - 15-25 % quantum efficiency
- Polycristalline Si
  - 12-17 % quantum efficiency
- Amorphous Si
  - 6-8 % quantum efficiency



Silver

100µm to 500 µm Si wafer

Silver

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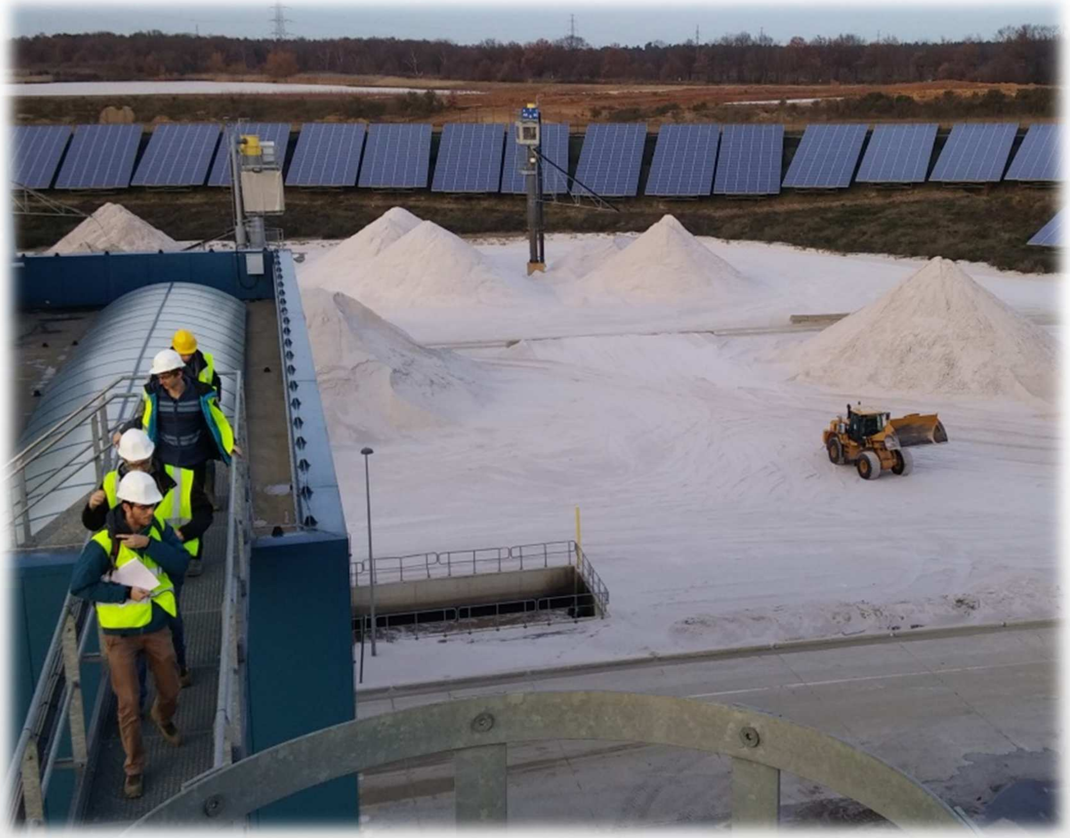
Solar Power Generation Technologies

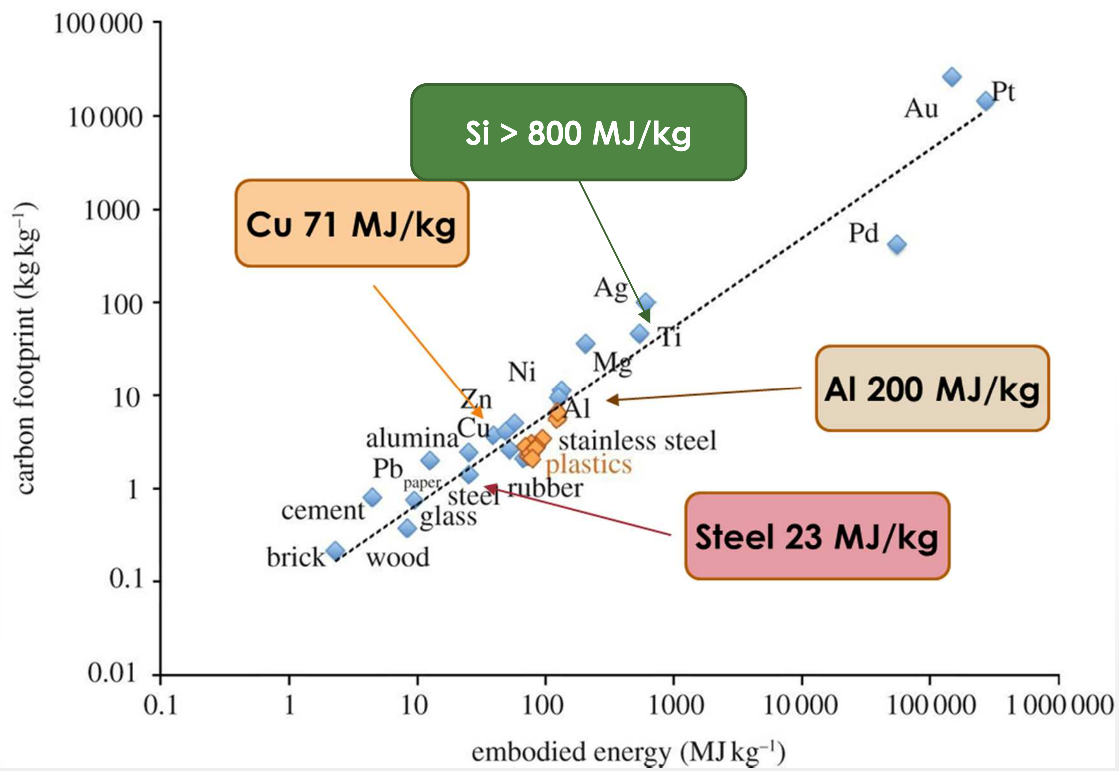
- About Silicon
  - Most abundant element of the crust after O
  - 33%

- High Purity Sources
  - Lump Quartz
  - Silica sand / sandstone
    - << 20 ppm total impurities
    - < 2 ppm Fe
    - < 0.5 ppm Ti



Solar Power Generation Technologies

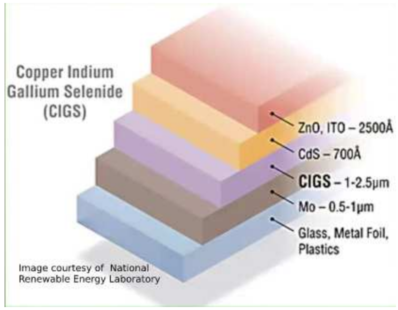
- Production of PV Grade
  - Melting and refining
    - Fusion @ 1900°C
    - Refining to 6N (99.999999 %) or 9N
    - Monocrystal growing



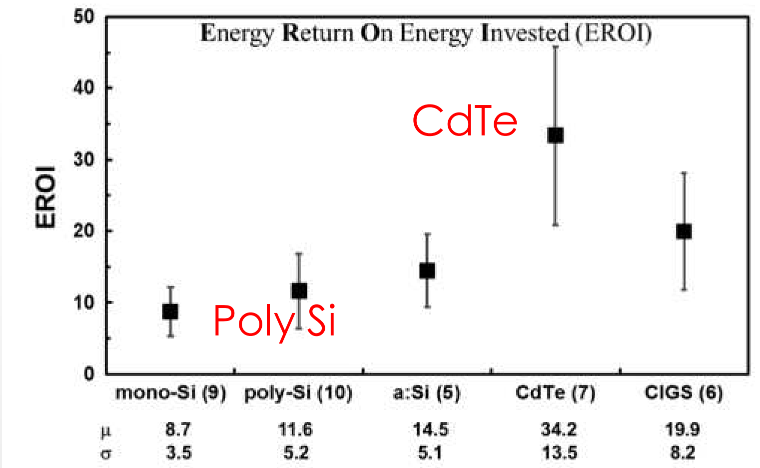
Gutowski et al., 2013, *The energy required to produce materials: constraints on energy-intensity improvements, parameters of demand*
https://doi.org/10.1098/rsta.2012.0003

Solar Power Generation Technologies

- Alternative thin-film (2-3µm) technologies
  - CdTe
  - CIGS (Cu – In – Ga – Se)
  - GaAs
  - Perovskite (MAPI - methylammonium Pb triiodide)



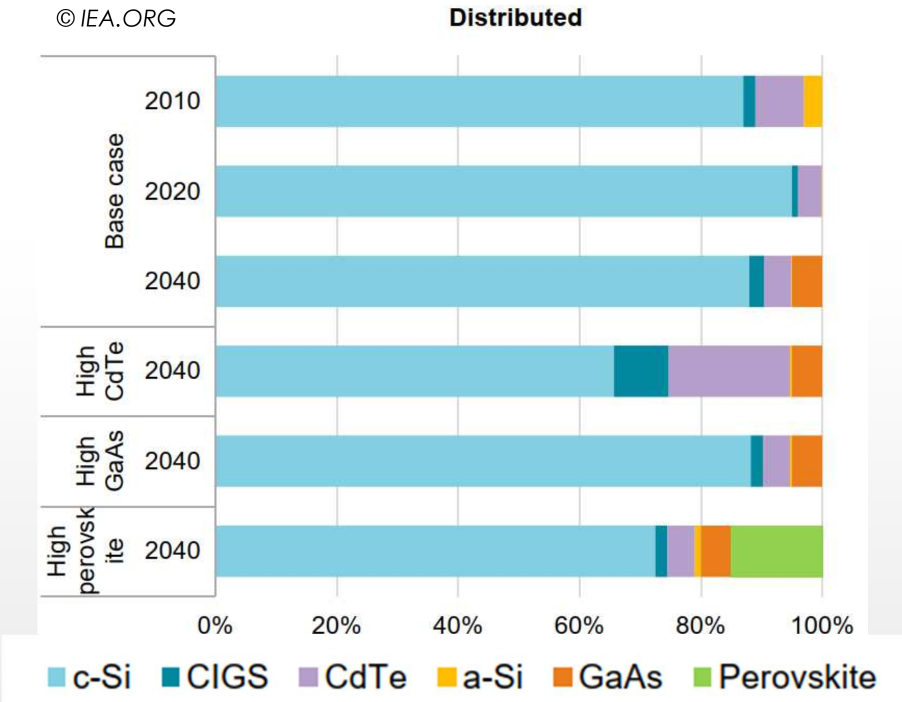
- Energy Return on Energy Invested
  - In optimal conditions
  - Lifetime 25 yrs+



Bhandari et al., 2015, Energy payback time (EPBT) and ***Energy Return On Energy Invested (EROI)*** *of solar photovoltaic systems, Renewable and Sustainable Energy Reviews 47, 133–141*

Solar Power Generation Technologies

- Scenarios for technology deployment
  - Largely dominated by Si



By-products: Indium, Gallium, Selenium, Tellurium, Cadmium

Metal	Type	Metal Intensity (t/GW)	Ref.	Price (USD/t) [1]
Indium	CIGS	23	[12]	520,000
Gallium	CIGS	7.5	[12]	317,000
Selenium	CIGS	45	[36]	48,700
Tellurium	CdTe	97.5	[75]	77,000
Cadmium	CdTe	85	[75]	1470
Silver	All	80	[76]	~~505,000~~ 874 000
Steel	All	1,100,000	[62]	81
Aluminum	All	32,000	[77]	1940
Copper	All	4000	[2]	5650

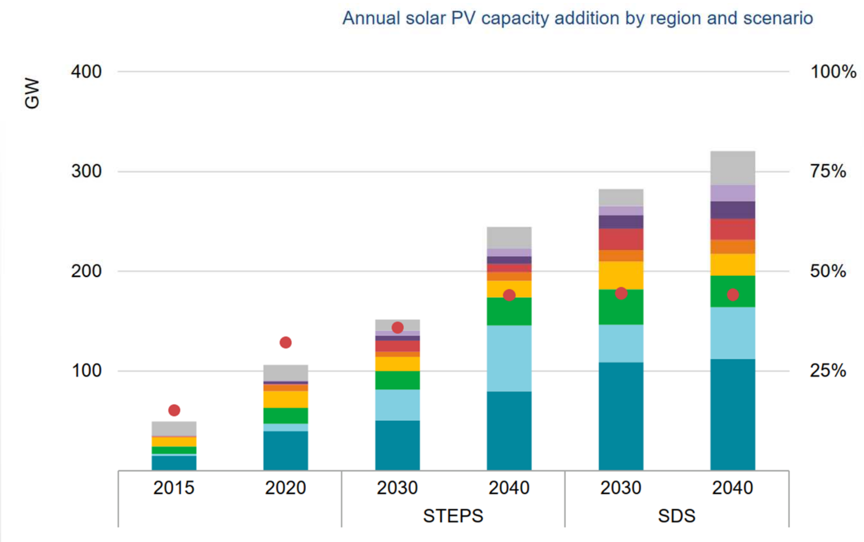
Note: [1] Metal price is for 2015 from USGS database [78].

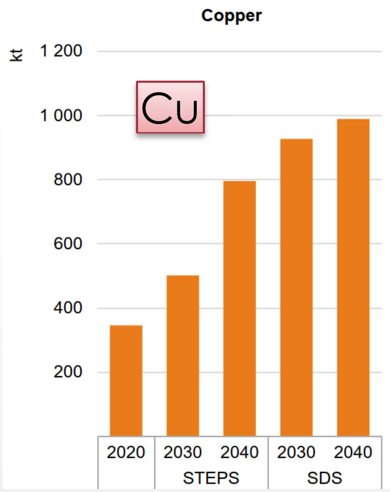
Watari et al., 2018, Analysis of Potential for Critical Metal Resource Constraints in the International Energy Agency's Long-Term Low-Carbon Energy Scenarios, Minerals, 8, 156

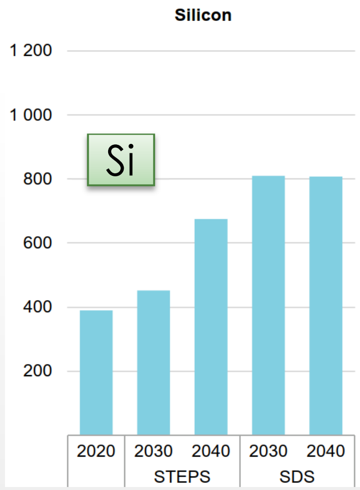
SDS scenario (COP21) + 200 GW by 2040 would require ***1400 tons of Te****!*
Current world production is ***400 tons/yr*** *of Te as by-product of Cu only!*

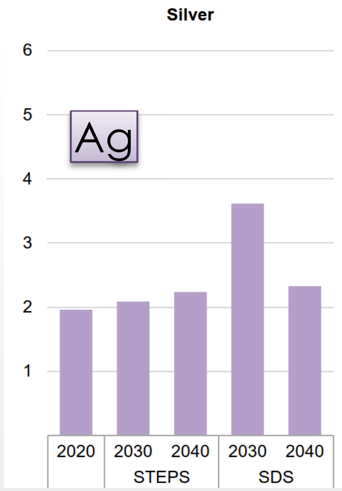
Solar Power Generation Technologies

- Solar PV capacity addition
  - Under STEPS and SDS scenarios (IEA)
    - STEPS = Stated Policies Scenario
      - ✓ Based on current policies
    - SDS = Sustainable Development Scenario
      - ✓ Paris agreement









Wind Power Generation Technologies

- Windmills

Norther – Belgium's off-shore windfarm consists of 44 wind turbines (total 370 MW) ~= 400,000 households

- 2MW terrestrial
  - Basement
    - 840 tons of concrete
  - Mast
    - 300 tons of steel : soldered conical sections
  - Blades
    - Prepreg composite (epoxy + carbon fiber)
    - 25 tons
      - ✓ A 45 m blade weights 6,5 tons

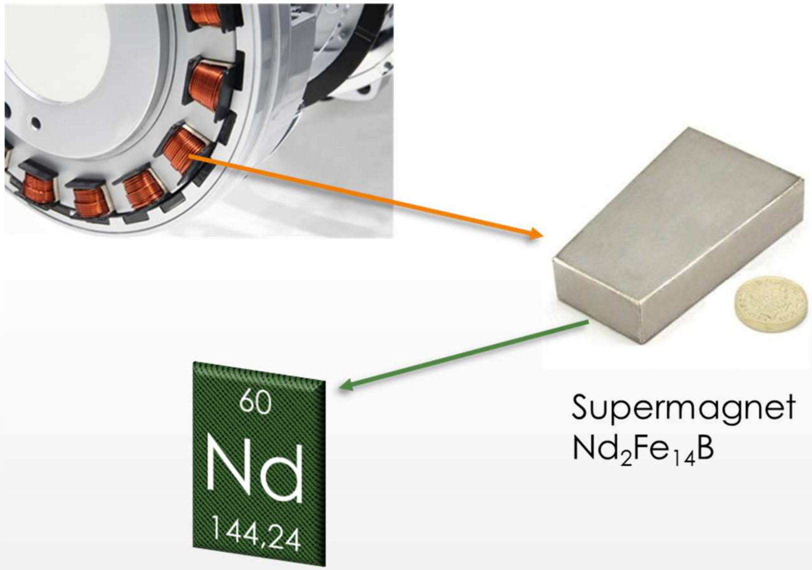
Windmill, Ersa, Cap Corse

Wind Power Generation Technologies

- 2MW Windmill with Permanent Magnet Generator (PMG)
  - 4 tons Cu
  - 1,3 tons $Nd_2Fe_{14}B$
    - ✓ 400 kg Nd
    - ✓ Mostly in large offshore windmills

- Cabling
  - 1 ton Cu

- Transformer
  - 1.4 tons Cu



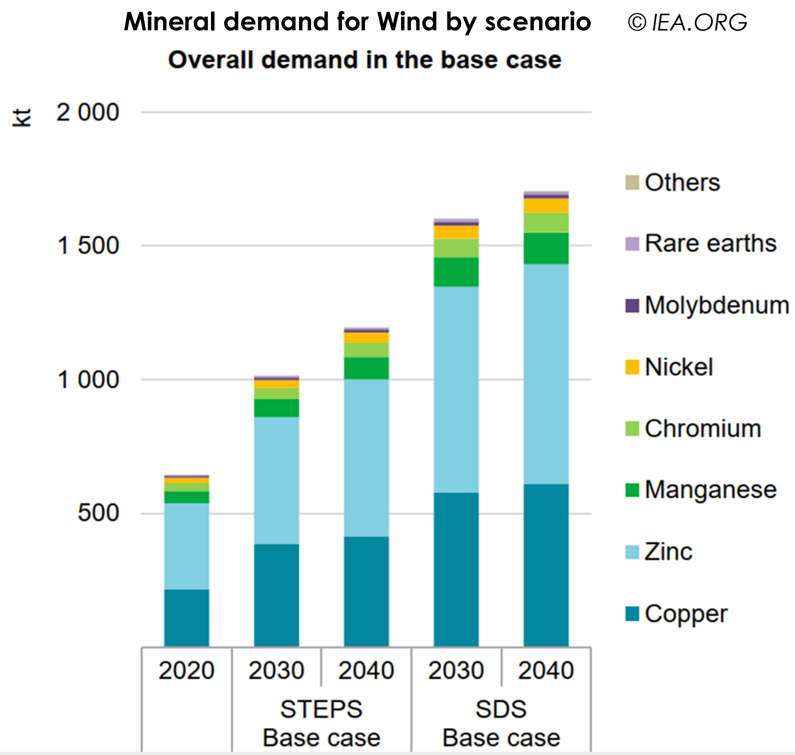
Wind Power Generation Technologies

- Metal intensities

Metal	Type	Metal Intensity (t/GW)	Ref.	Price (USD/t) [1]
Dysprosium	PMG	27.7	[17]	240,000
Neodymium	PMG	198	[17]	42,000
Steel	All	103,000	[19]	81
Aluminum	All	1060	[77]	1940
Copper	All	3000	[19]	~~5560~~ 10200 $/t

Note: [1] Metal price is for 2015 from USGS database [78].

Watari et al., 2018, Minerals, 8, 156



*SDS scenario (COP21) + 100 GW by 2040 would require **20 000 tons of Nd**!*
*Current world production is about **12 000 tons/yr** of Nd!*

Energy Storage Technologies

Batteries & Hydrogen

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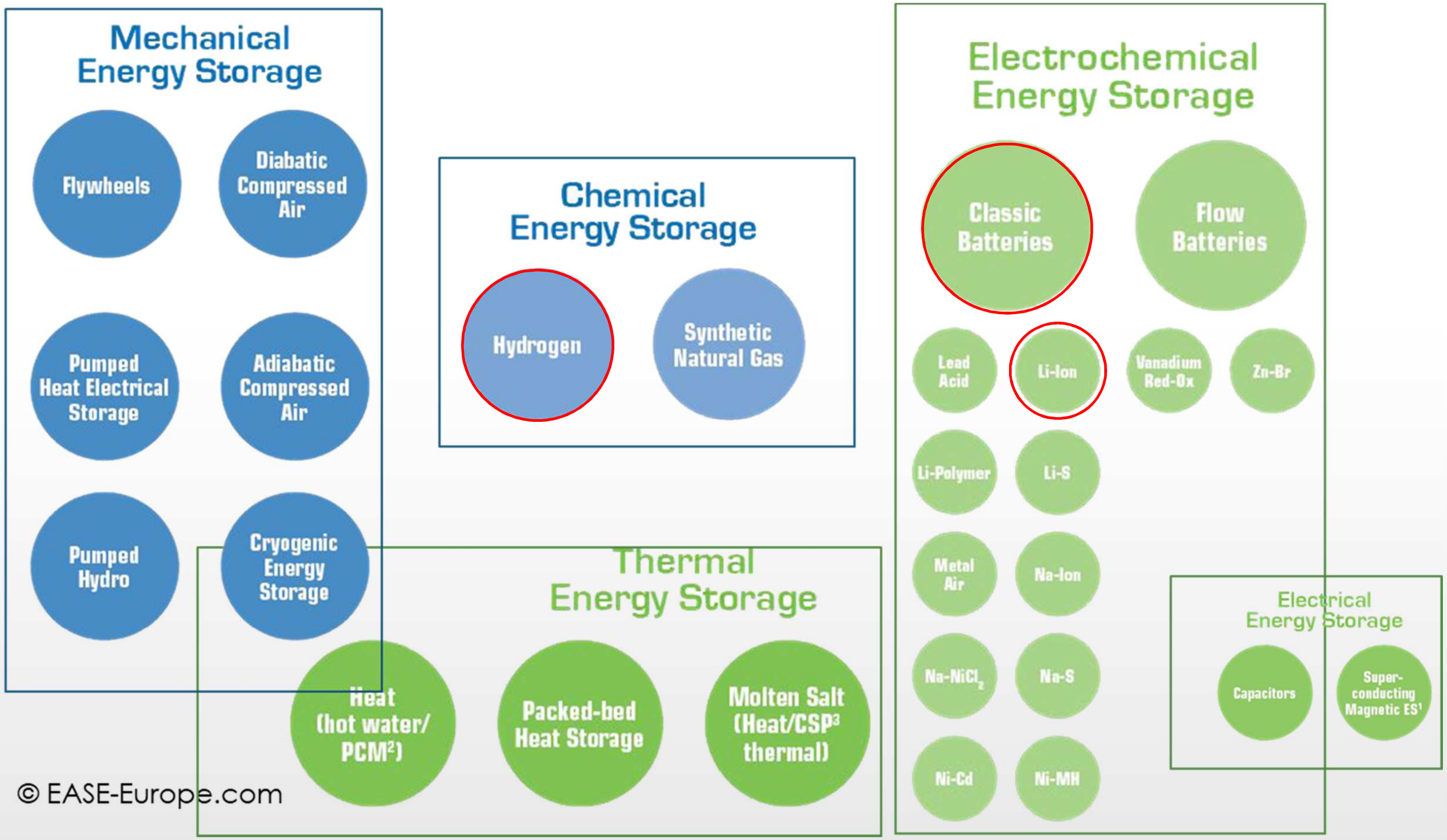
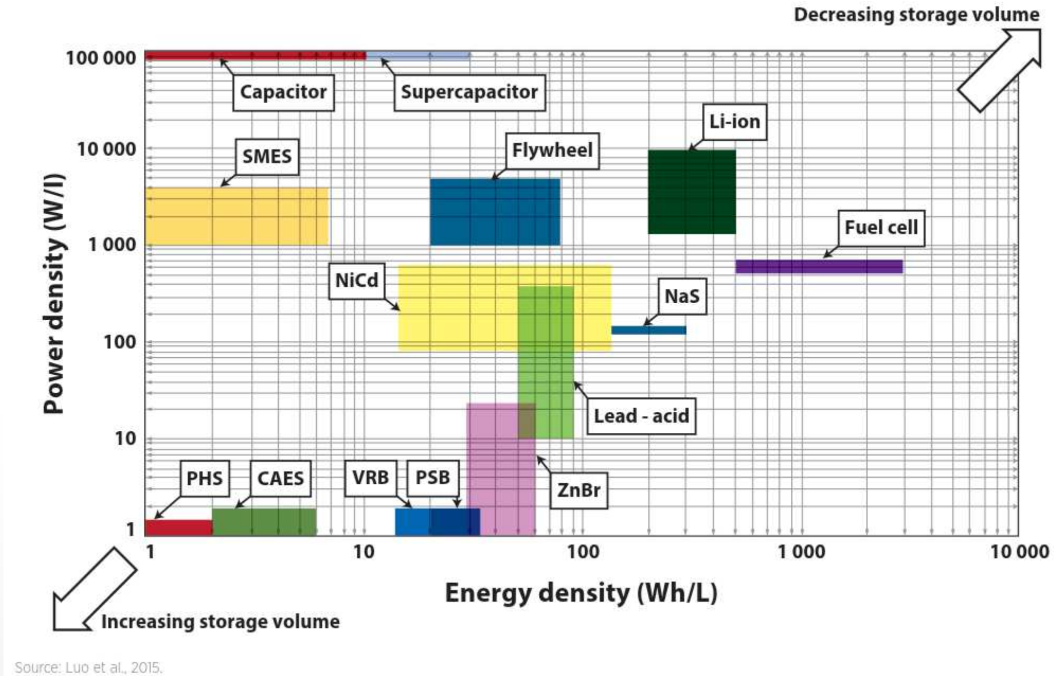
Energy Storage Technologies



Electrochemical Energy Storage

- Electrochemical Energy Storage

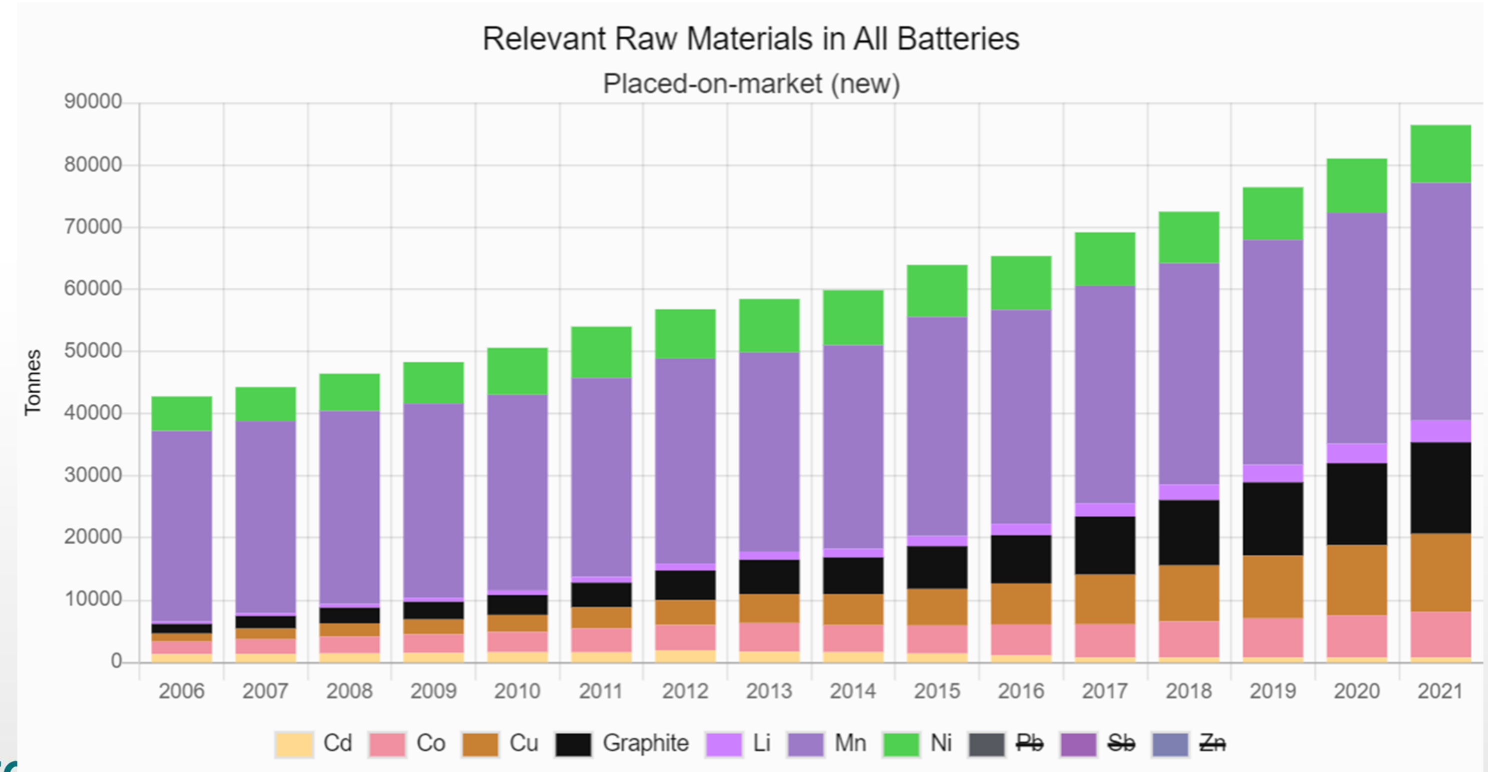
eStor-Lux (2021) - 10 MW/20MWh Li-ion battery storage station

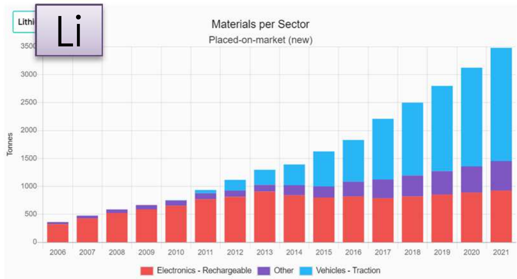


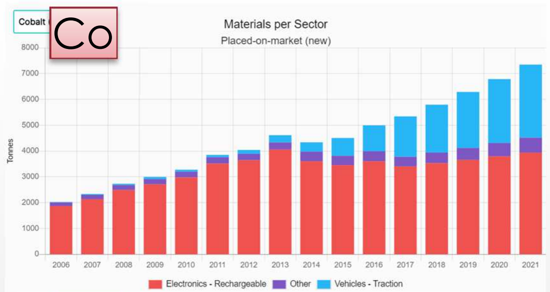
- Li-ion cathode material
  - NMC : $Li\ (Ni_{0,5}Mn_{0,2}Co_{0,3})O_2$
    - => $Li\ (Ni_{0,8}Mn_{0,1}Co_{0,1})O_2$)
  - $LiCoO_2$; NCA (Ni, Co, Al) ; LFP (Fe, P) ; LTO (Ti)

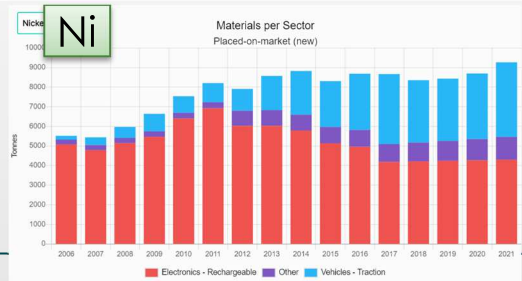
Electrochemical Energy Storage

- Total weight of raw materials in primary and industrial batteries placed on market in the EU *(excl. Pb and Zn)*



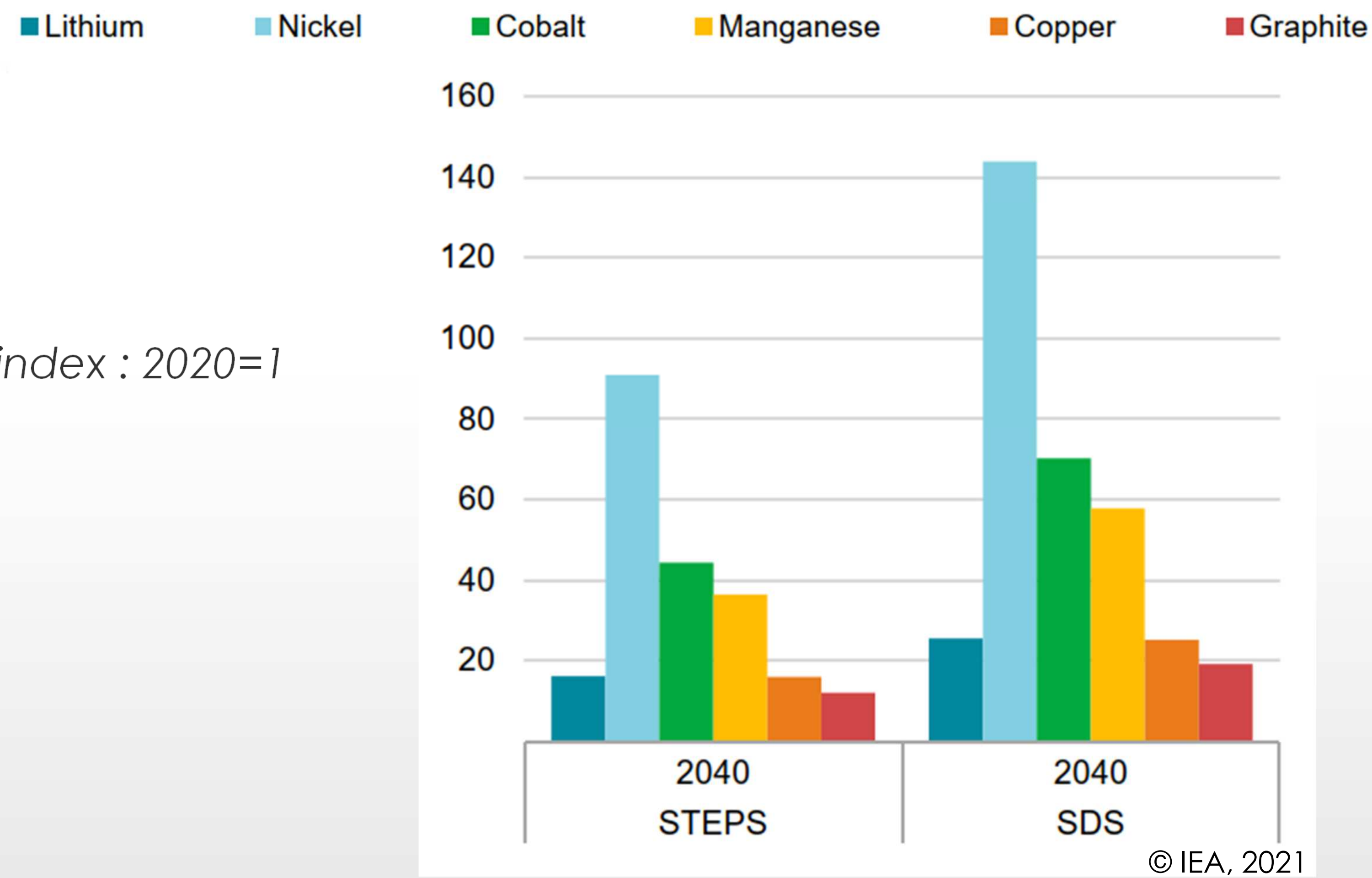






Electrochemical Energy Storage

- *Growth index : 2020=1*



E-Mobility

EVs use around six times more minerals than conventional vehicles

Typical use of minerals in an internal combustion engine vehicle and a battery electric vehicle

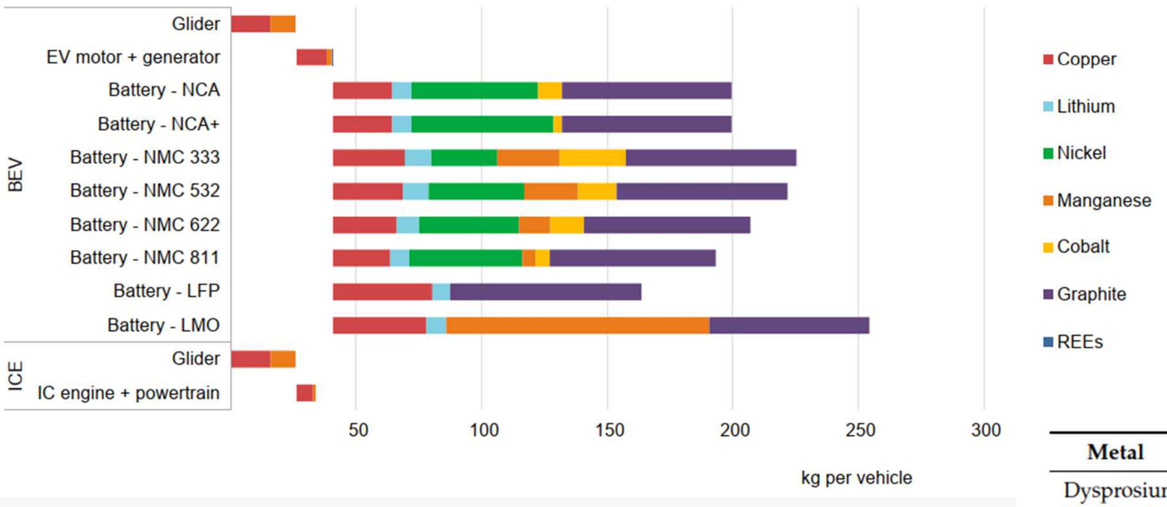
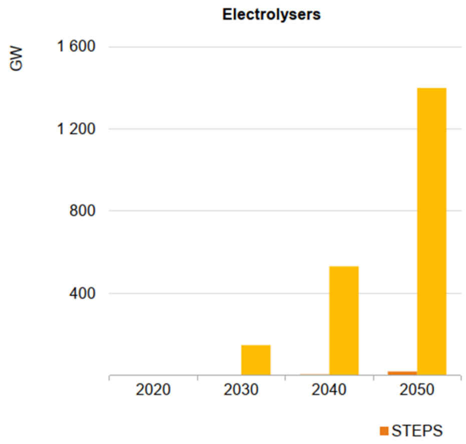


Table 6. Metal intensity in next-generation vehicles (Unit: g/vehicle).

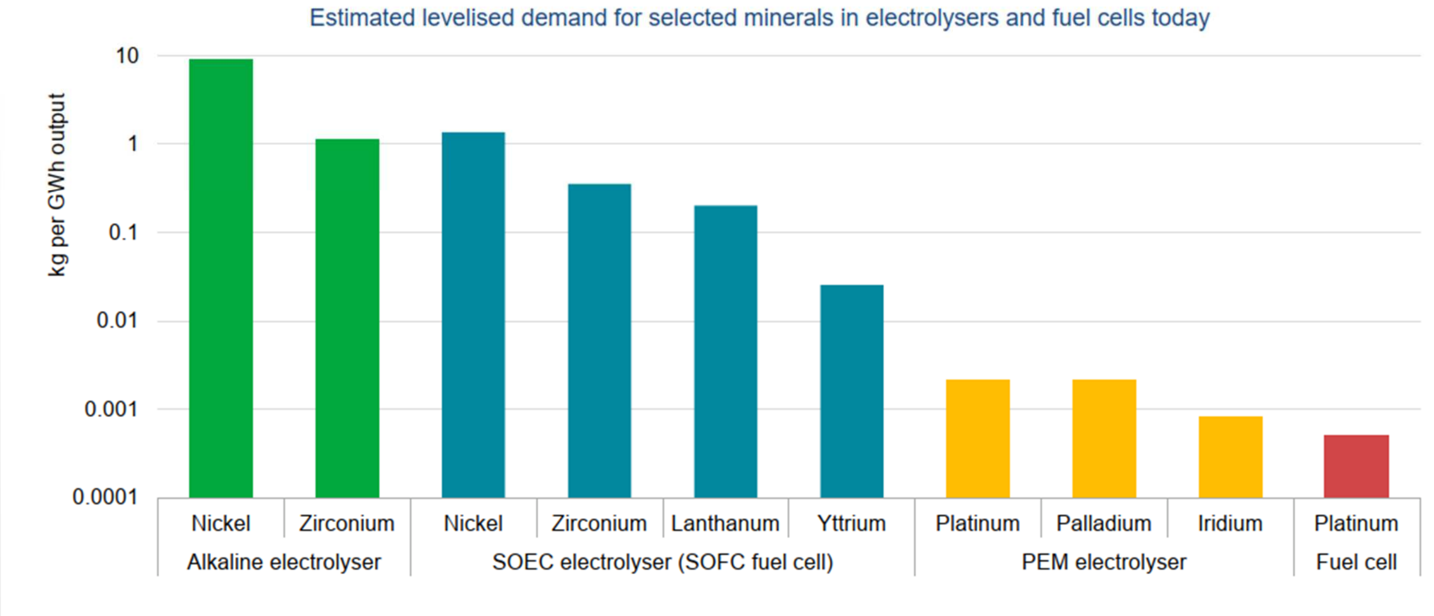
Metal	ICEV	HEV	PHEV	EV	HFV	Ref.	Price (USD/t) [1]
Dysprosium	0	83	83	83	0	[17]	240,000
Neodymium	0	695	695	695	0	[17]	42,000
Lithium	0	0	5100	12,700	0	[52]	4540
Cobalt	0	660	3500	8800	0	[52]	29,200
Nickel	0	3200	18,600	46,500	0	[52]	11,800
Platinum	0	0	0	0	60	[28]	13,500,000
Steel	921,900	1,056,200	1,185,900	909,500	911,800	[35]	81
Aluminum	71,300	114,500	162,400	78,600	65,000	[35]	1940
Copper	23,000	40,000	60,000	83,000	23,000	[3]	5650

Note: [1] Metal price is for 2015 from USGS database [78].

Hydrogen Electrolysis & Fuel Cells



- Several technologies
  - PEM : Polymer Electrolyte Membrane electrolyzers
    - Typical lifetime = 7 yrs
  - AEL : Alkaline
  - SOEC : Solid Oxide Electrolyzer Cells



Hydrogen Electrolysis & Fuel Cells

- Several technologies
  - PEM : Polymer Electrolyte Membrane electrolyzers
    - Typical lifetime = 7 yrs
  - AEL : Alkaline
  - SOEC : Solid Oxide Electrolyzer Cells

Stack	CRM	Amount required for green hydrogen in 2050, as % of current global annual production	Also used in
PEM	Iridium	122%	Electronics (43%), electrochemistry (27%), chemical industry (7%)
PEM&AEL	Platinum	25%	Car catalysts (80%), jewelry (10%), chemical industry (5%)
AEL	Raney-Ni	0.4%	Ni: stainless steel, magnets, batteries, coinage, alloys, chemical industry
AEL	Nickel (class 1)	2%	Same as described for Ni above
AEL	Cobalt	0.1%	Batteries (42%), alloys (23%), materials (10%)

Based on 8100 PJ of green hydrogen production by 2050 (50% PEM, 50% AEL)

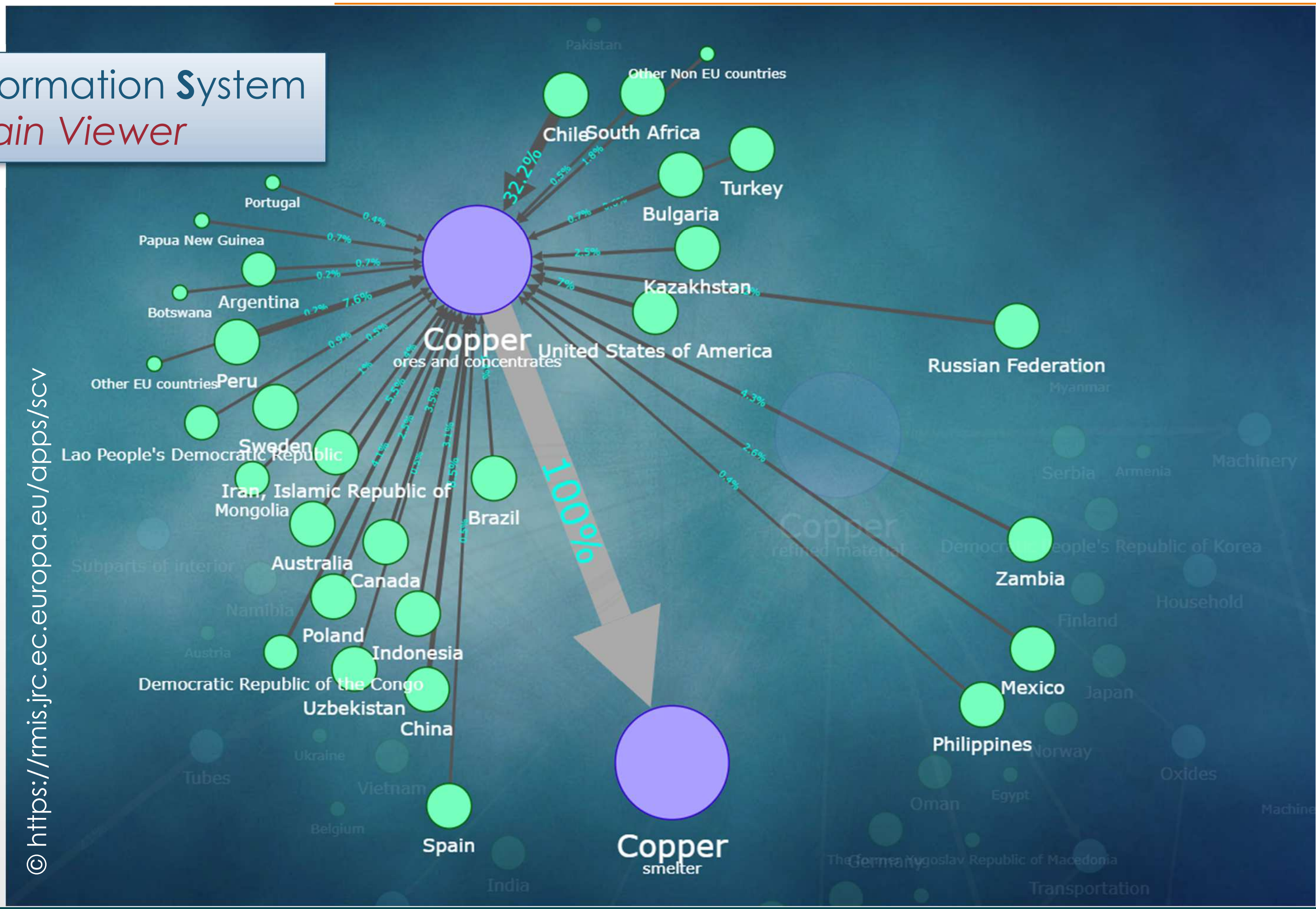
Wieclawska & Gavrilova, 2021, TOWARDS A GREEN FUTURE, TNO
Part 1: How raw material scarcity can hinder our ambitions for green hydrogen and the energy transition as a whole

Supply Chains

Why metals became critical

EU **COPPER** Supply Chain

Raw **M**aterials **I**nformation **S**ystem
Supply Chain Viewer



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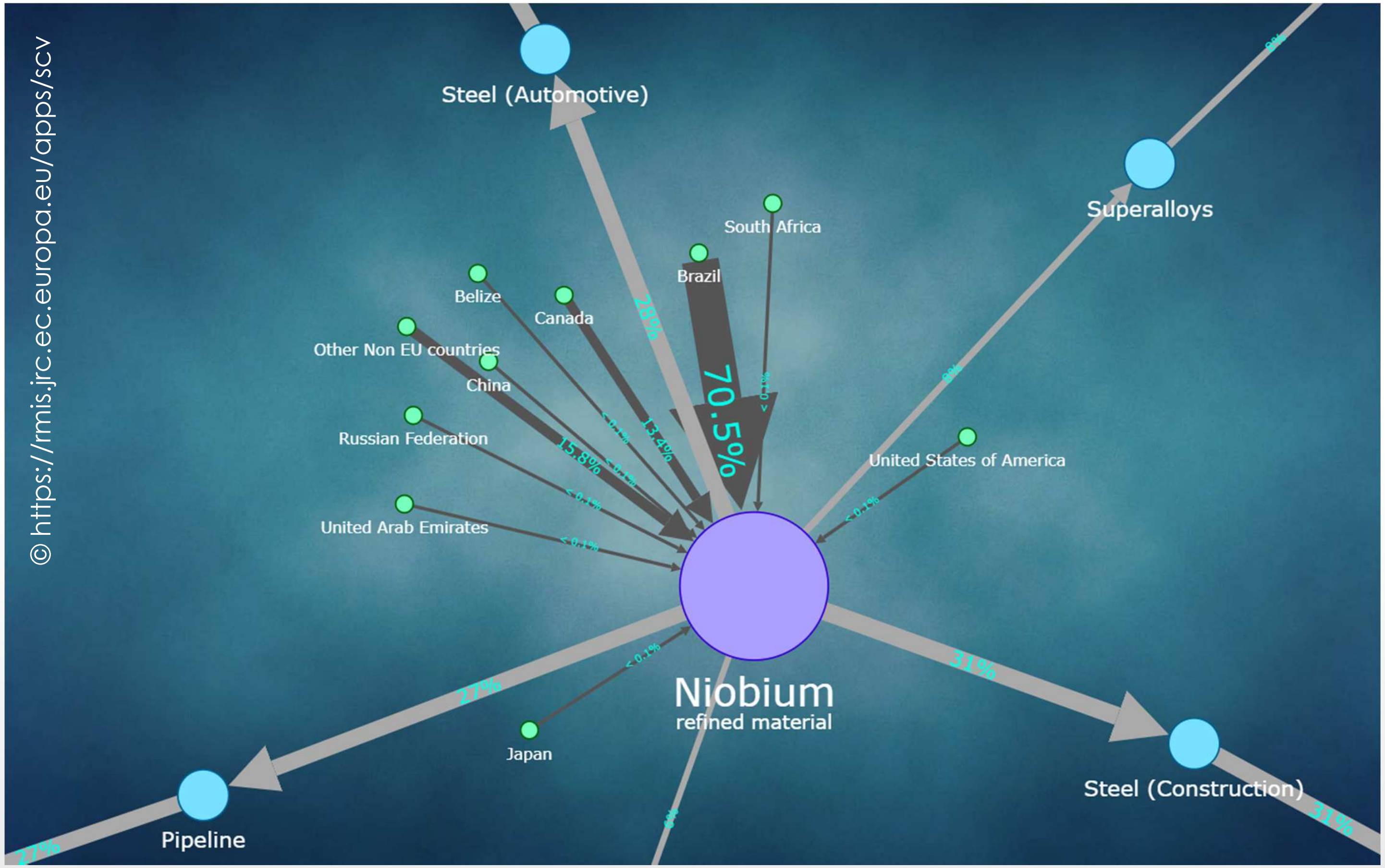
EU **NIOBIUM** Supply Chain



Critical Raw Materials for the EU

- Collecting data

Share of global production

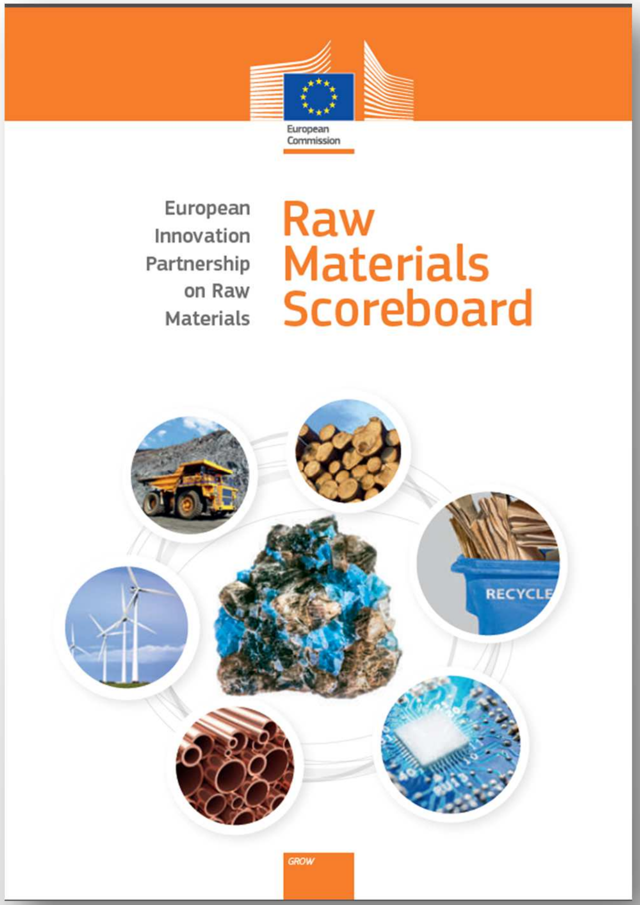
Share of imports

Value added and jobs

Knowledge & skills

Mining activity

Mineral Exploration



Social License to Operate

Waste managment

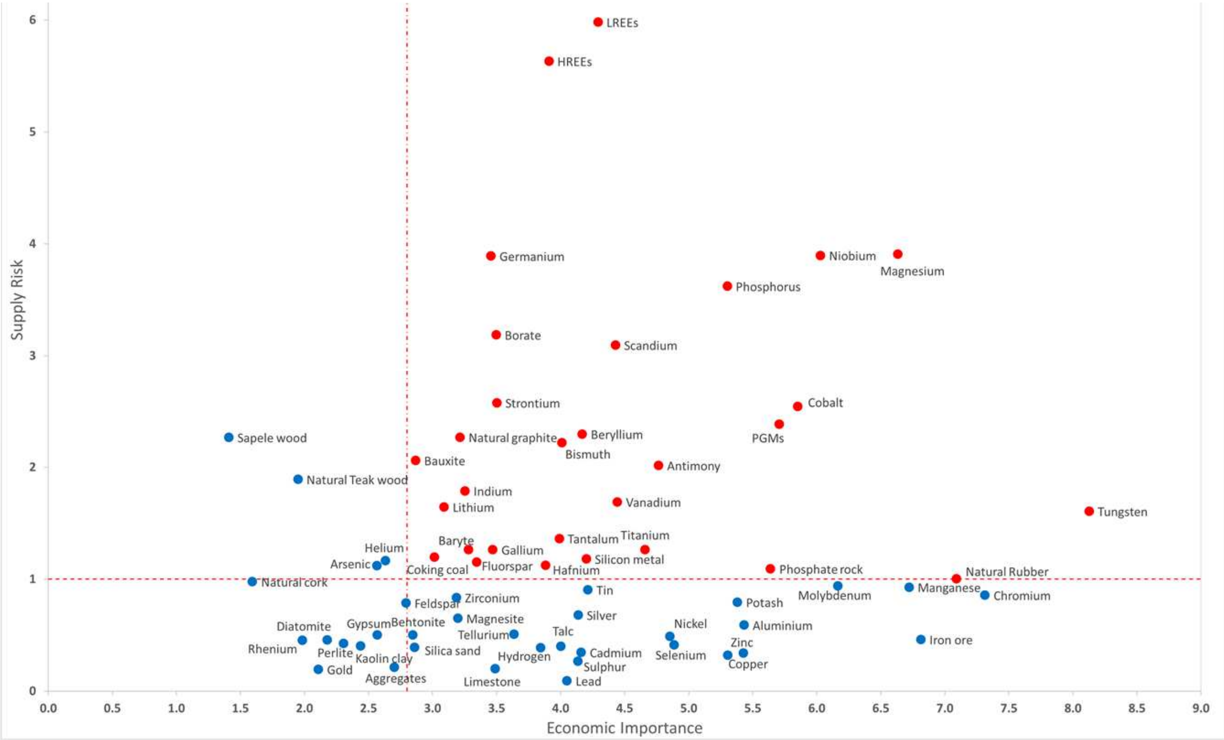
Environmental Impact

Circular Economy

Recycling

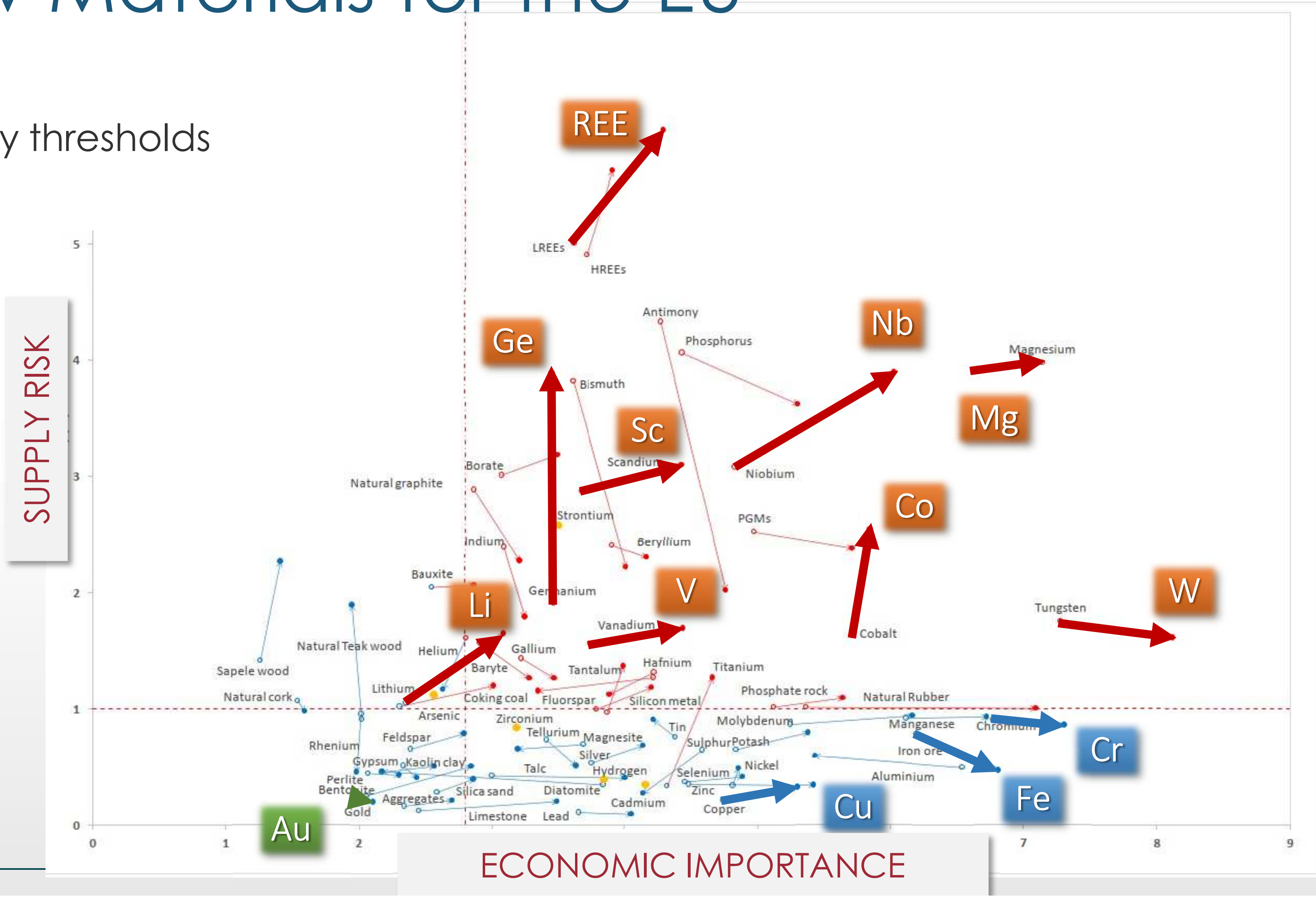
Critical Raw Materials for the EU

- Often reduced to list of 30 CRMs
  - Arbitrary threshold on supply risk and economic importance



Critical Raw Materials for the EU

- 2D plot with arbitrary thresholds
  - List of 30 CRMs
  - 2017->2020



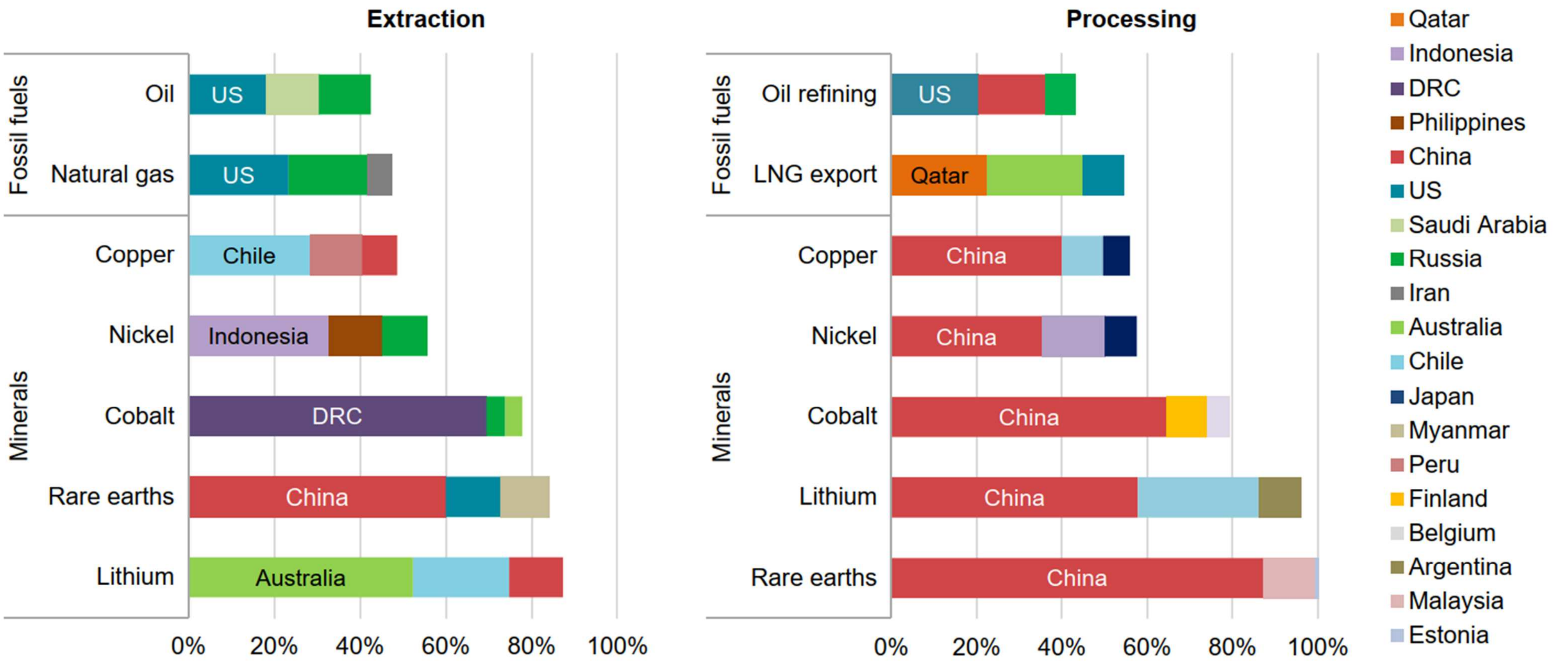
Critical Raw Materials for the EU

- Multi-factor assessment of risks all over the value chain
  - Dynamics of demand and supply
  - Concentration of production at various stages of the value chain
  - Dynamics of technology development
  - Known resources / reserves
  - Social license to operate of the primary sector
  - Potential for recycling
  - Social factors, governance, …
  - Potential for substitution
  - Prices
  - Restrictions to international trade, regulations
  - Access to funding for mining projects

- Importance of scale (**geographic**)
  - Continent, Country, Industry,…
- Importance of time (**dynamic**)
  - New innovations,

More concentrated than fossil fuel production

Share of top three producing countries in production of selected minerals and fossil fuels, 2019



Metals and SDGs

Towards Certification of Metals

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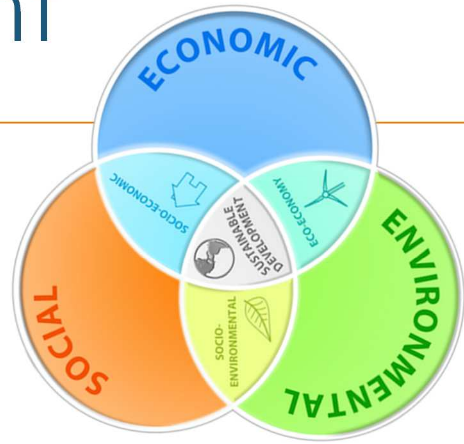
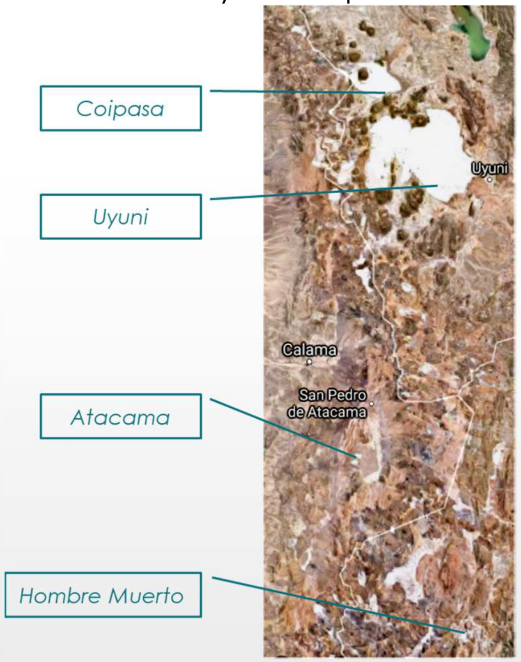
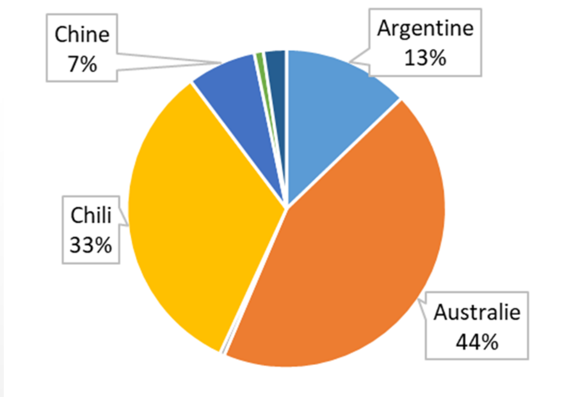
Metals and Sustainable Development



- Lithium – An economic dilemma
  - Sourced from HARD ROCK or from BRINES ?
    - Li carbonate vs hydroxide
    - Static vs. dynamic production rates



Salt lakes in the « white triangle »
CHILE-BOL-ARG



World production of Li
(data USGS,2017)

Tanco pegmatite (CAN) 6.6Mt@ 2.76%Li_2O

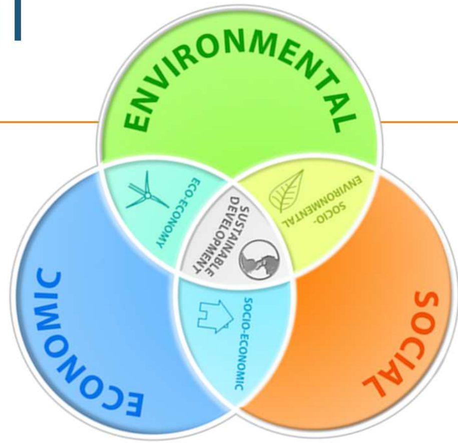
Metals and Sustainable Development

- Cobalt – A social dilemma
  - Sourced from INDUSTRIAL or ARTISANAL mines?
    - *Need for social impact indicators*

Mutanda mine (DRC). Industrial operators contribute 20 000 t Co/yr - 1800 employees

Artisanal mines (DRC) contibute 5 000 t Co/yr – 150 000 diggers

Metals and Sustainable Development



- Nickel – An environmental dilemma
  - Sourced from SIBERIAN MASSIVE SULPHIDES or TROPICAL LATERITES ?
    - *Need for environmental impact indicators*

NORILSK (RUS) 1,5% Ni

Ni sulphides
Underground mine
Pyrometallurgy
Arctic ecosystem

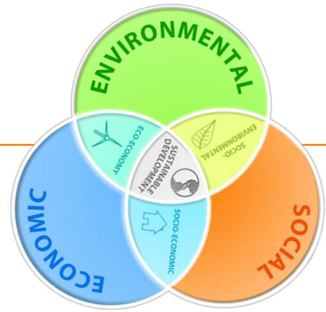
TIEBAGHI (N CAL) 1,5% Ni

Ni silicates
Open pit mining
Pressure acid-leaching
Tropical ecosystem (coral reefs)

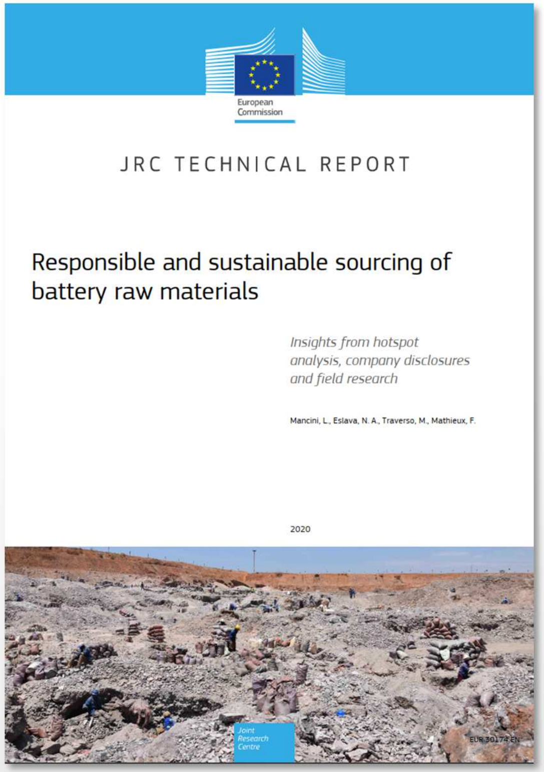
GSR (CLARION-CLIPPERTON) 1,5% Ni

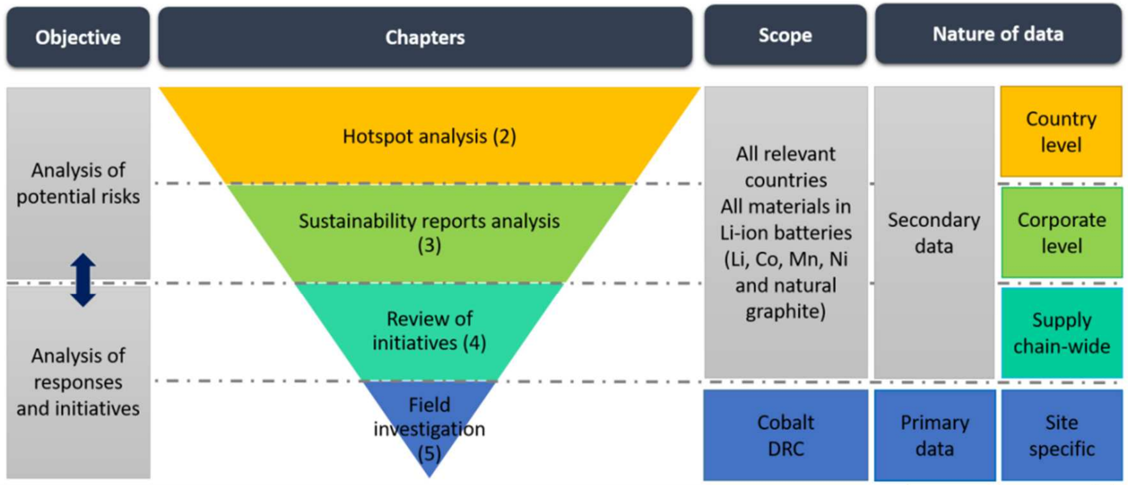
Ni hydroxides
Deep Sea mining
Acid-leaching?
Pristine environment (-4500m)

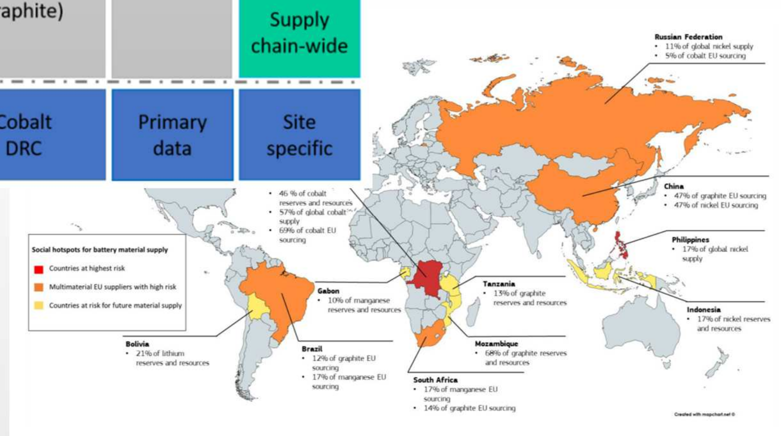
Metals and Sustainable Development



- JRC Technical Report, 2020

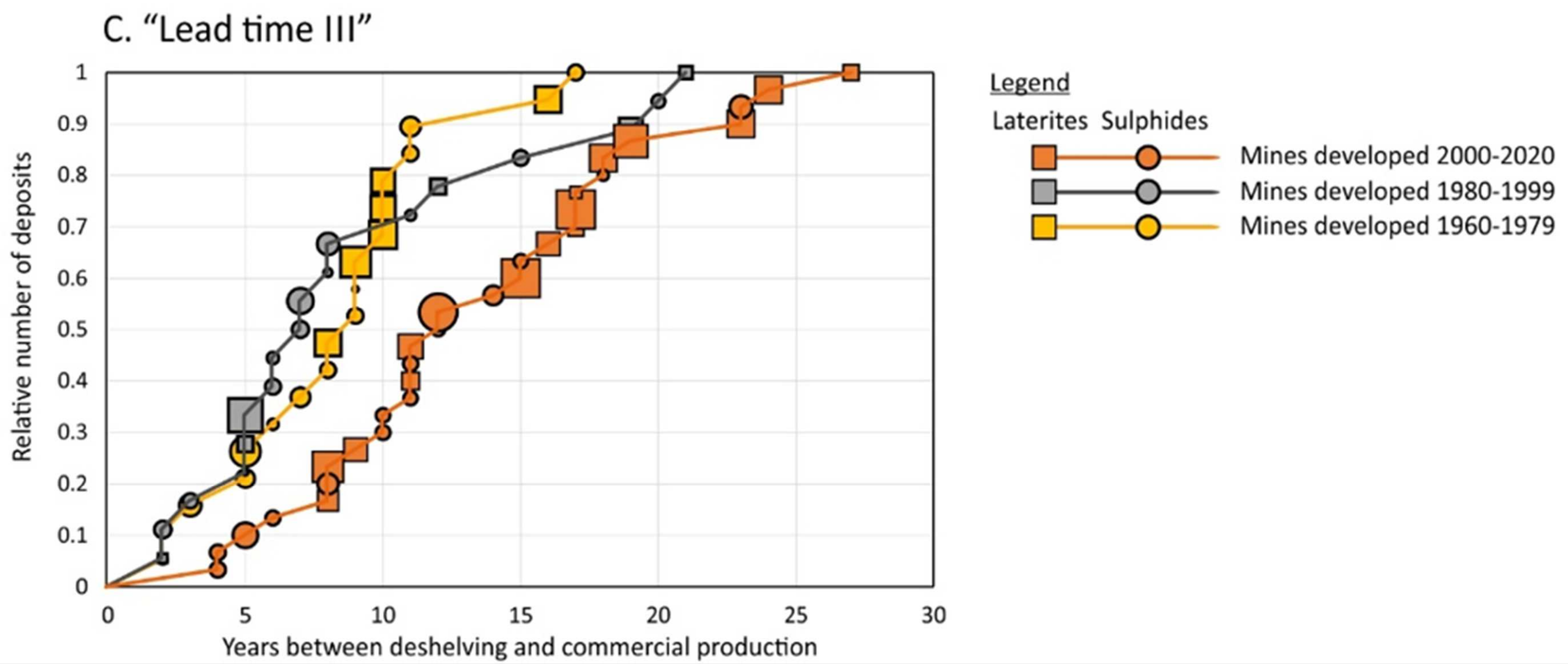






Metals and Sustainable Development

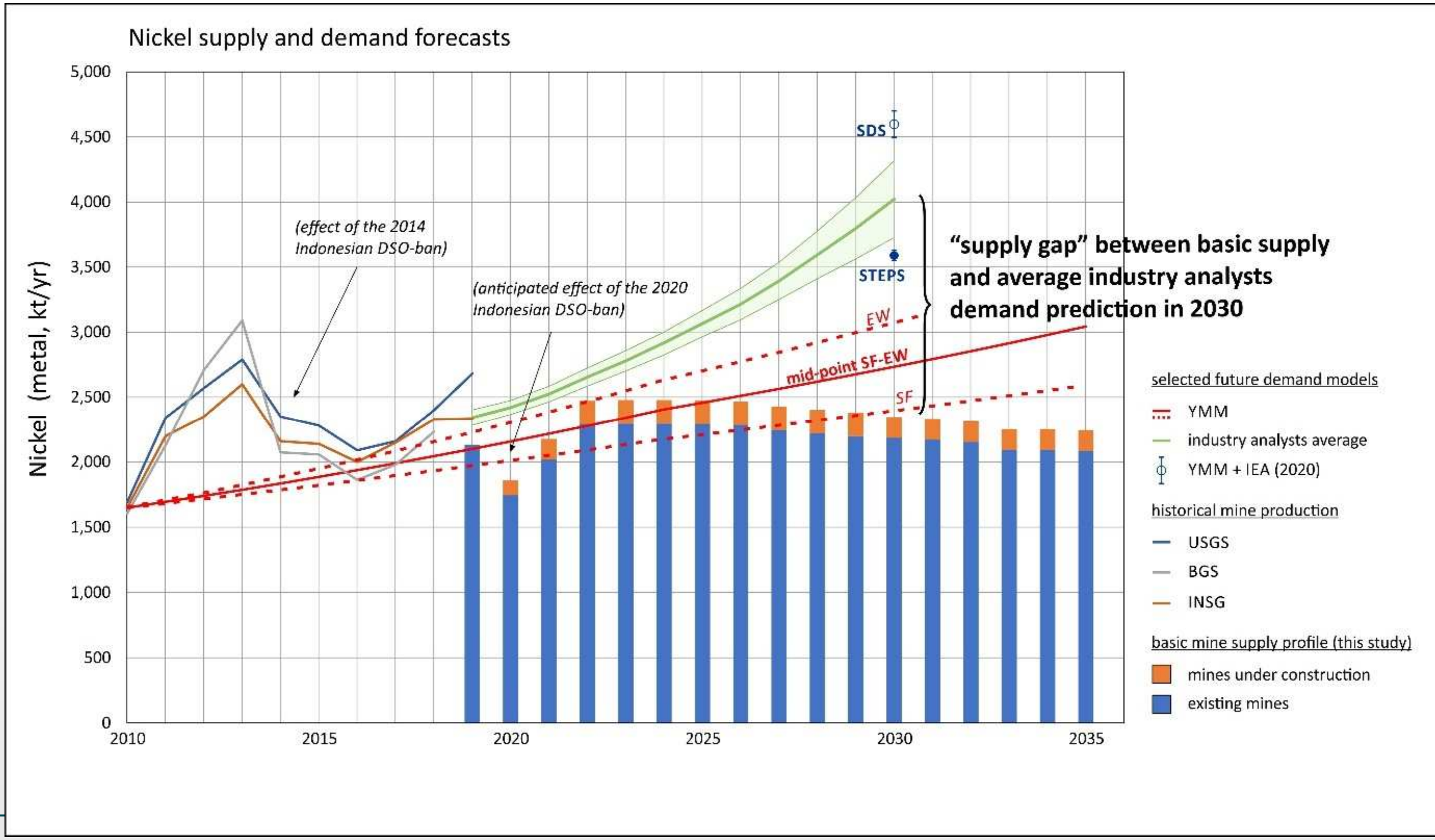
- From deshelving to production
  - *Nickel mines (Heijlen et al., 2021)*



Metals and Sustainable Development

- Anticipated supply gap for Ni
  - *(Heijlen et al., 2021)*

Figure 6. Evolution of basic primary nickel supply from land-based mines over the 2019-2035 period compared with historical production estimates from different sources (2010-2019) and with several several forecasts for total nickel metal demand. Note that these different demand models concern primary refined nickel and do not concern nickel recovered from steel scrap (i.e. recycled nickel). The light green field represents the standard error on the average demand growth prediction from six major industry analysts (Bloomberg, Bernstein, Benchmark Mineral Intelligence, Wood Mackenzie, Roskill and DBS Group Research). Red hatched lines represent demand predictions from the minimum ("SF") and maximum ("EW") scenarios from the Yale Major Metals model (YMM; Elshkaki et al., 2018). Thick red line is the mid-point growth curve for these two extremes. Blue points and associated error bars represent predicted demand growth for the EV-sector according to the STEPS- and SDS-scenario of the IEA (2020) in combination with the mid-point growth curve from the YMM-scenarios for non-EV demand. Error bars represent possible variability due to battery chemistry.



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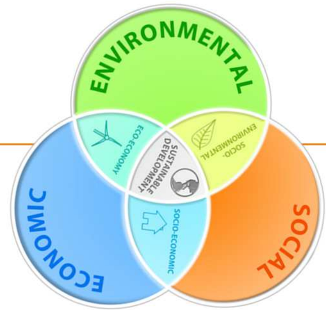
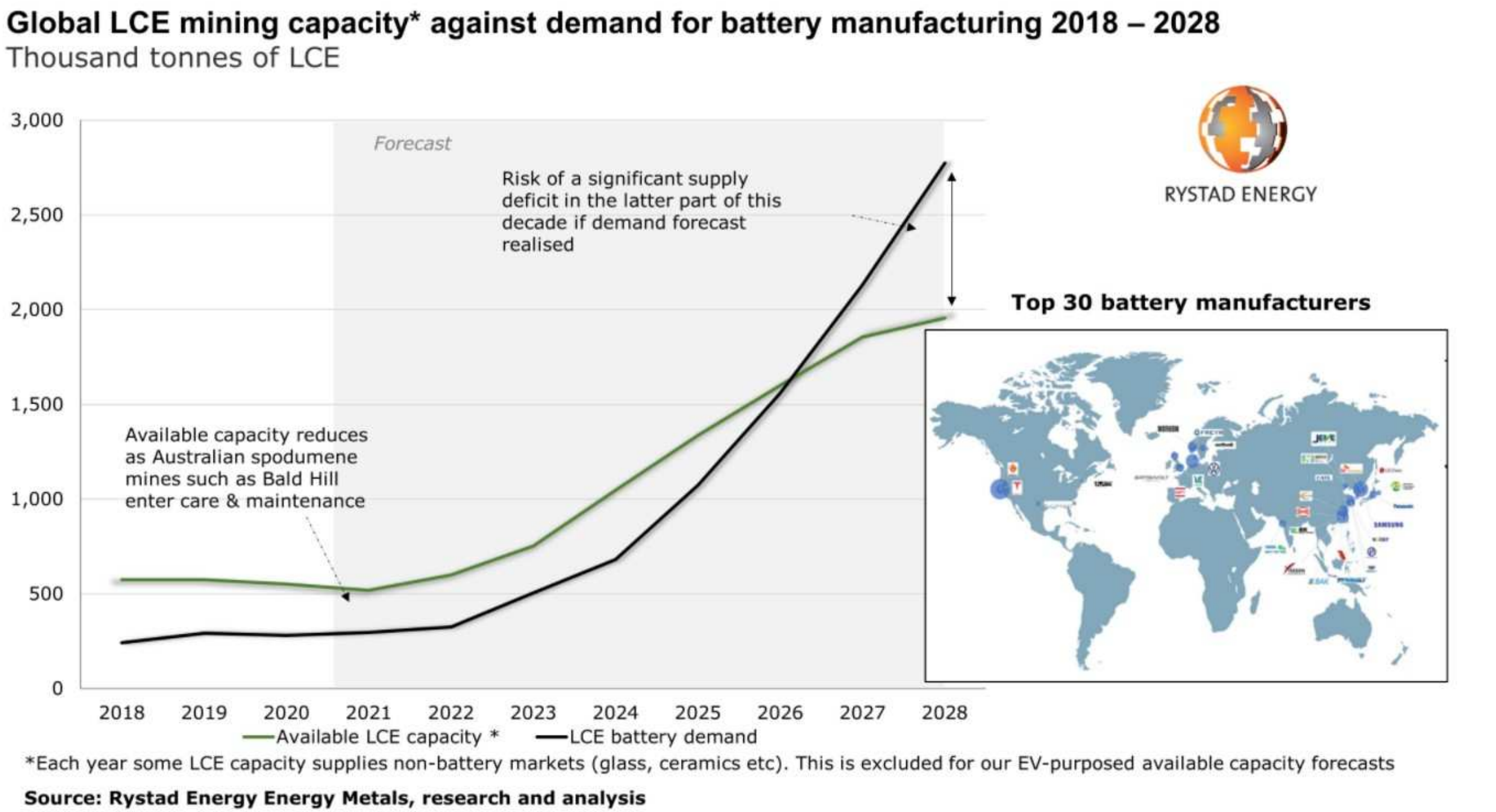
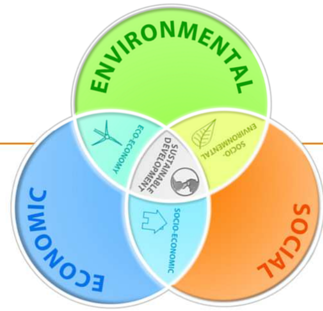
Metals and Sustainable Development



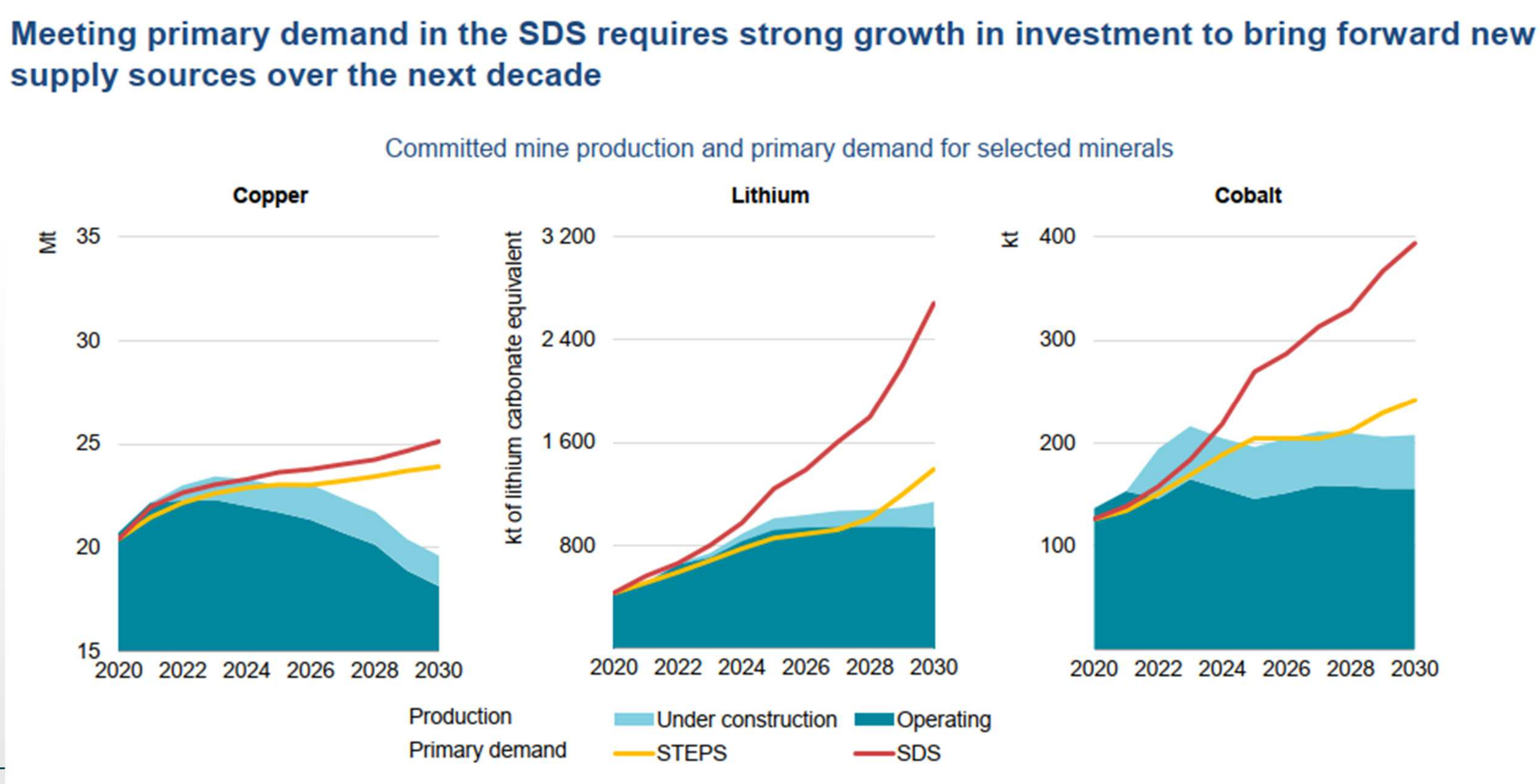
- Anticipated supply gap for Li
  - *Rystad, 2021*



Metals and Sustainable Development



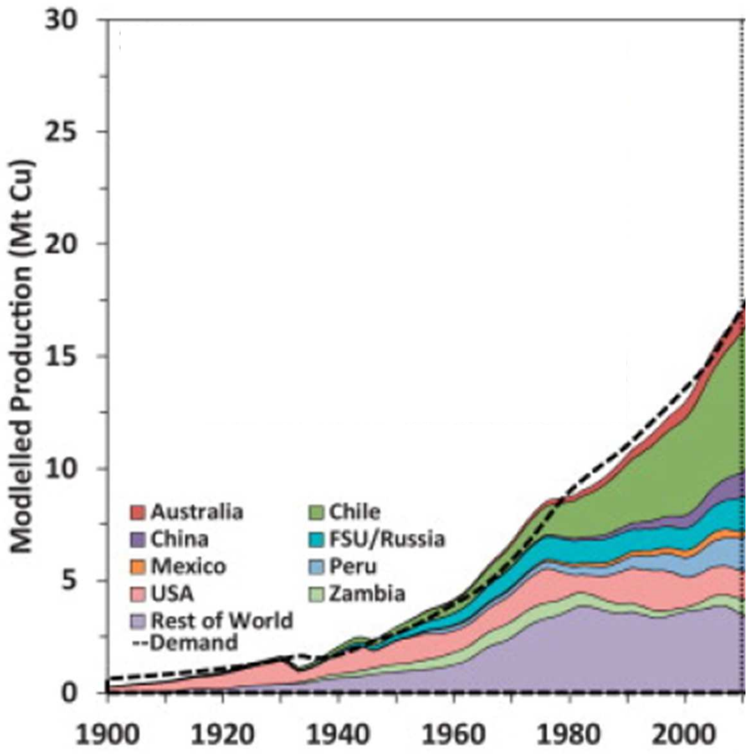
- Anticipated supply gap for Cu, Li and Co under different scenarios



Peak Everything?
Ultimate Resources

Ultimate Resources

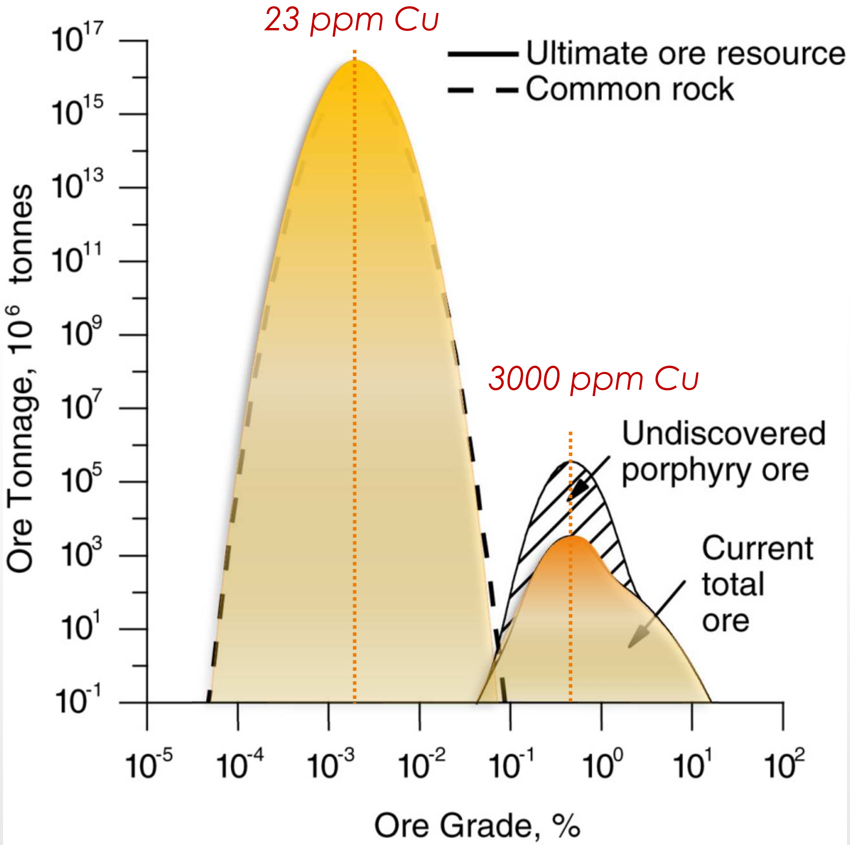
- Peak copper?



Northey et al., 2014, Modelling future copper ore grade decline based on a detailed assessment of copper resources and mining

Ultimate Resources

- Tentative modelling based on the « mineralogical barrier »



Gerst, 2008, Economic Geology
Yale Center for Industrial Ecology

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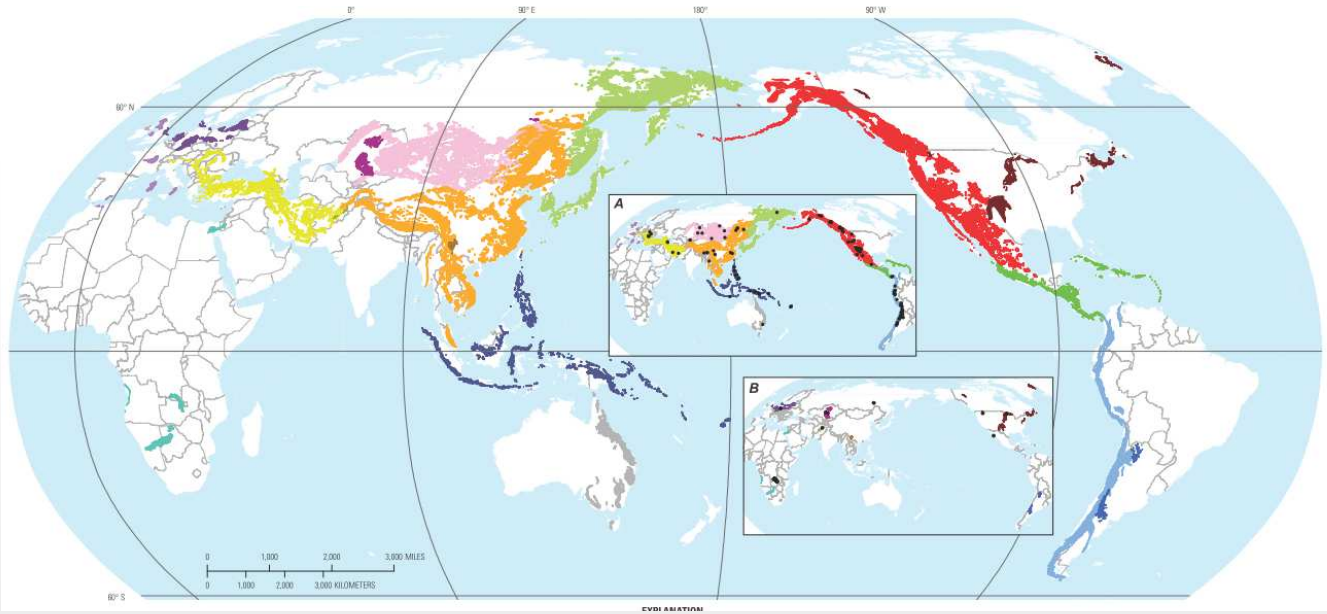
Ultimate Resources

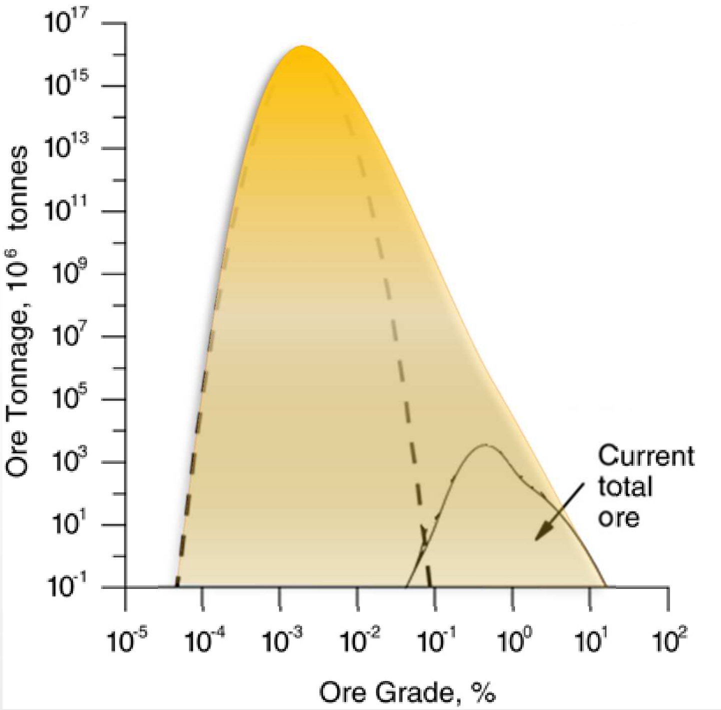
- Estimation of undiscovered resources
  - Johnson K. et al, 2014, US Geological Survey, *Estimate of undiscovered copper resources of the world*
  - 2,1 Gt identified resources + 3,5 Gt expected resources = **5,6 Gt Cu**



Based on known regions and excluding the huge potential of Africa, Greenland, etc. !?

Ultimate Resources

- Alternative model with no concentration gap



- Prospection under cover (vegetation/sand/ice)
  - Still 50 % of deposits to be discovered
- Prospection of deeper targets
  - Potential for mining down to 3km
- Potential for **89 Gt Cu**
  - Kesler, S.E., and Wilkinson, B.H., 2008, Earth's copper resources estimated from tectonic diffusion of porphyry copper deposits, Geology 36, 255–258

2000+ years?

Resource Availability

From Geosphere to Anthropopshere

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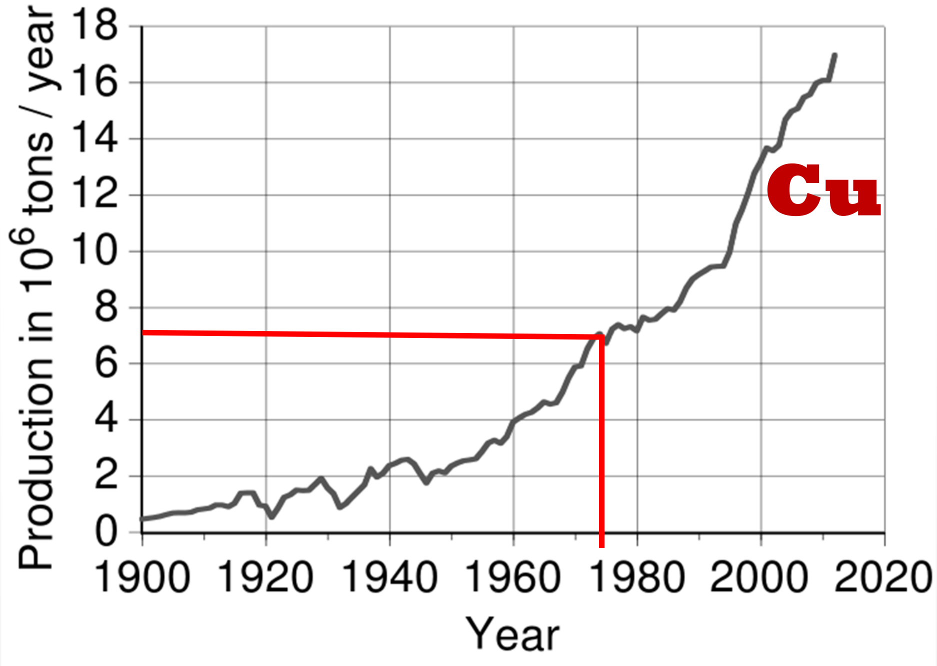
Metals and Circular Economy

- The four challenges of a more circular economy

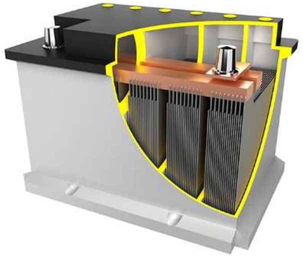
Challenge n°1 : FEED the loop

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

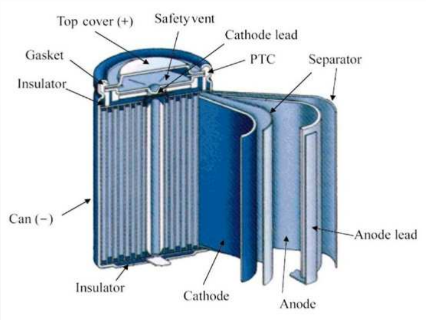


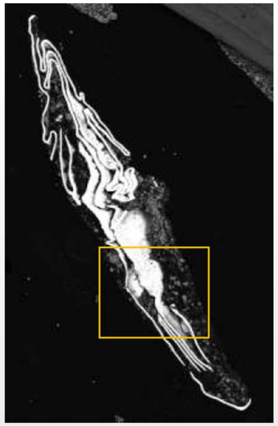
Challenge n°2 : DESIGN the loop

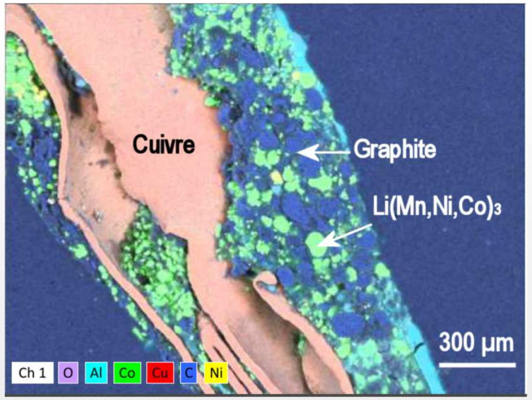
- Recyclability of products is going the wrong way
  - Lead-Acid Battery
    - Optimal collection and recycling



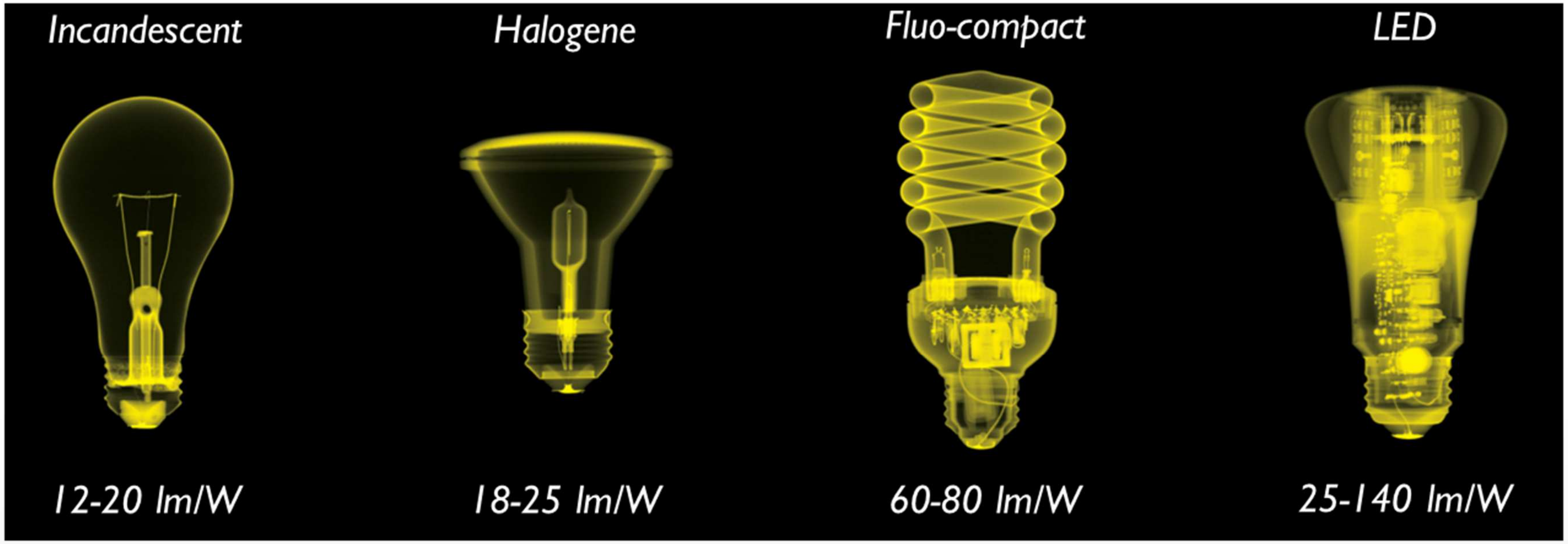
  - Li-ion Battery
    - Sorting Problems
    - Limited recovery of Co, Ni,…
    - Non-recovery of graphite, Li, …







Challenge n°2 : DESIGN the loop



Incandescent	Halogene	Fluo-compact	LED
Tungsten Glass,…	Tungsten Iodine, Bromine, … Glass,…	Tungsten Mercury, Rare Earths,… Glass, Plastics,…	Gallium Indium, Cerium, Yttrium, Copper, Silver, Silicium, … Plastics, …

Products have been optimised for their functionality. Now we have to be concerned about their recyclability and the sustainable availability of resources

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Challenge n°3 : SLOW DOWN the loop

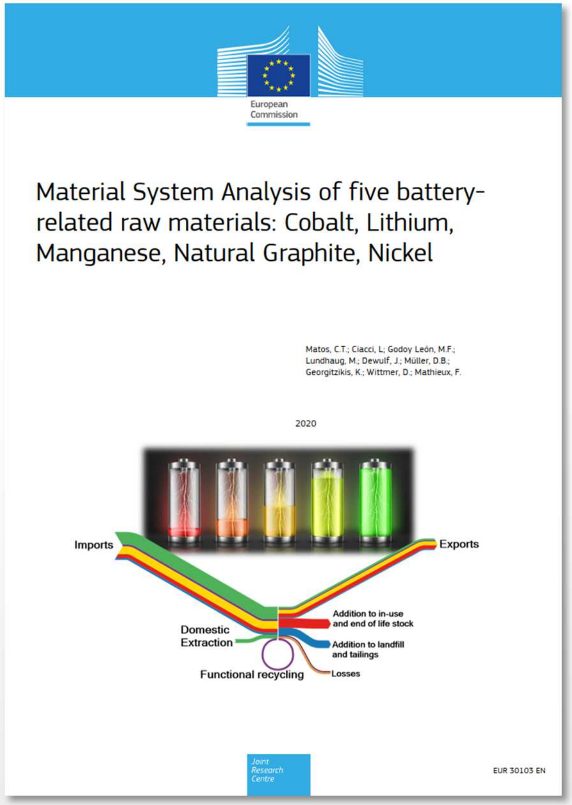
- Lifetime of most products is much too short
  - Consumer education
  - Sharing economy

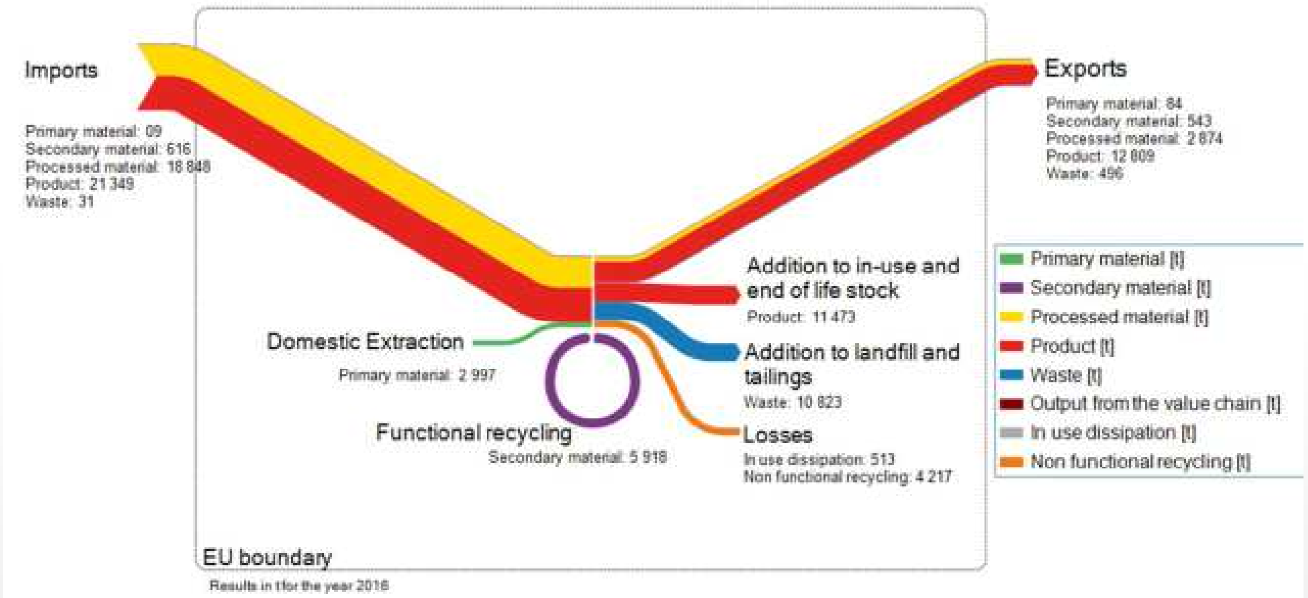
Challenge n°4 : CLOSE the loop

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

  - Educate engineers!

Material System Analysis (MSA)

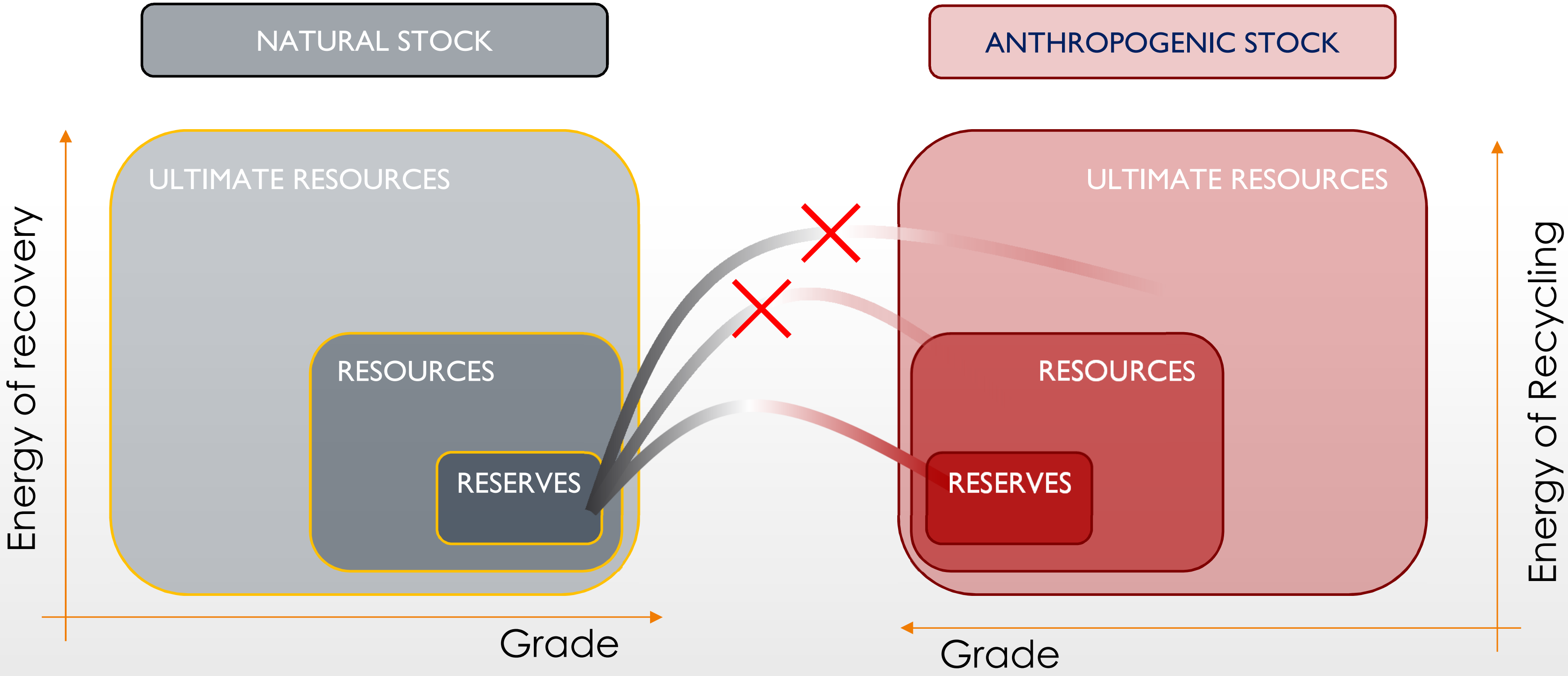




Simplified Sankey diagram of the flows of cobalt in the EU (without the UK).

Natural cycles and anthropic activities

- Geomimetism – rebuild tomorrow's deposits
  - Grade – Tonnage – Recovery



THANK YOU!

Any question ?

eric.pirard@uliege.be

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