EPFL

ENG-410

Energy supply, economics and transition: Demand and supply materials of the energy transition

Francisco Martin del Campo

Laboratory for Human-Environment Relations in Urban Systems

May 21st, 2025

Energy transition perspectives

Christophe Ballif / Philippe Thalmann / Claudia Binder

Socio-technical perspective of the energy transition

Multi-level perspective and social tipping points

Claudia R. Binder

Behavioral perspective

Diffusion of innovations and the role of proximity effects

Maria Anna Hecher and Glòria Serra Coch

Actors' perspective

Complex actor network of the Swiss energy sector

Susan Mühlemeier

Material perspective

Demand and supply materials of the energy transition

Francisco Xavier Felix Martin Del Campo

Objectives of today's lecture

Christophe Ballif / Philippe Thalmann / Claudia Binder

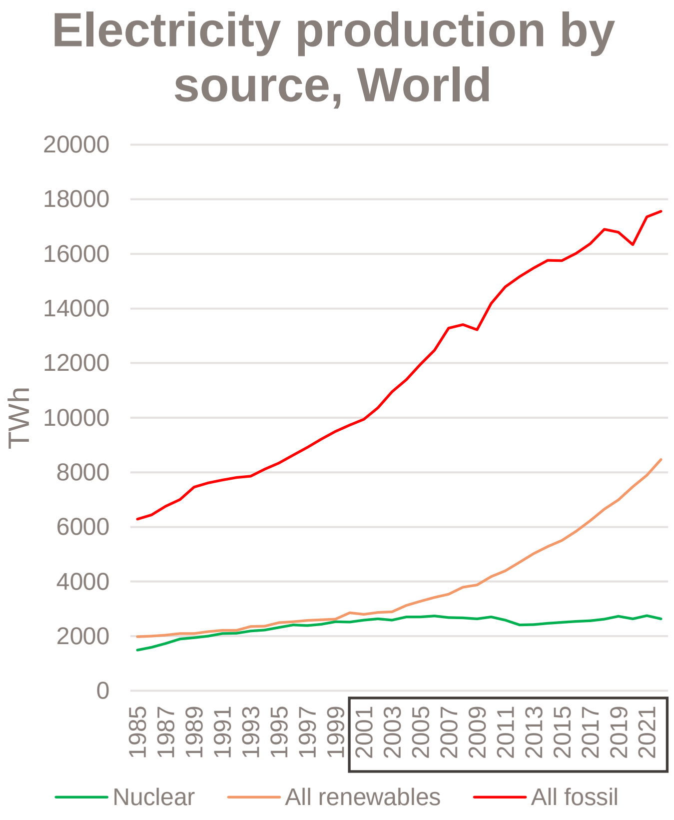
- Gain insight into the material prerequisites for sustainable energy development and their broader implications for environmental sustainability and resource management.
- Explore the evolving significance of certain materials within renewable energy technologies, and analyze the potential ramifications for global energy transition dynamics
- Explore methods to assess material criticality and the complexities of material supply, demand, and recycling.
- Touch upon the geopolitics of the energy transition, learning about the main suppliers of critical materials, and implications for energy security

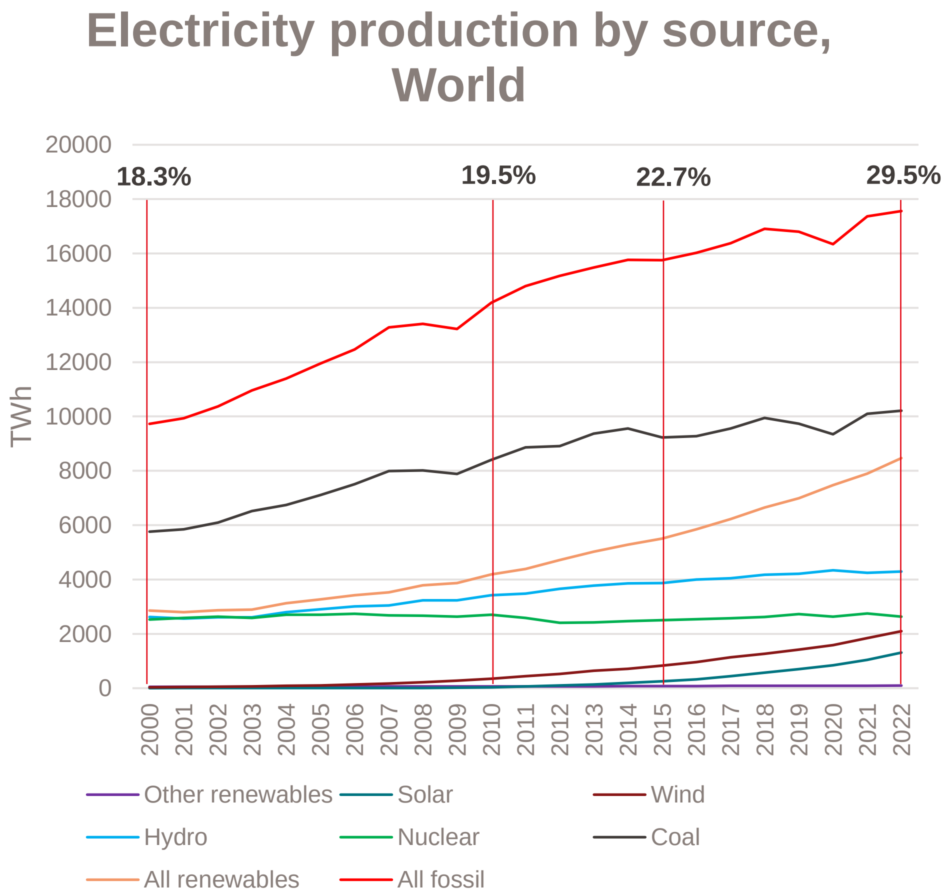
A perspective on the energy transition

- Focusing our vision from a fuel-based system (e.g., coal, oil, gas) into a material-based system (e.g., concrete, steel, copper)
- Moving from a flow of fossil fuels to a stock of materials requires building a new system
- Supply side: increasing share of renewables, including solar, wind, etc.
- Demand side: increasing share of electricity in industry, buildings, and transportation

To think about: Can a global energy system based exclusively on renewable energy sources be sustainable from a material point of view?

Transition to a low carbon energy system





Source: Our World in Data (2024); IEA, 2024a, 2024b

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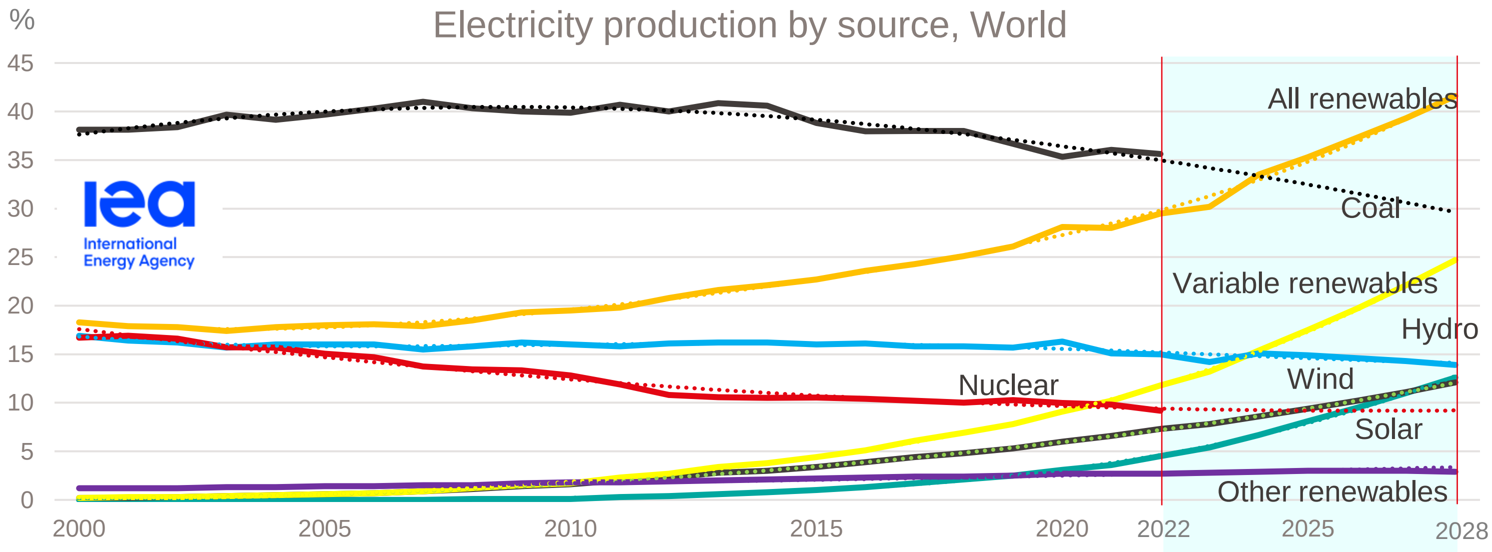
Transition to a low carbon energy system

- In 2025, renewables surpass coal to become the largest source of electricity generation.
- Wind and solar PV each surpass nuclear electricity generation in 2025 and 2026 respectively.
- In 2028, renewable energy sources account for over 42% of global electricity generation, with the share of wind and solar PV doubling to 25%.



Source: Our World in Data (2024); IEA, 2024a, 2024b

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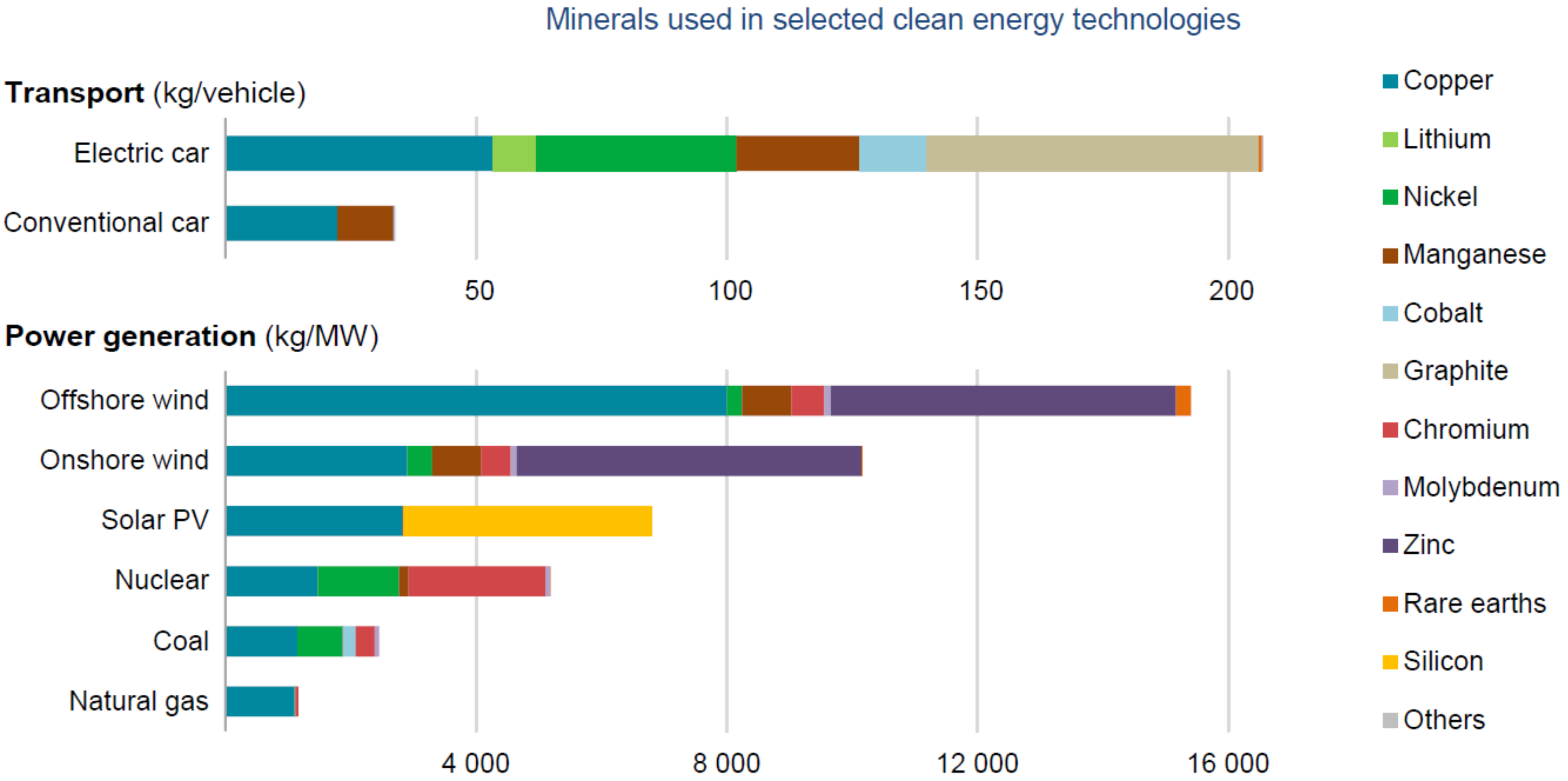
Do “high” and “low” carbon systems compare in material terms?

Christophe Ballif / Philippe Thalmann / Claudia Binder

AEP Mountaineer Plant (Coal) – West Virginia, U.S.
Capacity: **1,300** MW

Hornsea Project two – United Kingdom
Capacity: **1,300** MW

Do "high" and "low" carbon systems compare in material terms?



Source: IEA 2021 - The Role of Critical Minerals in Clean Energy Transitions

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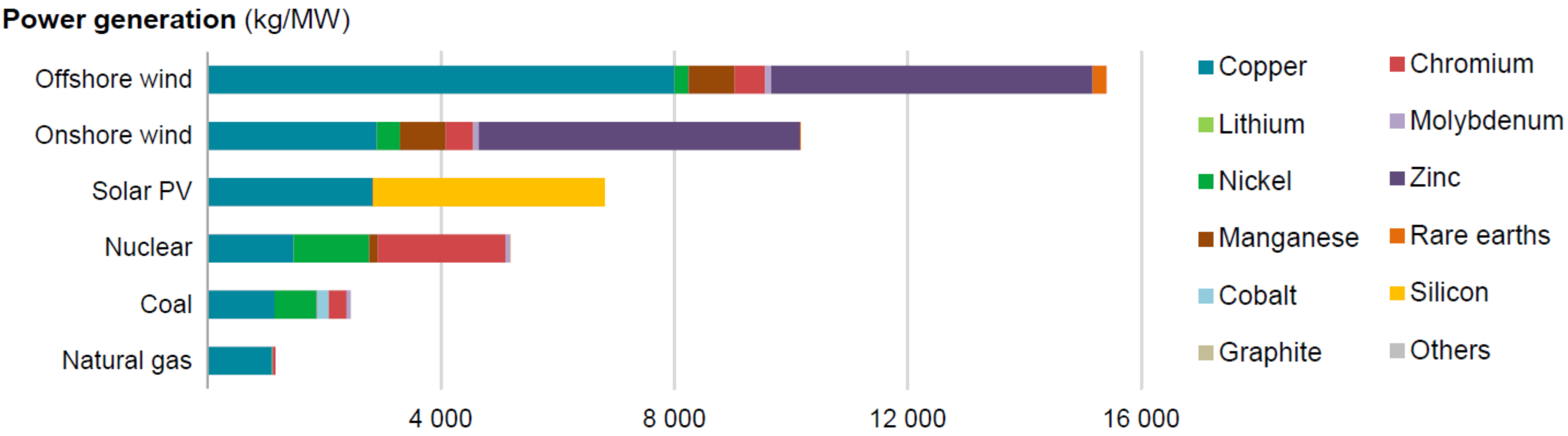
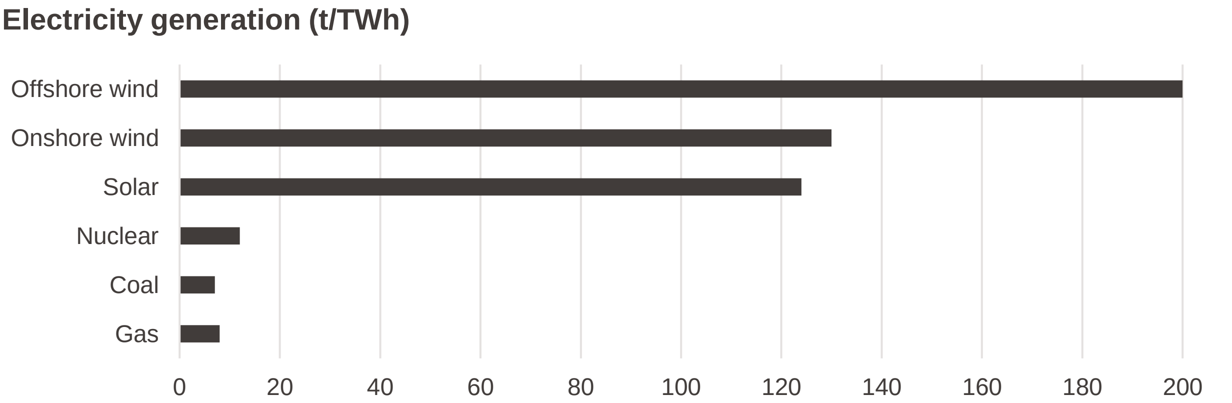
Material intensities of energy supply technologies





Considering:

- Capacity factor
- Lifetime

Source: World Nuclear Association - 2024

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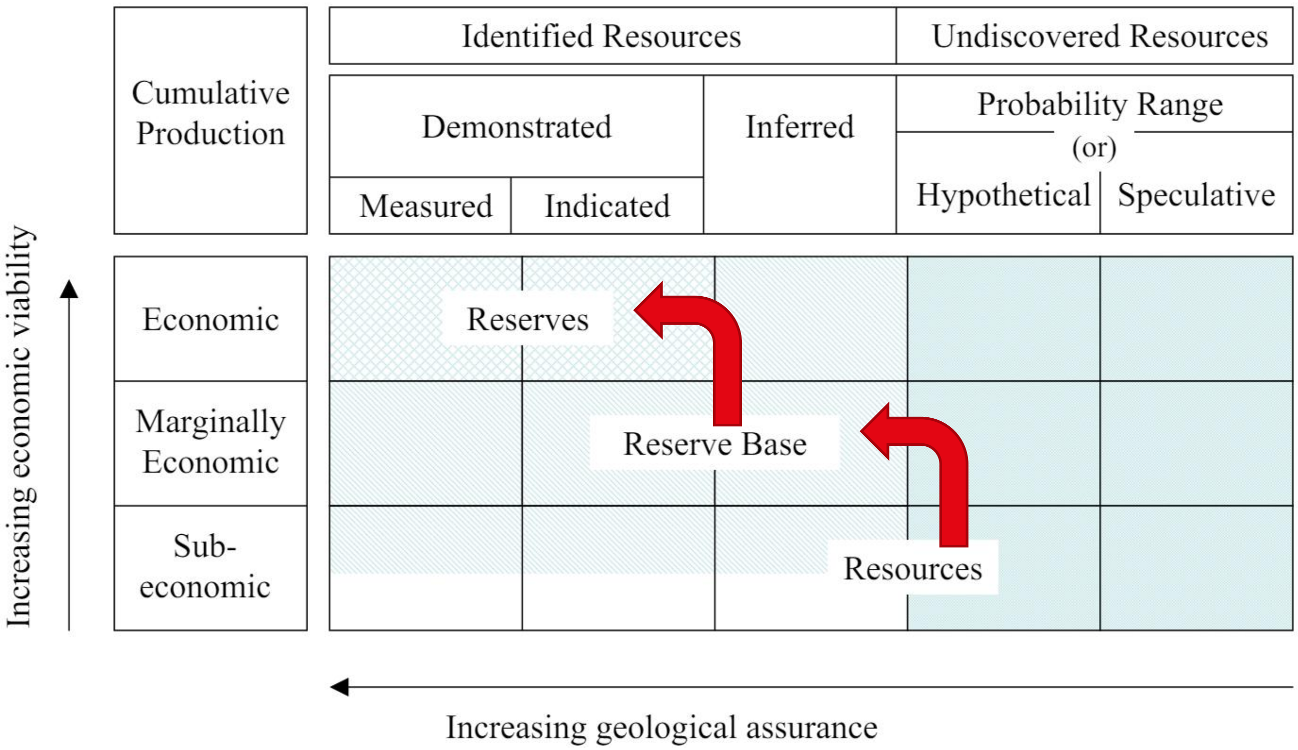
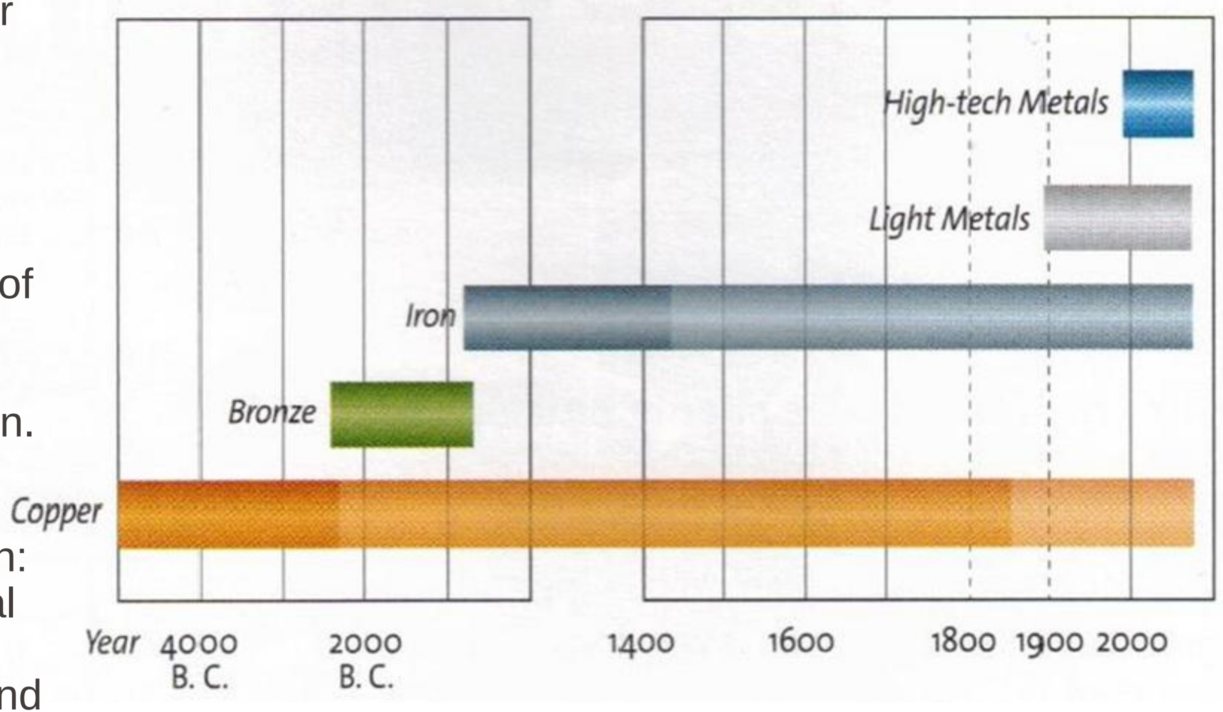
Resources management: The McKelvey chart



- ***Reserves***: "that part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth
- ***Resources***: "concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible"

Use of metals from prehistoric to modern times in Central Europe

- Material needed for their specific properties (e.g. conductors)
- Markers of stages of development of civilizations: sone, copper, bronce, iron.
- Industrial revolution: evolution of mineral industry in more diverse products and technologies



Source: Wellmer & Steinbach, 2011

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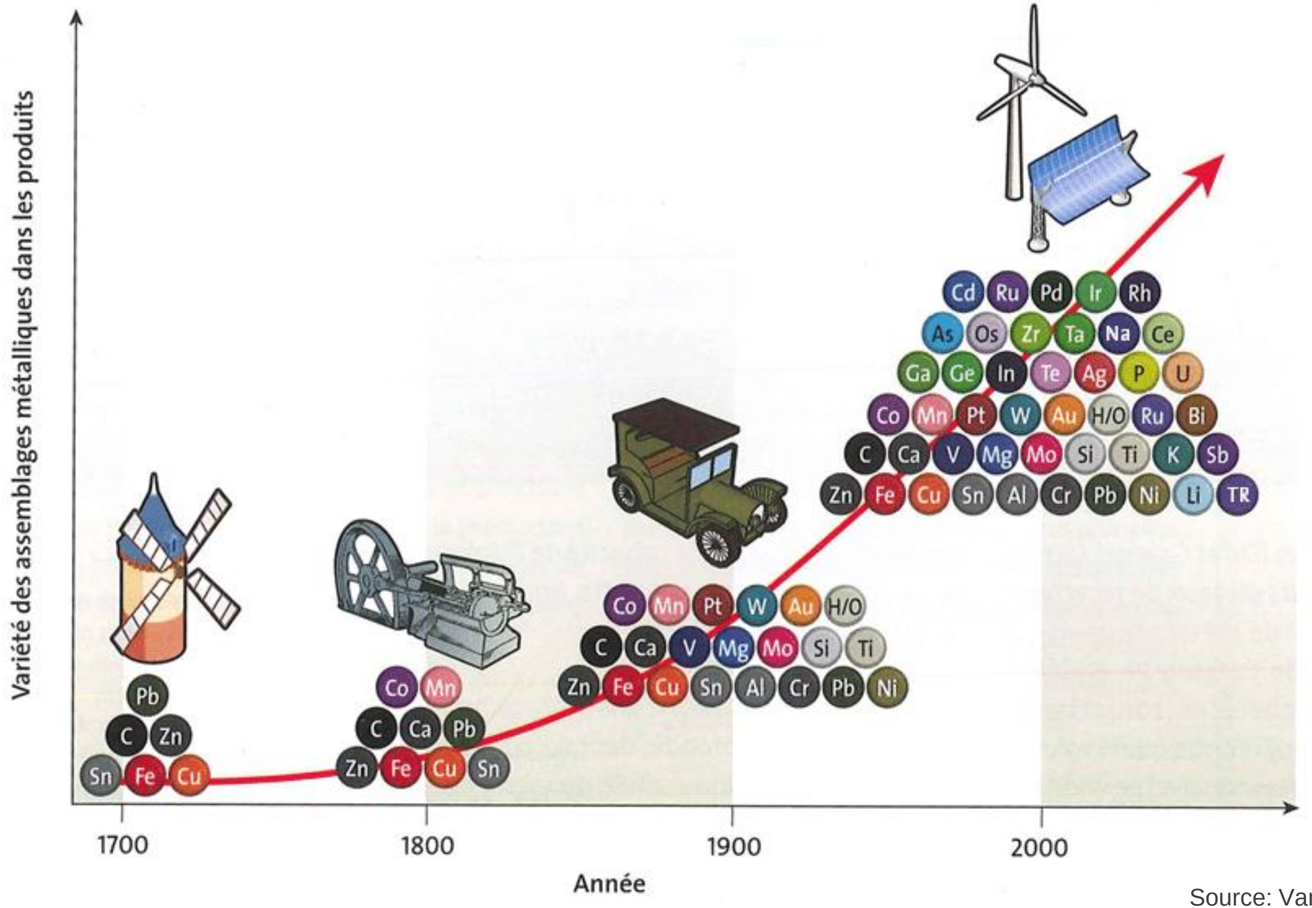
Increased material complexity of technologies



Source: Van Schaik et Reuter, 2012

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Increased material complexity of technologies

Critical mineral needs for clean energy technologies

	Copper	Cobalt	Nickel	Lithium	REEs	Chromium	Zinc	PGMs	Aluminium*
Solar PV	●	○	○	○	○	○	○	○	●
Wind	●	○	◐	○	●	◐	●	○	◐
Hydro	◐	○	○	○	○	◐	◐	○	◐
CSP	◐	○	◐	○	○	●	◐	○	●
Bioenergy	●	○	○	○	○	○	◐	○	◐
Geothermal	○	○	●	○	○	●	○	○	○
Nuclear	◐	○	◐	○	○	◐	○	○	○
Electricity networks	●	○	○	○	○	○	○	○	●
EVs and battery storage	●	●	●	●	●	○	○	○	●
Hydrogen	○	○	●	○	◐	○	○	●	◐

Notes: Shading indicates the relative importance of minerals for a particular clean energy technology (● = high; ◐ = moderate; ○ = low)
CSP = concentrating solar power; PGM = platinum group metals.
* In this report, aluminium demand is assessed for electricity networks only and is not included in the aggregate demand projections.

Source: IEA, 2021

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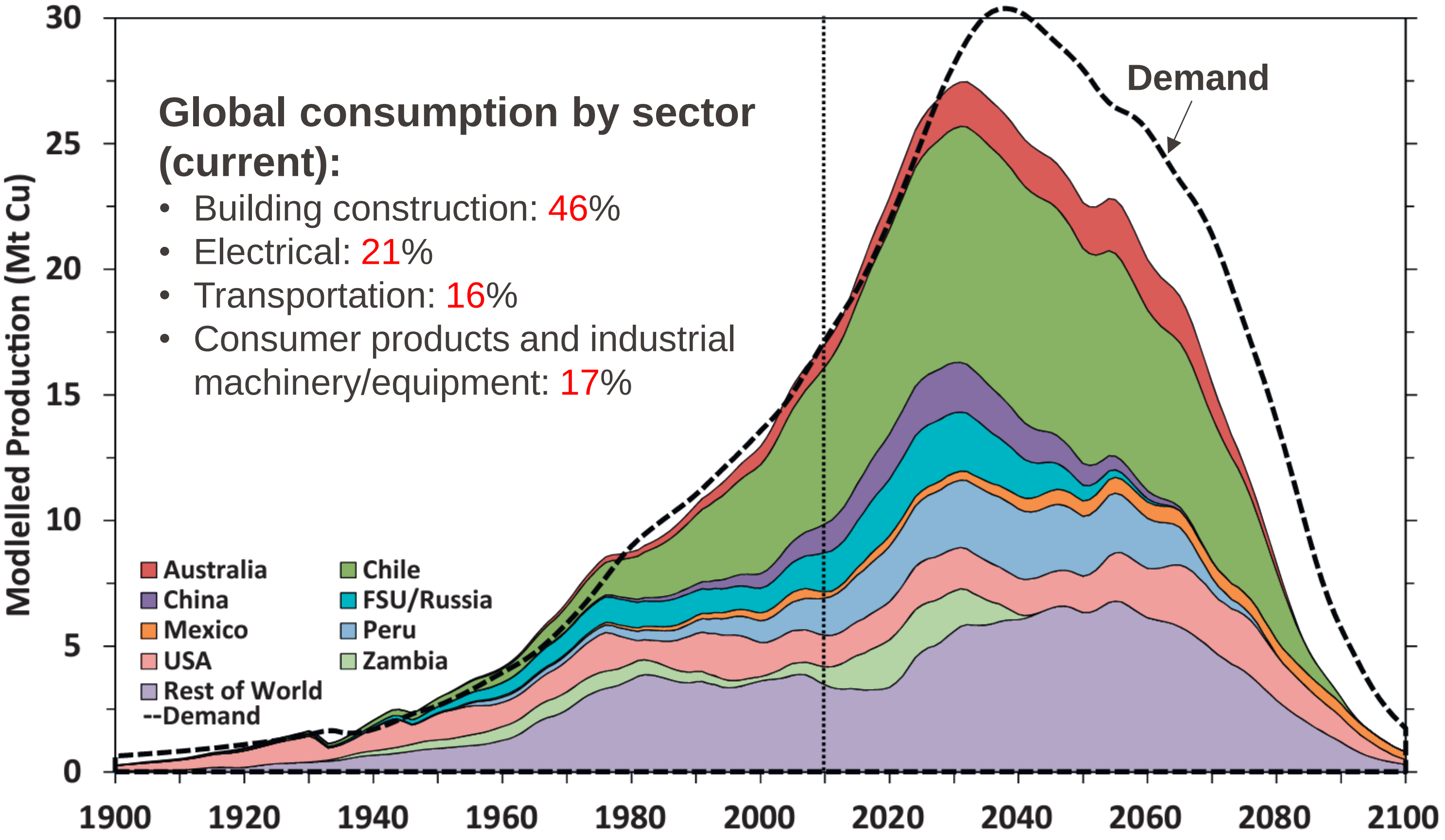
Copper as one of the critical metals

Global consumption by sector (current):

- Building construction: 46%
- Electrical: 21%
- Transportation: 16%
- Consumer products and industrial machinery/equipment: 17%



Source: Northey et al. 2014; Copper Development Association 2021

Copper as one of the critical metals

05-13-2025

Geologists discover the largest copper, gold, and silver deposit in the last three decades

By Jordan Joseph
Earth.com staff writer

Critical metals and global demand

The deposit includes high-value copper, which is crucial for green energy, electronics, and large-scale machinery. Experts note that surging electric vehicle manufacturing and renewable power installations will likely keep demand strong.

THE EXPRESS TRIBUNE
TODAY'S PAPER | MAY 20, 2025 | EPAPER

World

South America's largest copper discovery in 30 years found on Chile-Argentina border

Lundin Mining estimates Filo del Sol project holds 13 million tons of copper, plus gold and silver deposits.

News Desk | May 06, 2025

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Methodology: Supply/demand for energy metals

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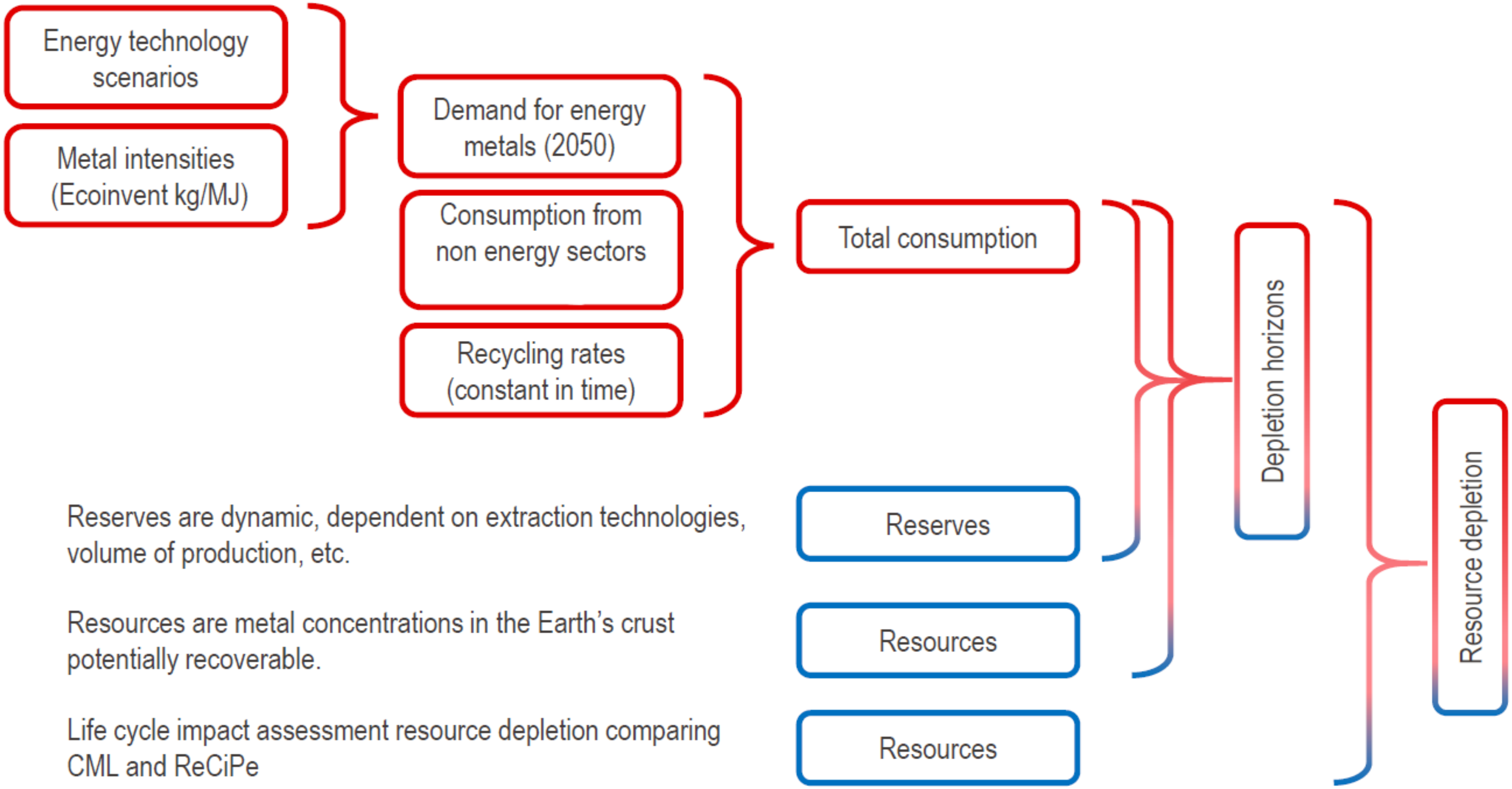


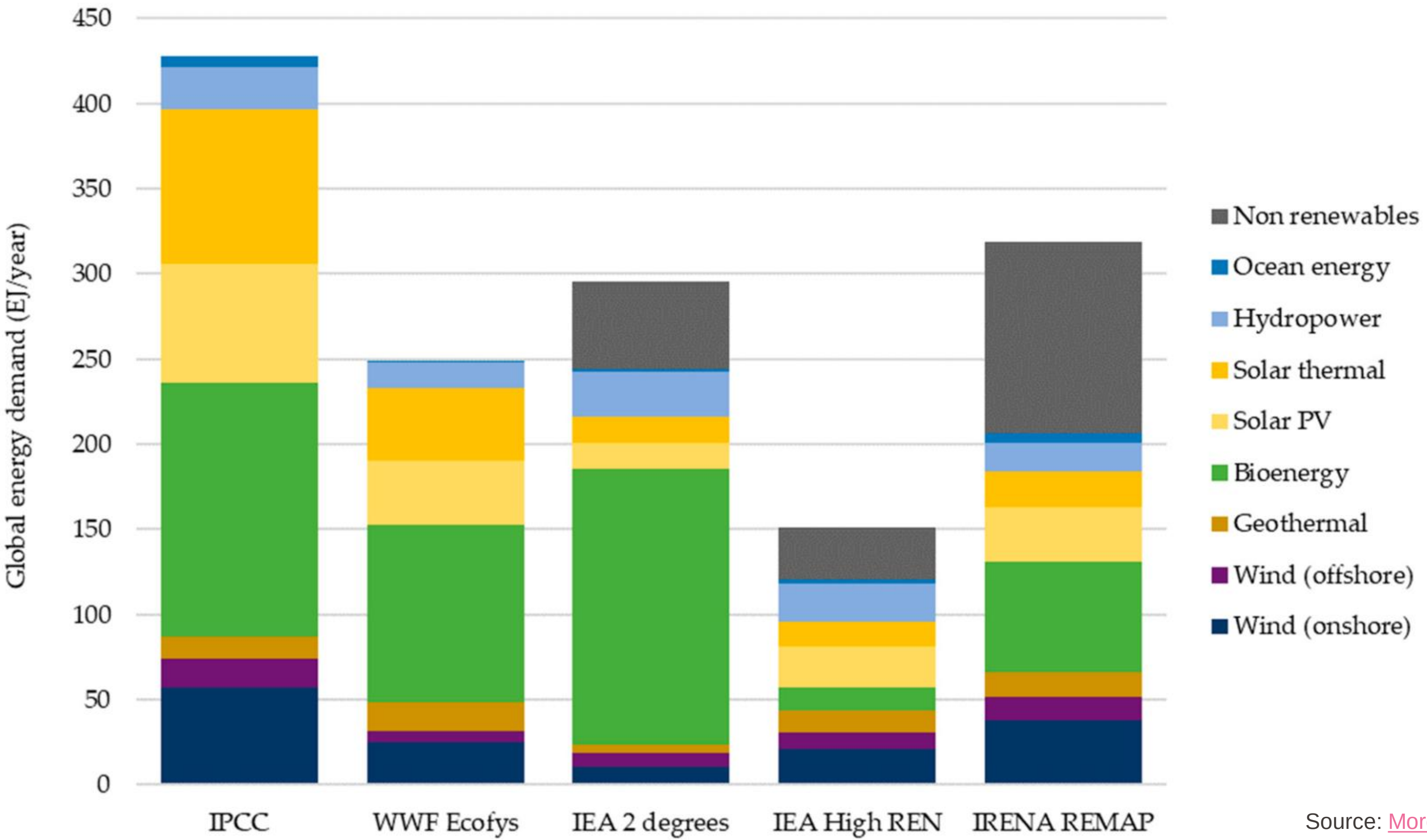
Reserves are dynamic, dependent on extraction technologies, volume of production, etc.

Resources are metal concentrations in the Earth's crust potentially recoverable.

Life cycle impact assessment resource depletion comparing CML and ReCiPe

Source: Moreau et al., 2019

Scenarios for global energy supply/demand by 2050



Source: Moreau et al., 2019

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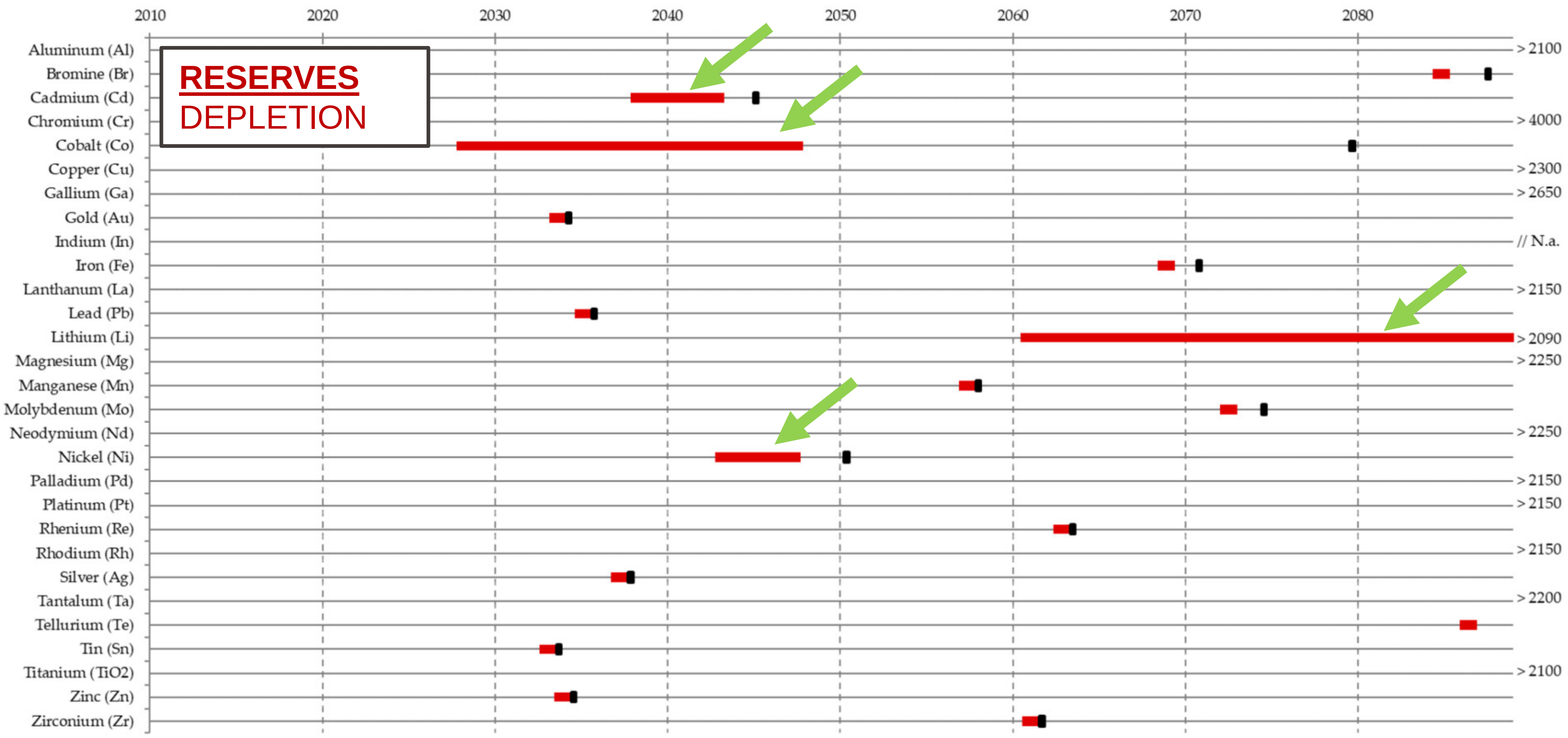
Reserves depletion: current vs low carbon constraints



*Range indicates variation across renewable energy scenarios. N.a.= No data available
*Black dots indicate the depletion years given the current demand alone, that is, without the deployment of a renewable energy system

Source: Moreau et al., 2019

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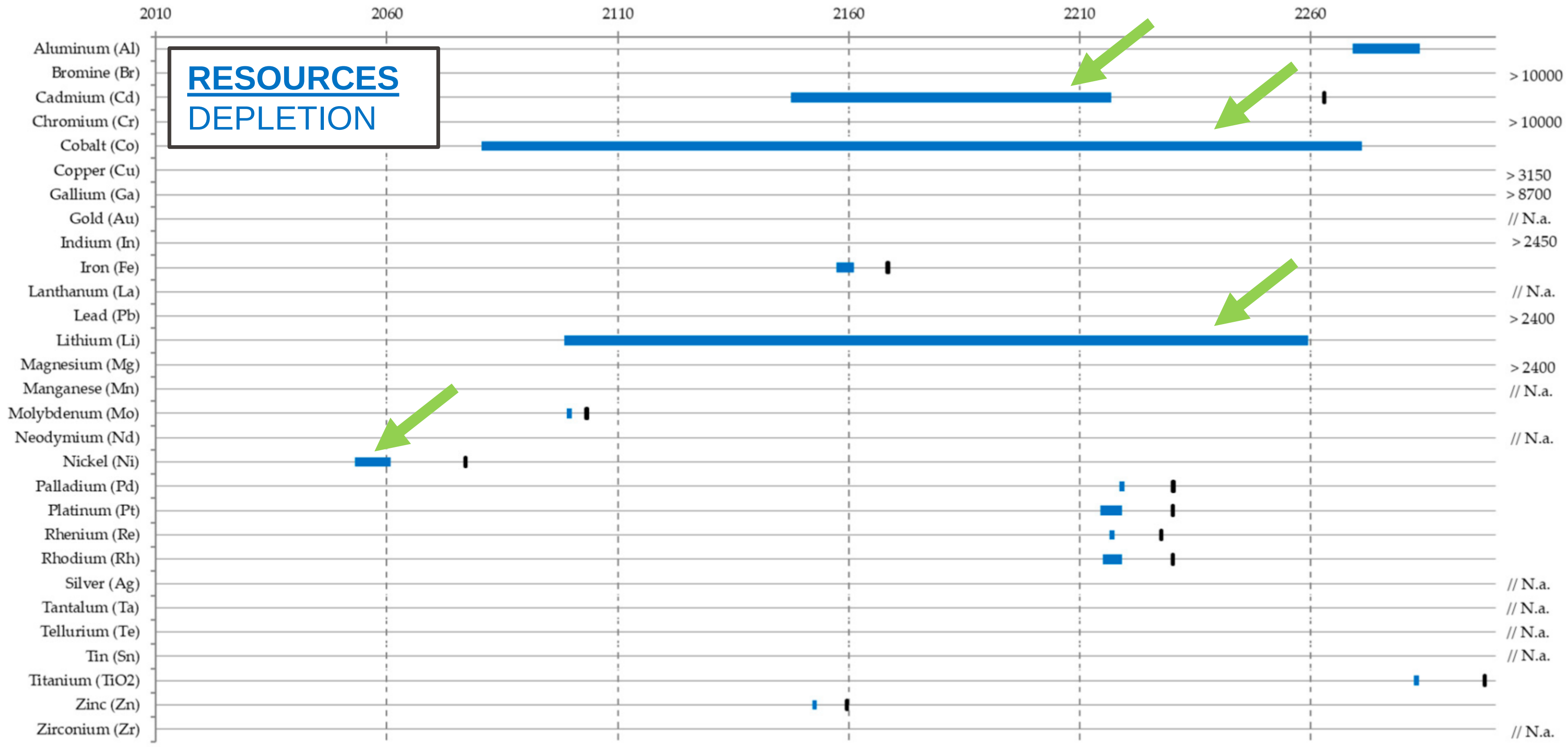
Resources depletion: current vs low carbon constraints



*Range indicates variation across renewable energy scenarios. N.a.= No data available
*Black dots indicate the depletion years given the current demand alone, that is, without the deployment of a renewable energy system

Source: Moreau et al., 2019

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Resource depletion in Life Cycle Assessment

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- **Abiotic depletion**: Removal of abiotic resources from the earth, or the depletion of non-living natural resources
- For mineral and other materials, the ***Abiotic Depletion Potential*** (**ADP**) is estimated according to their stock **availability** at a global scale

- $ADP_i = \dfrac{Rate\ of\ extraction_i}{{Reserves_i}^2} \times \dfrac{Reserves\ of\ reference\ substance^2}{Rate\ of\ extraction\ of\ reference\ substance}$

Rate of extraction: world annual production (in kg/year) of the material *i*

Reserve: estimated global reserve (in kg) of the material *i*

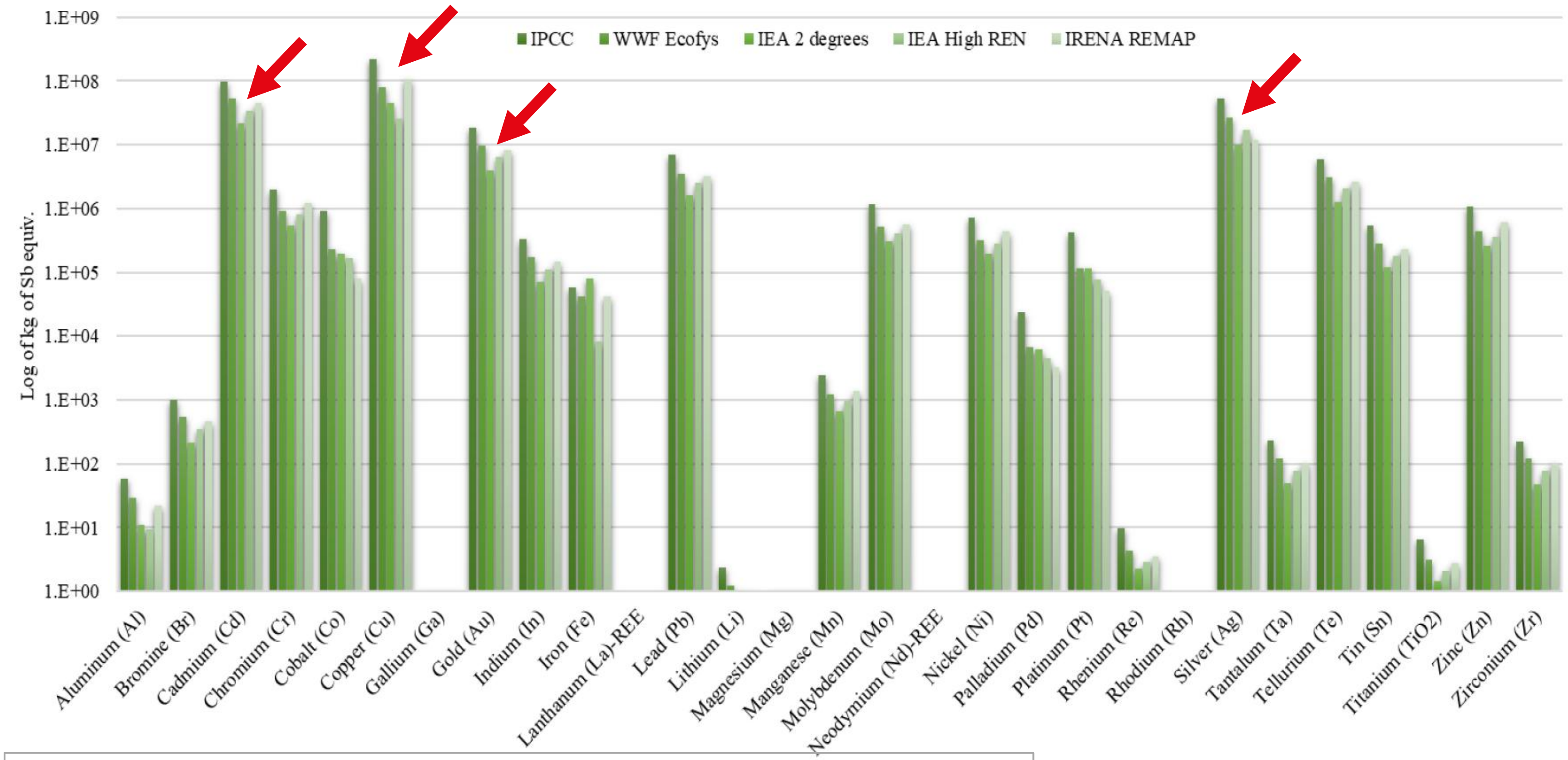
- Reference substance (metal) in Life Cycle Assessment methodologies:

Copper (Cu) for ReCiPe methodology

Antimony (Sb) for CML methodology

Source: Designing Buildings Ltd., 2024; Moreau, 2021

Resource depletion in Life Cycle Assessment



*Impact scores on a log scale per material and scenario using **CML**

Source: Moreau, 2021

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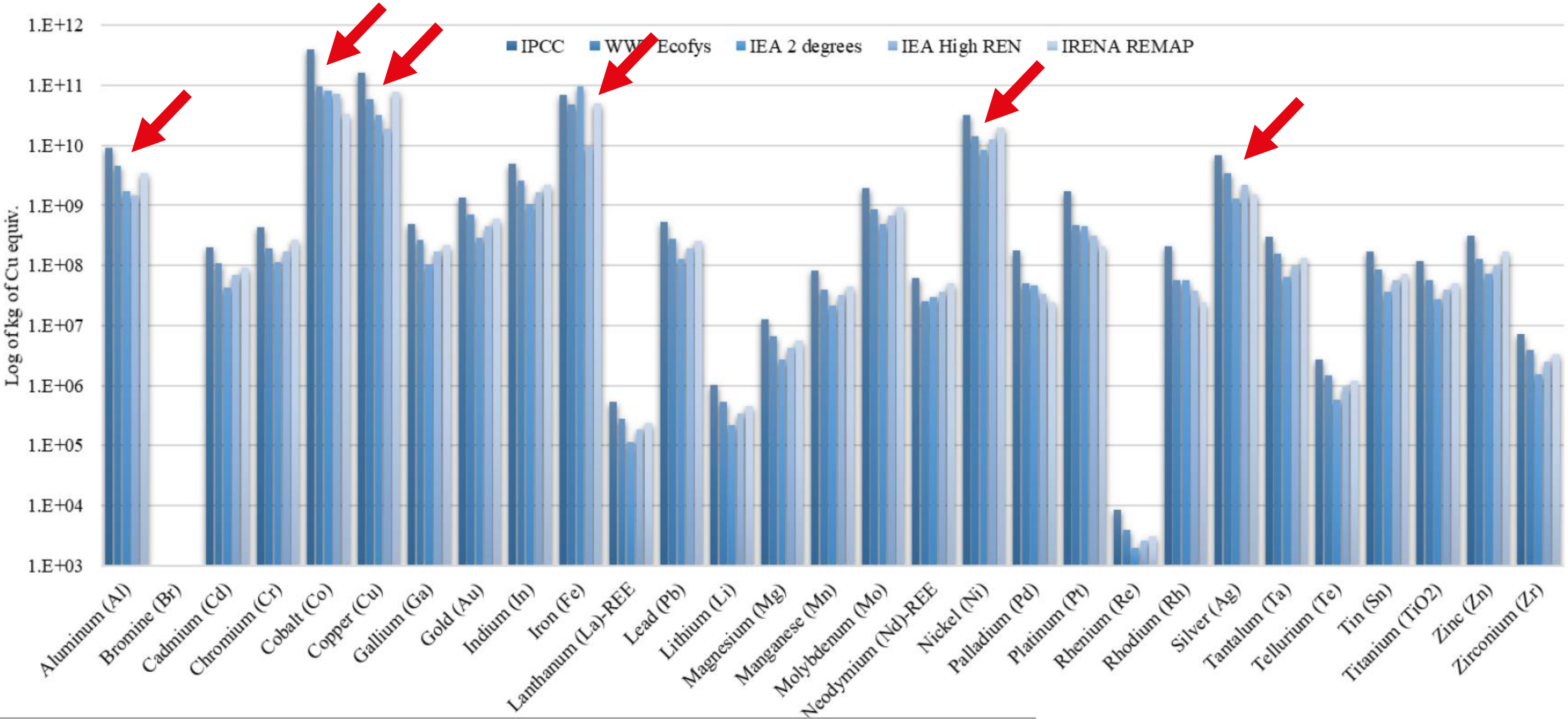
Resource depletion in Life Cycle Assessment



*Impact scores on a log scale per material and scenario using **ReCiPe**

Source: Moreau, 2021

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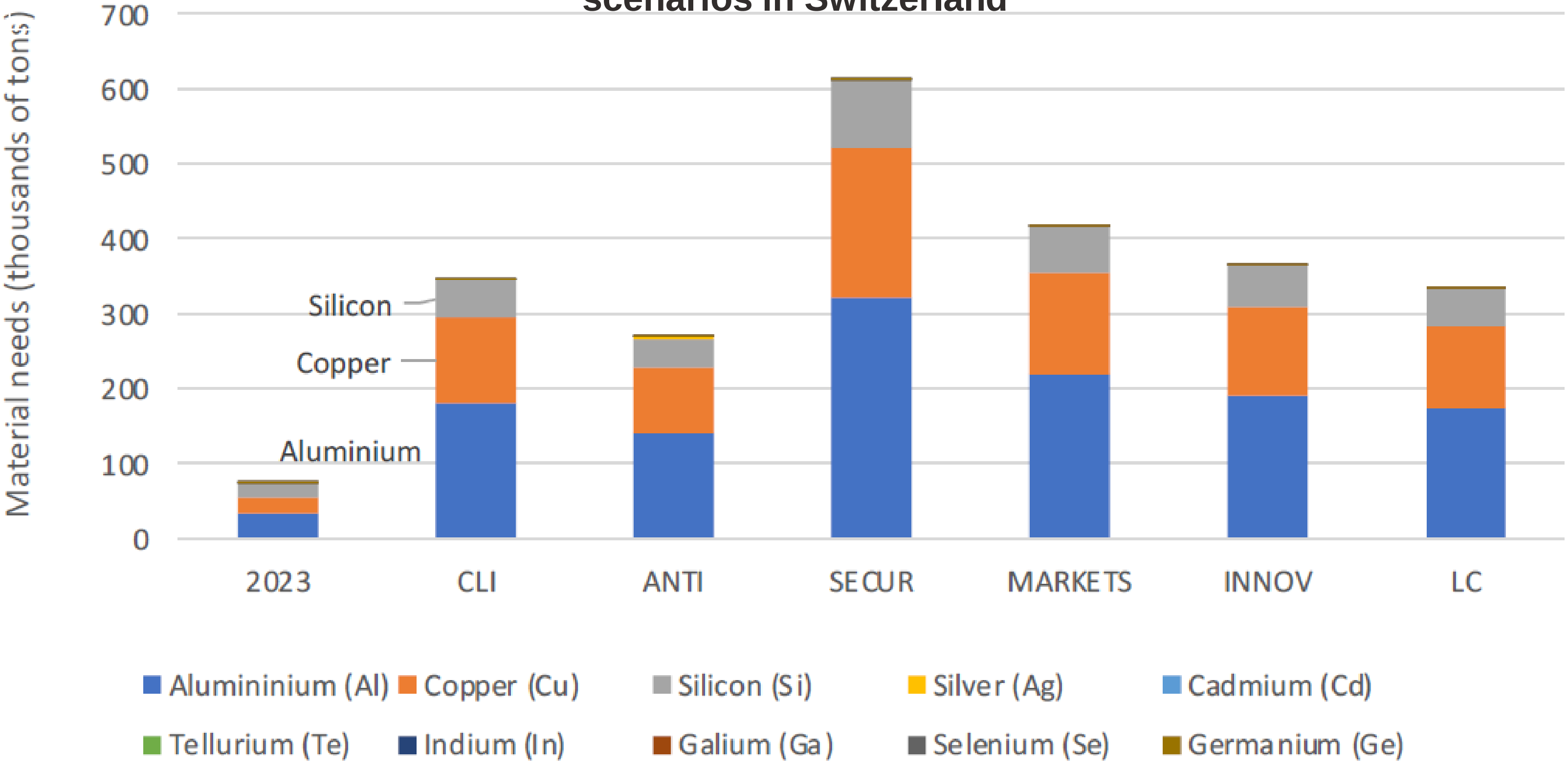
The Swiss Energy transition

Scenario	Description	Switzerland in 2050
CLI	Full implementation of the energy agreements	- Environmental policies and practices put in place. - Energy demand reduced in end-hand sectors. - European level CO2 grids.
ANTI	Low international cooperation in mitigating climate change	-Limited technological progress leads to high capital costs for low carbon solutions. - Development at local scales (high willingness to pay, local energy networks & self-sufficiency)
SECUR	International trade is controlled for energy carriers	-Restricted access to energy resources leads to an increase in energy import prices. - Domestic renewable energies exploited at their maximum potential. - Annual net energy imports as close to 0 as possible.
MARKETS	High global cooperation	-Increased availability of imported resources leads to more affordable energy -Development of local energy markets in coordination with national ones.
INNOV	Variant of MARKETS with closer international cooperation	-Increased R&D expenditures lead to low-carbon energies costs reduction.
LC	Least cost variant of the CLI scenarios	-Resource potentials are set to the levels of CLI.

Source: Panos et al, 2023, HERUS Laboratory, 2024

The Swiss Energy transition – Solar Panels

Current (2023) and 2050 raw material requirements for Solar Panels in different scenarios in Switzerland



Source: HERUS Laboratory, 2024

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The Swiss Energy transition – Solar Panels

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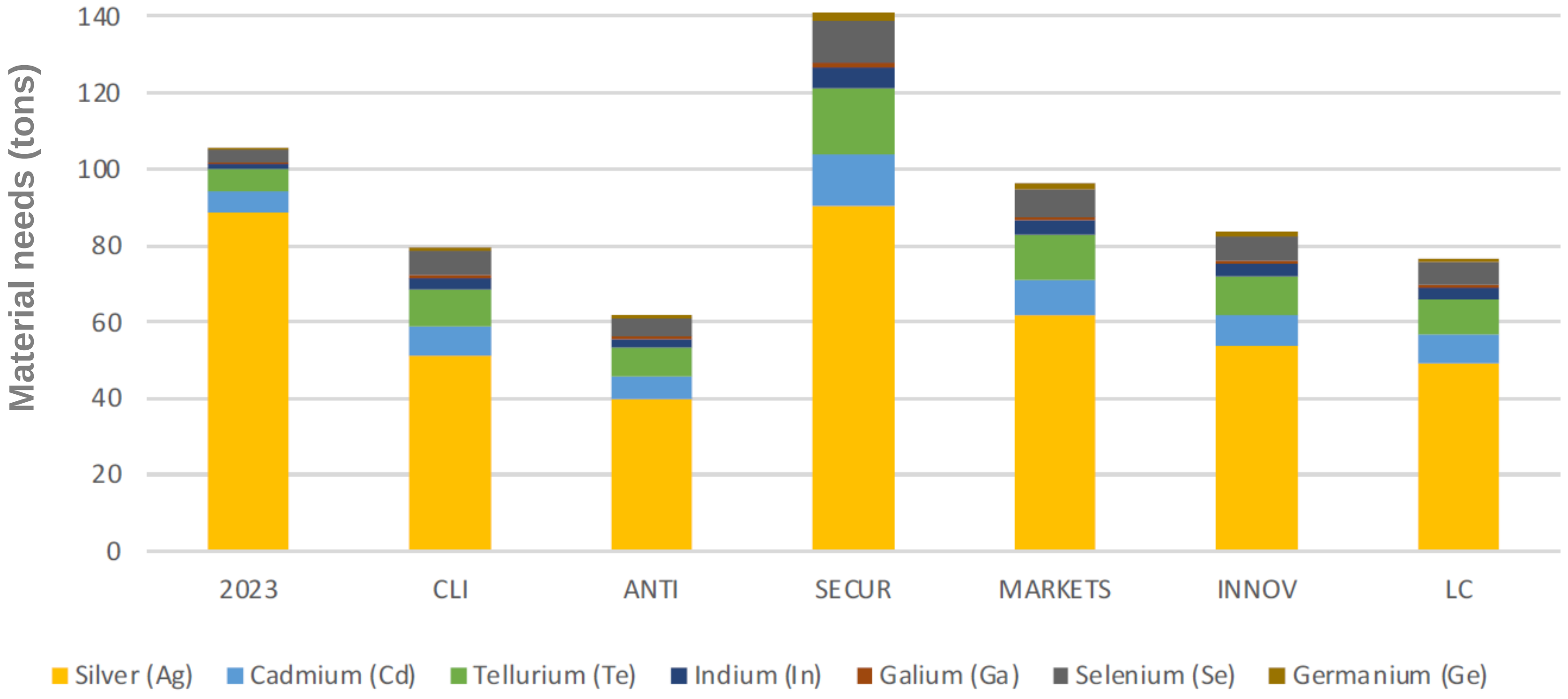
ENERGY SUPPLY, ECONOMICS AND TRANSITION

Current (2023) and 2050 raw material requirements for Solar Panels in different scenarios in Switzerland



Source: HERUS Laboratory, 2024

The Swiss Energy transition – Wind turbines

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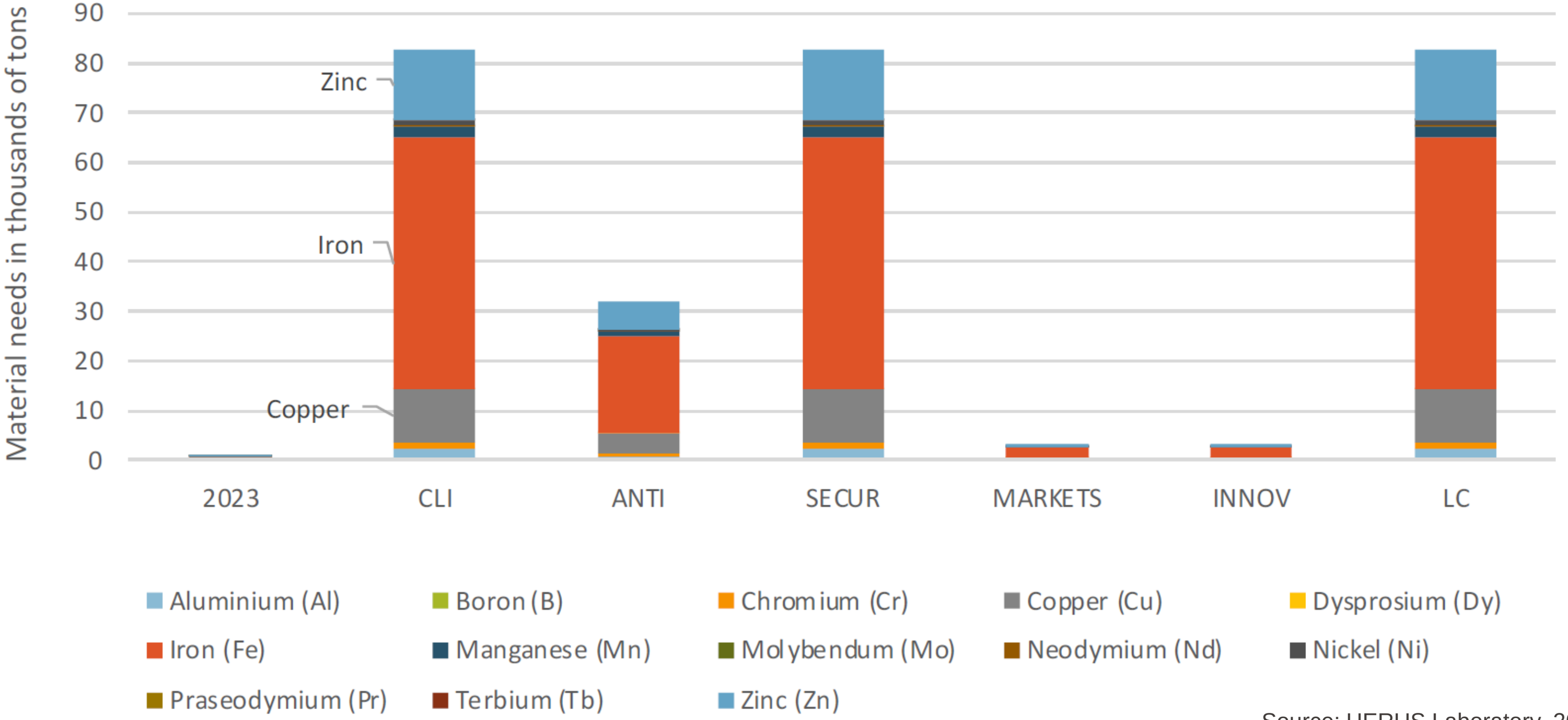
Current (2030) and 2050 raw material requirements for Wind Turbines in different scenarios in Switzerland



Source: HERUS Laboratory, 2024

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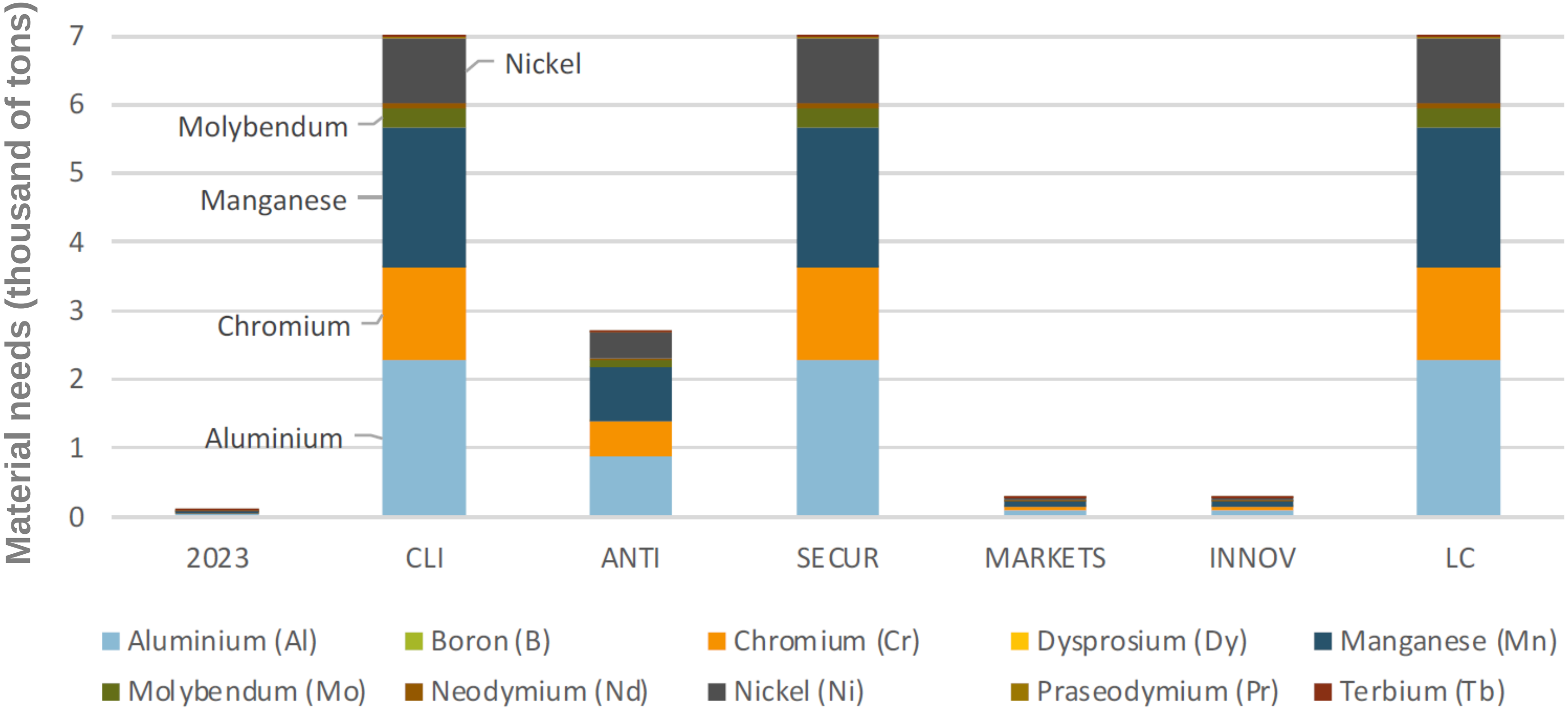
The Swiss Energy transition – Wind turbines

Current (2030) and 2050 raw material requirements for Wind Turbines in different scenarios in Switzerland



Source: HERUS Laboratory, 2024

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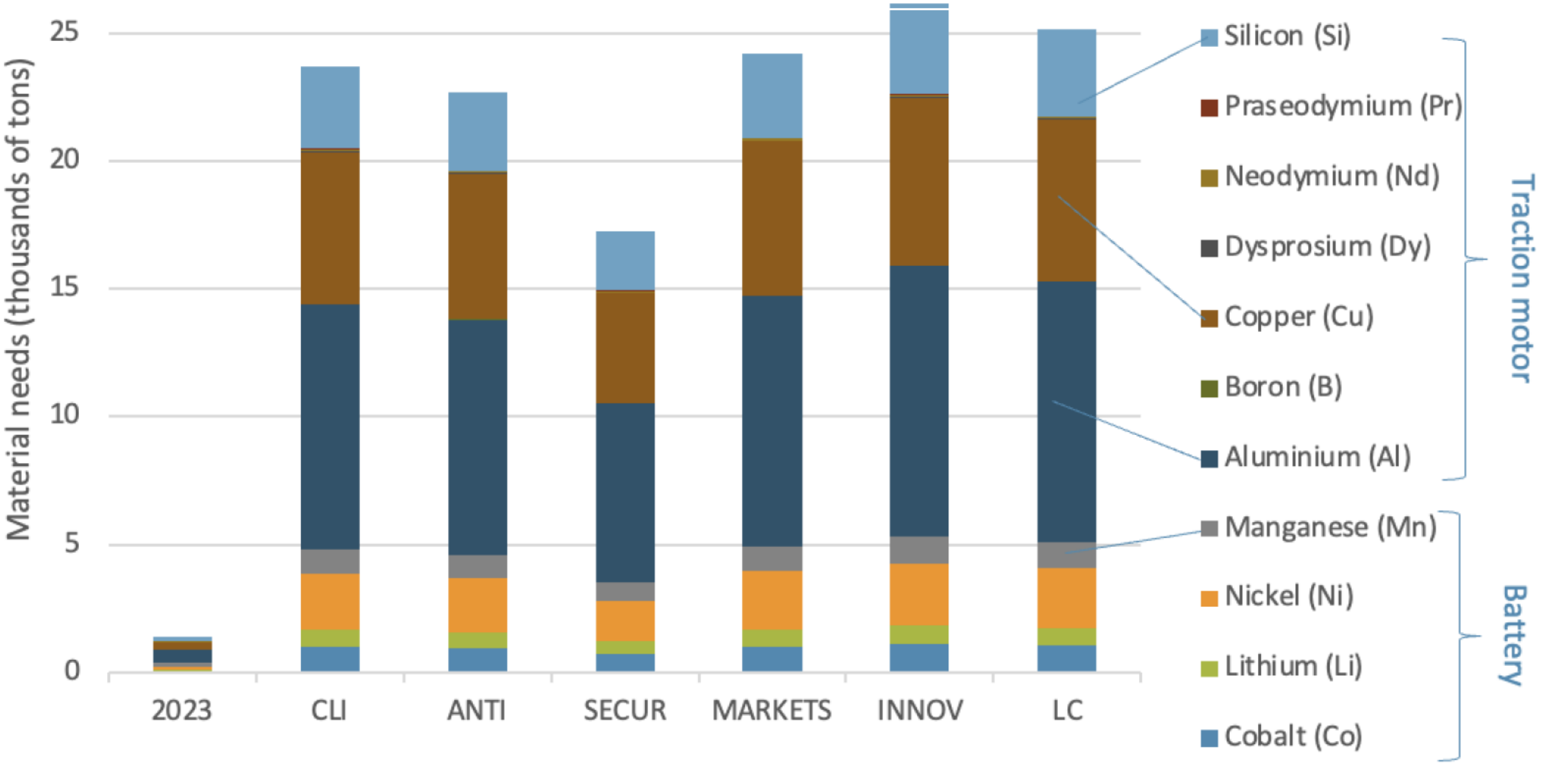
The Swiss Energy transition – Electric Vehicles

Current (2030) and 2050 raw material requirements for Electric Vehicles in different scenarios in Switzerland



Source: HERUS Laboratory, 2024

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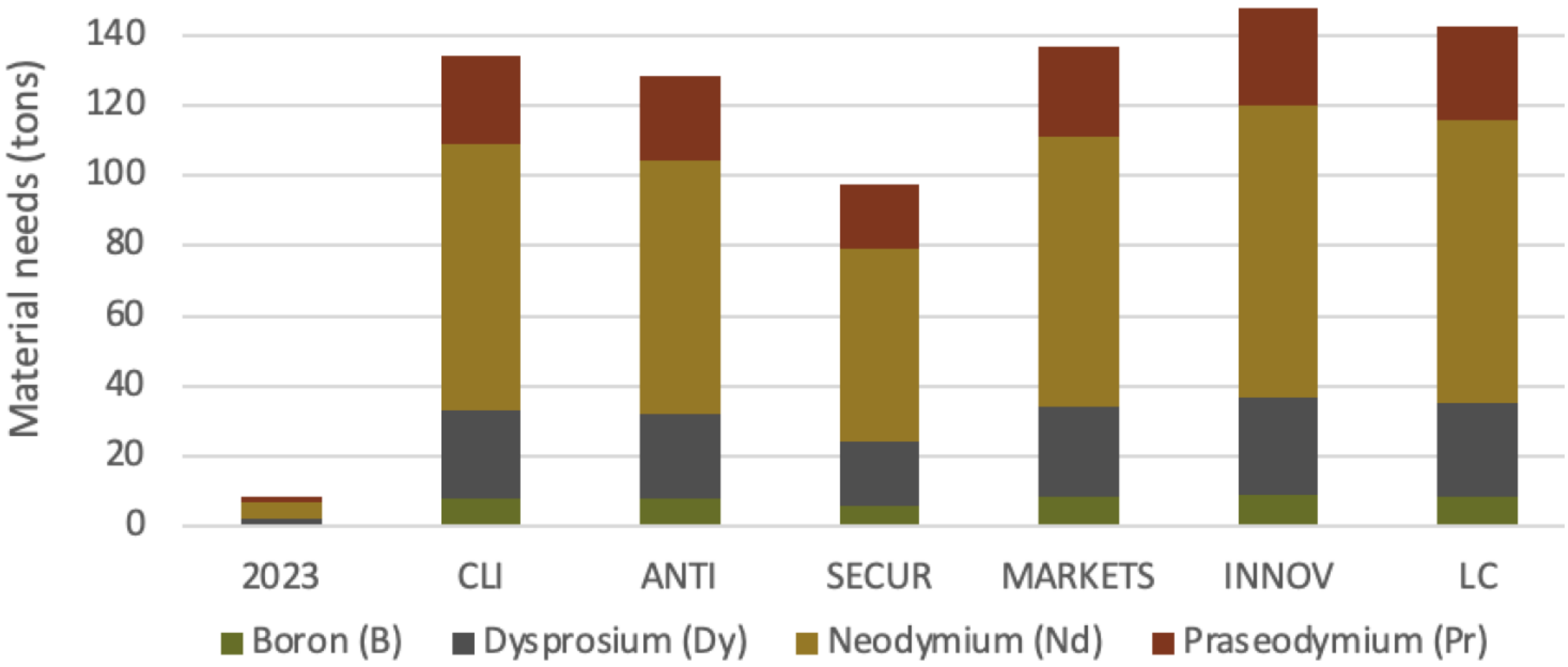
The Swiss Energy transition – Electric Vehicles

Current (2030) and 2050 raw material requirements for Electric Vehicles in different scenarios in Switzerland



Source: HERUS Laboratory, 2024

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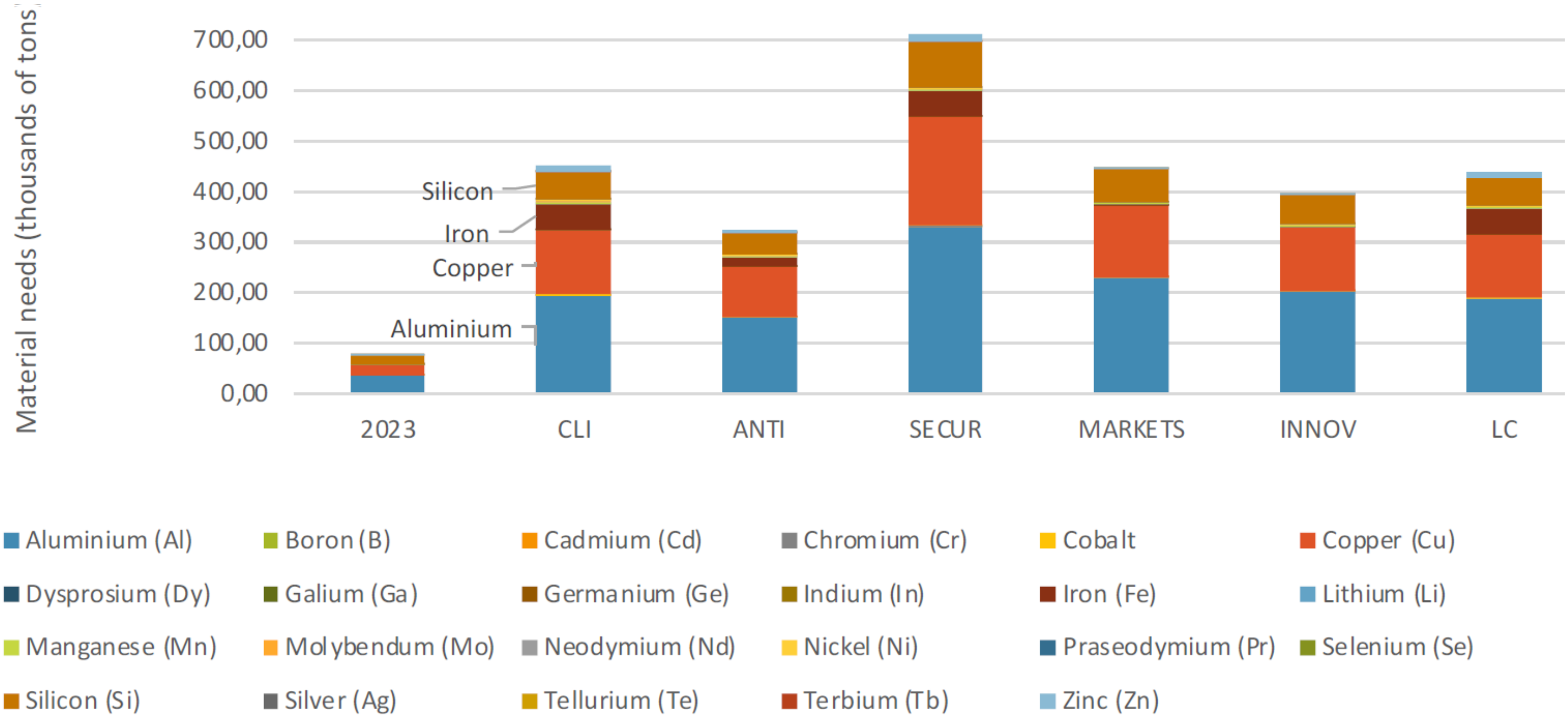
The Swiss Energy transition – All 3 technologies

Current (2030) and 2050 raw material requirements for All three technologies in different scenarios in Switzerland



Source: HERUS Laboratory, 2024

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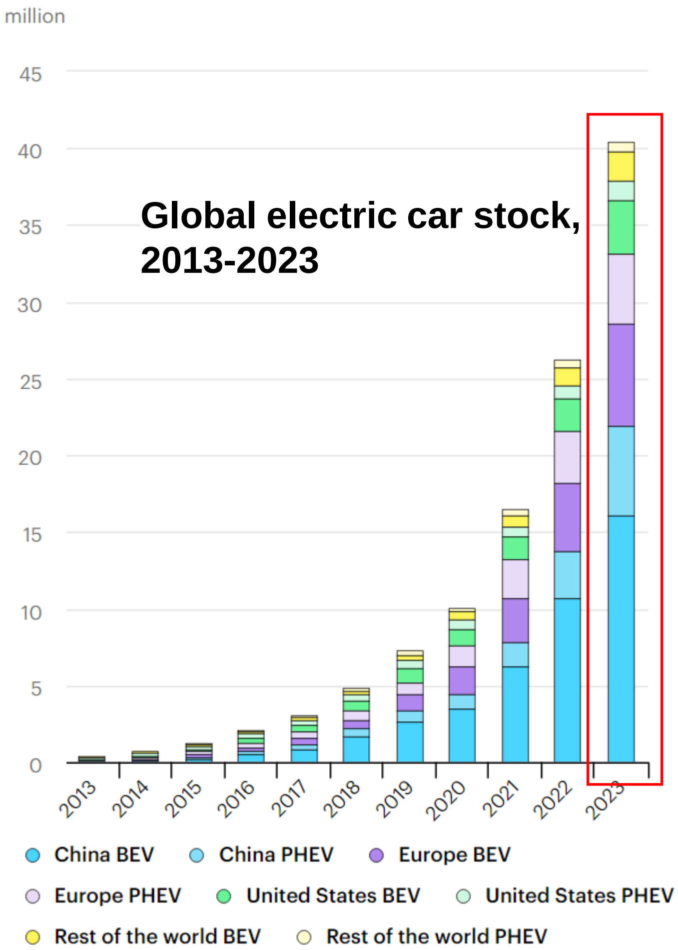
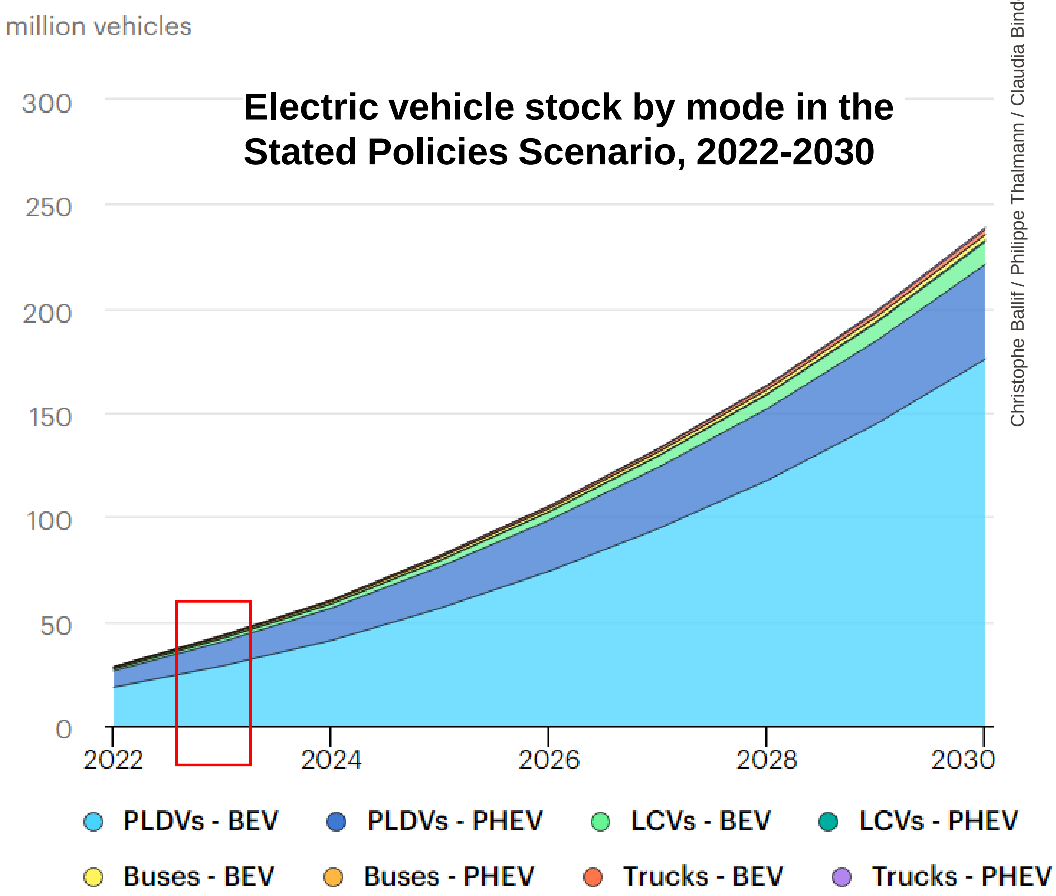
Trends in Electric Vehicles





Source: IEA, 2024; IEA, 2023

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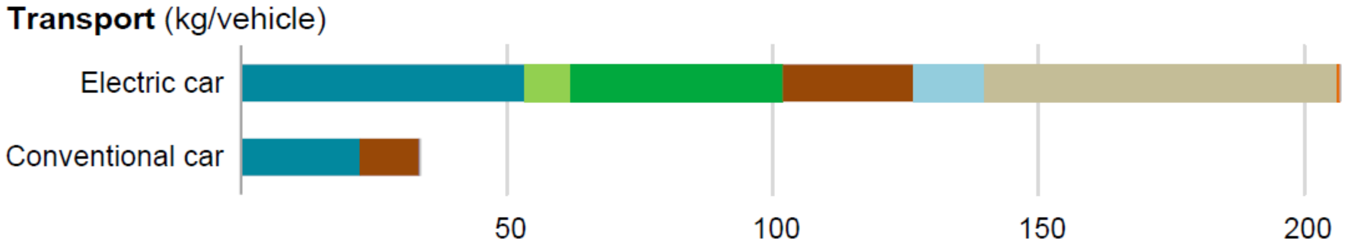
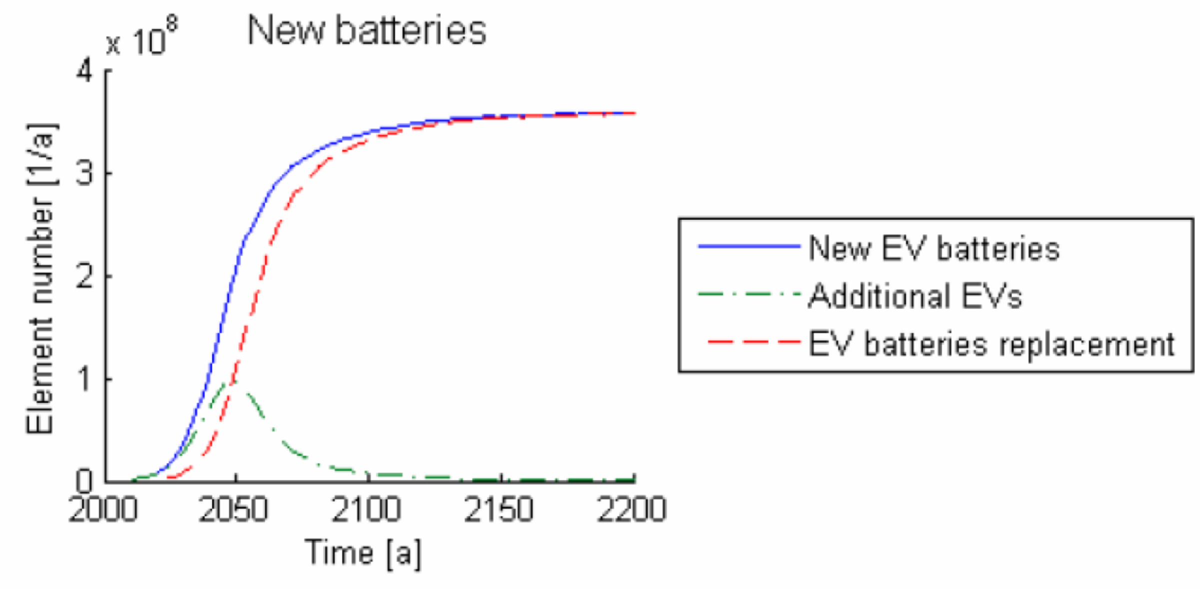
Trends in Electric Vehicles: Batteries





Source: IEA 2021; Carles, 2010

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Increased material complexity of technologies

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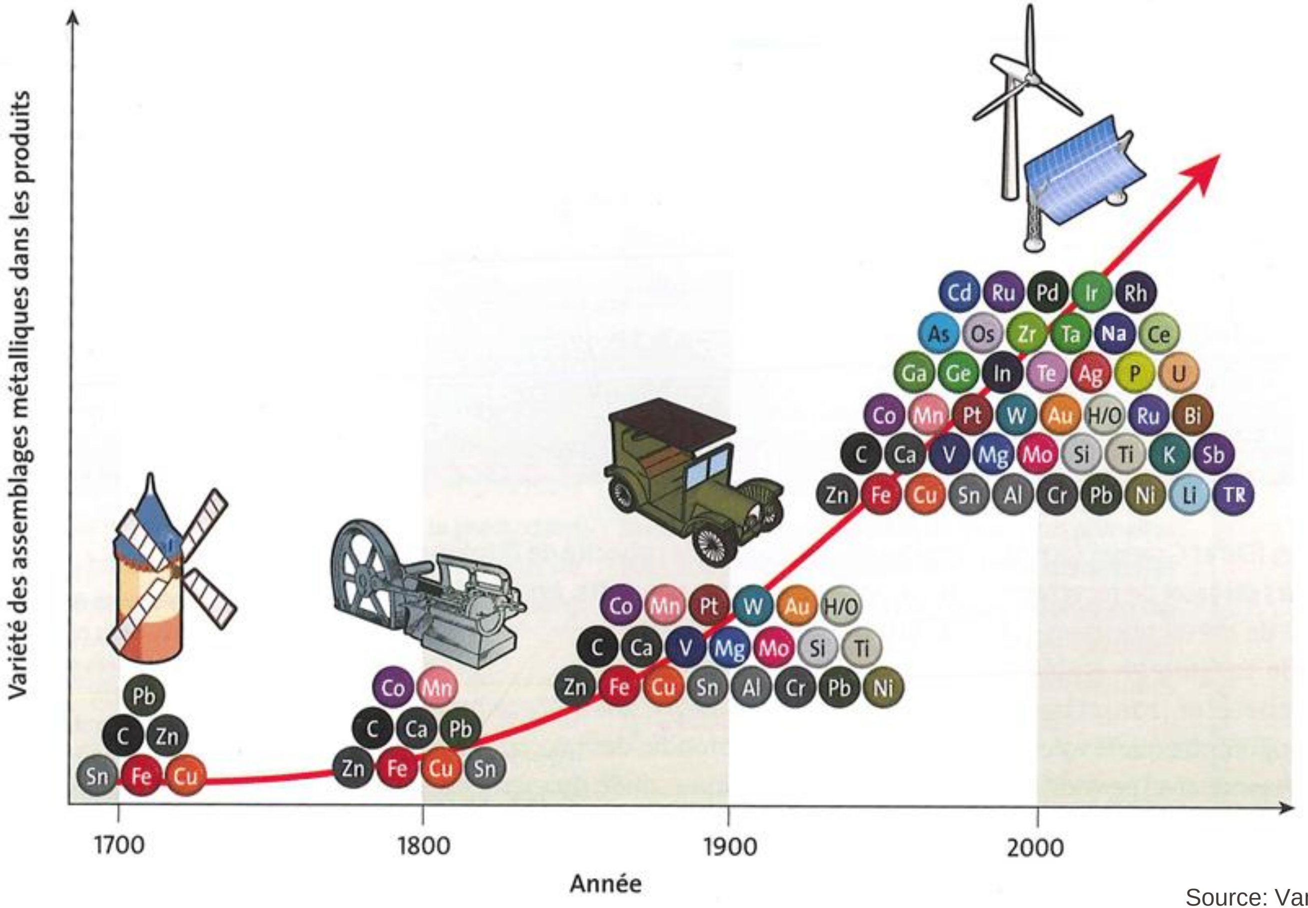
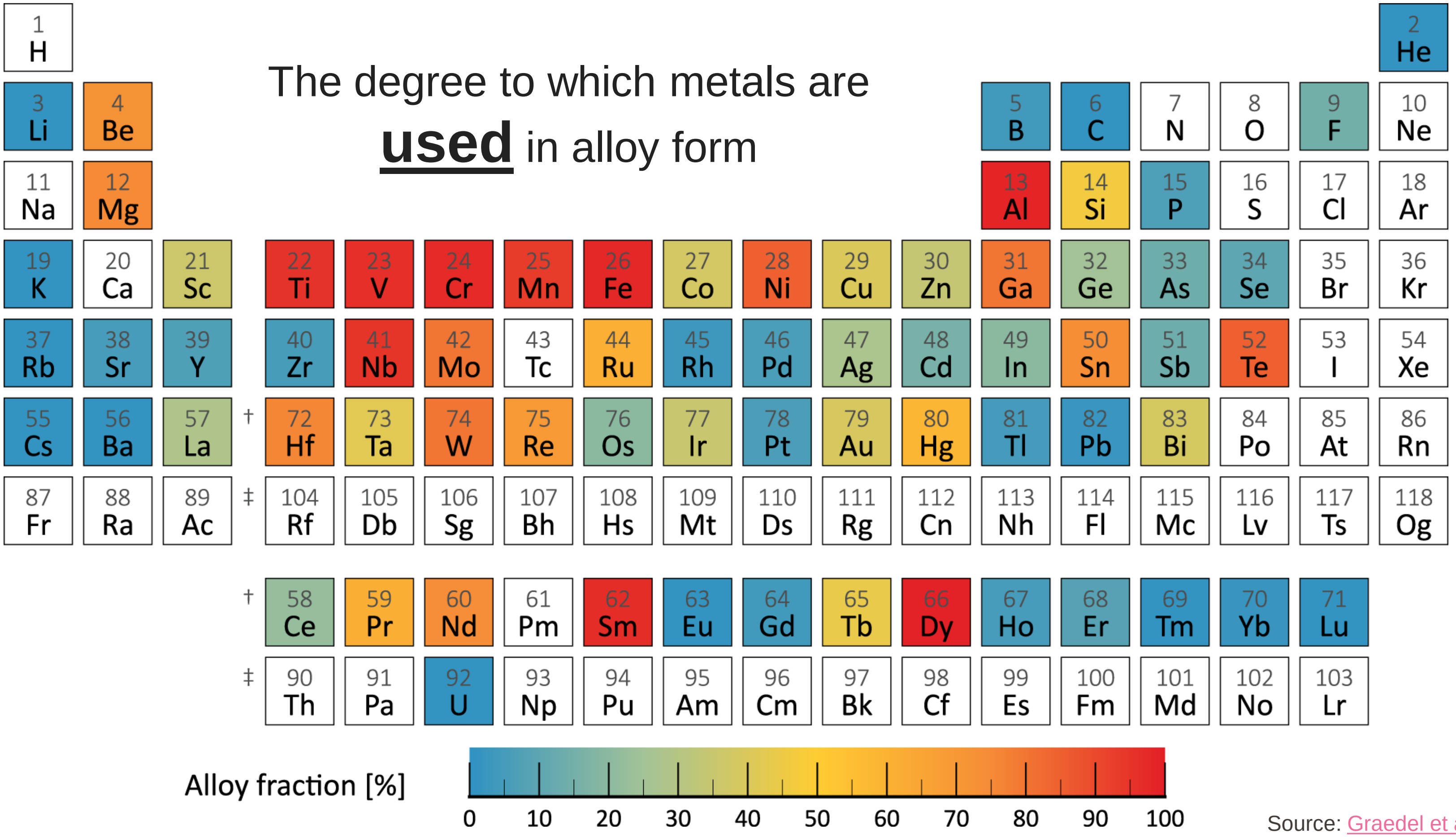


Source: Van Schaik et Reuter, 2012

Use of elements in alloy form challenges recycling

The degree to which metals are **used** in alloy form



Source: Graedel et al, 2022

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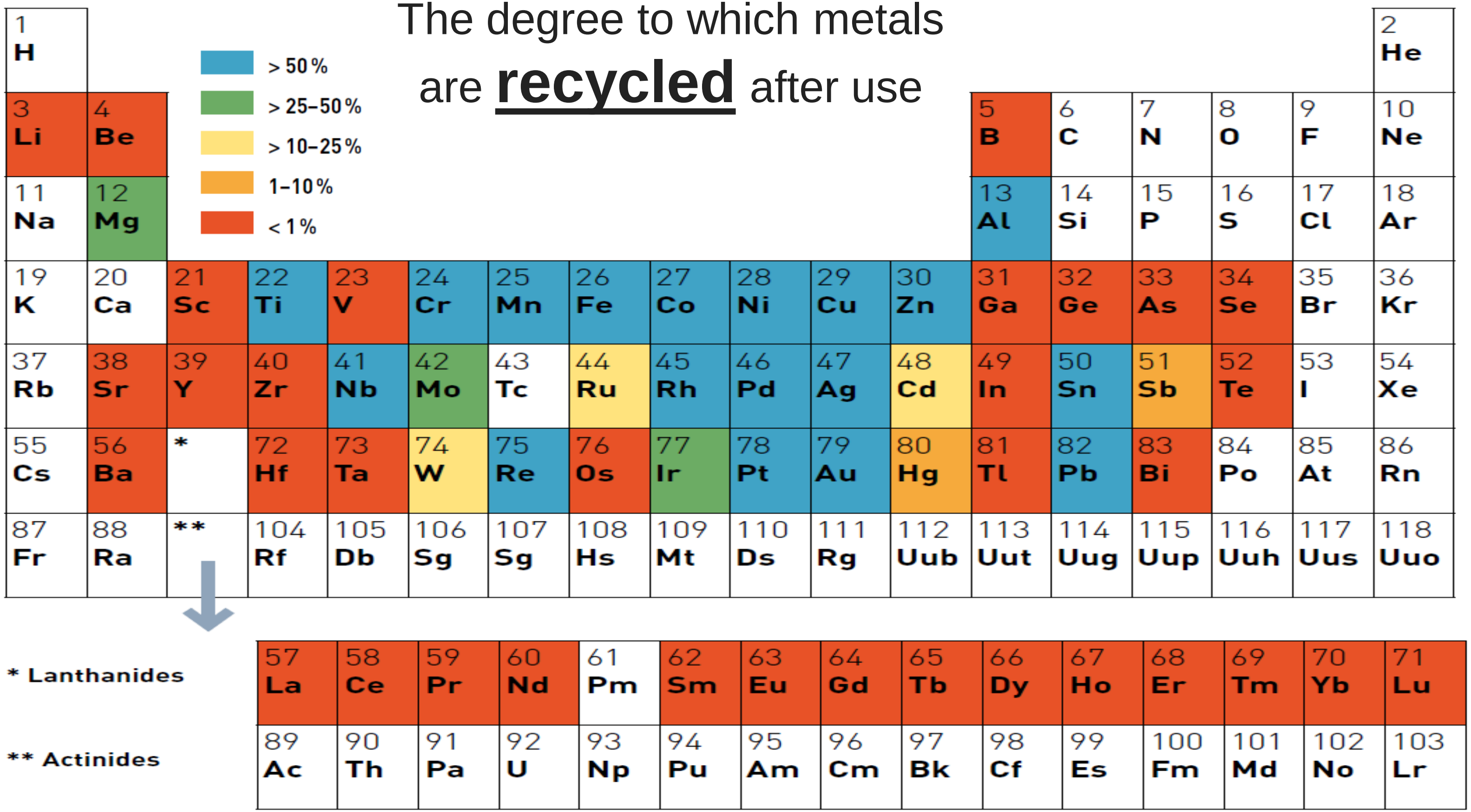
Use of elements in alloy form challenges recycling

The degree to which metals are **recycled** after use



Source: UNEP, 2011

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Wheel of metal companionality: Major vs Minor metals

- Minor amounts of metals are often recovered only as by-products during the processing of the major metals, their “host(s)

- The availability of these “by-product” or “companion” metals is thus dependent not only on the mining production of their host metal(s) but also on whether the companion metals are recovered rather than being discarded without having been processed

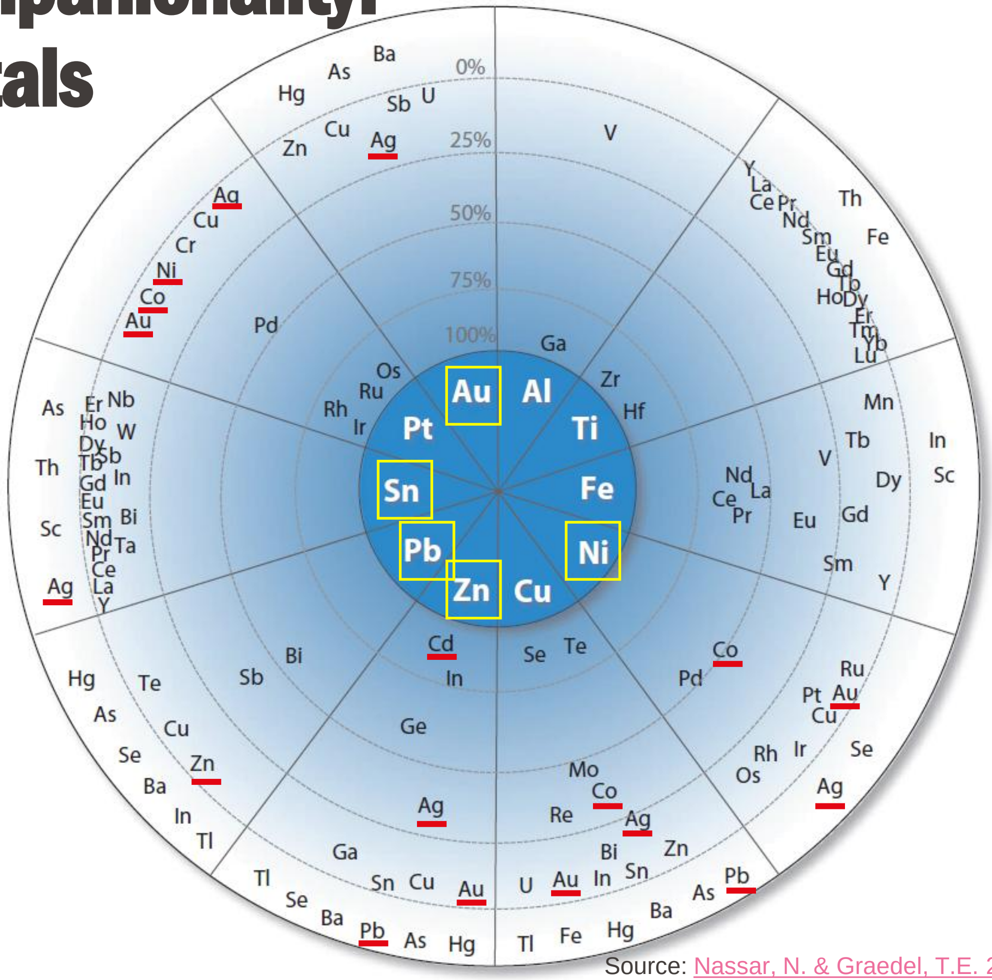
- Rapid deployment in a number of emerging electronic and solar energy applications (e.g., gallium and indium),
- Alloys in high-temperature applications (e.g., cobalt),
- and in technologies such as offshore wind (e.g., several of the rare earth elements)

Source: Nassar, N. & Graedel, T.E. 2015

Wheel of metal companionality: Major vs Minor metals

- **Critical with respect to reserves (2050):** Silver (Ag), Gold (Au), Cadmium (Cd), Cobalt (Co), lead (Pb), Nickel (Ni), Tin (Sn), Zinc (Zn)

- **Major metals:**
- Gold (Au),
- Aluminium (Al),
- Titanium (Ti),
- Iron (Fe),
- Nickel (Ni),
- Copper (Cu),
- Zinc (Zn),
- Lead (Pb),
- Tin (Sn)
- Platinum (Pt)



Source: [Nassar, N. & Graedel, T.E. 2015]

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Strategic and Critical metals

- “Strategic materials” have generally been **associated with material availability** for national defense purposes, in times of war, or national emergency (in the US)

- The US *Strategic and Critical Materials Stockpiling Act* (2005) defines strategic and critical materials as:

“…those that are needed to supply the military, industrial, and essential civilian needs of the US during a national emergency and which are not found or produced in the US in enough quantities to meet such needs”

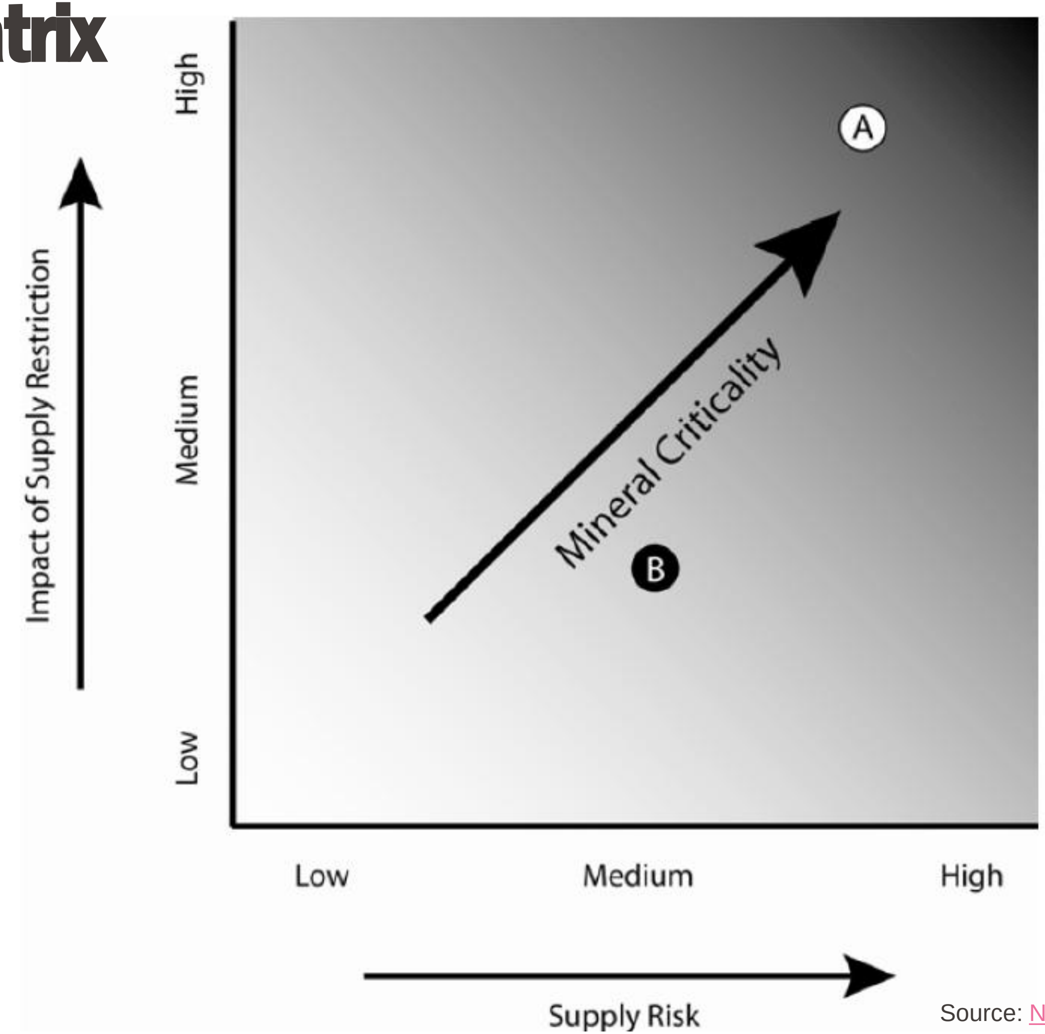
- “Critical” in general English usage can refer to something that is vital, important, essential, crucial, or significant.

Source: US Congress, 1979; US Congress, 2005

The criticality matrix

- The vertical axis embodies the idea of **importance in use** and represents the **impact of supply restriction**

- The horizontal axis embodies the concept of **availability** and represents **supply risk**



Source: NRC, 2008

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The criticality matrix: Dimensions

National Research Council – 2008: Scale from 1 to 4

Importance

- **Substitution**: Some nonfuel minerals or materials are more important in use than others
- Importance is **Low**: if substitution of one mineral for another in a product is easy technically, or relatively inexpensive
- Importance is **High**: if substitution is difficult technically or is very costly, as would be the cost or impact of a restriction in its supply

This concept of **importance** at a product level significantly includes the net **benefits** customers receive from using a product

Source: NRC, 2008

The criticality matrix: Dimensions

National Research Council – 2008: Scale from 1 to 4

Availability and Supply Risk

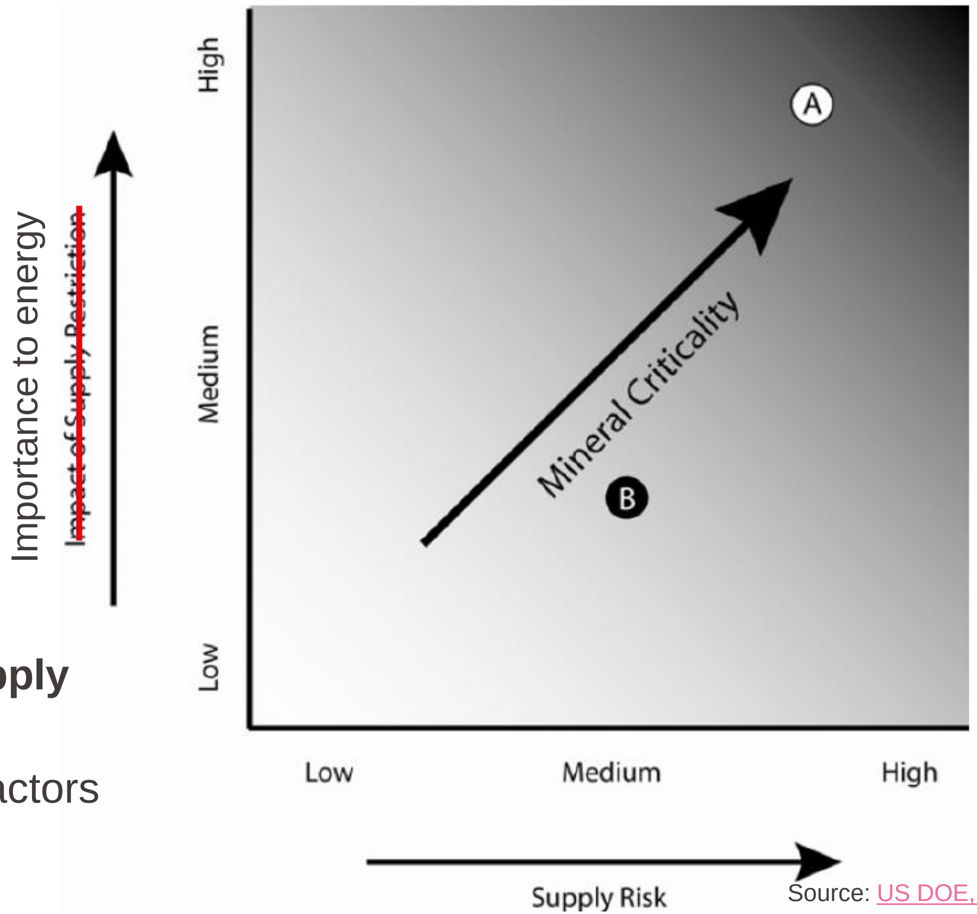
- **Geological**: Does the mineral exist?
- **Technical**: Do we know how to extract and process it?
- **Social and environmental**: can we extract and process it with a level of environmental **damage** that society considers **acceptable** and with **effects** on local communities and regions that society considers **appropriate**?
- **Political**: how do policies affect availability both positively and negatively?
- **Economic**: can we produce a mineral or mineral product at costs consumers are willing and able to pay?

Source: NRC, 2008

The criticality matrix: Dimensions

US Department of Energy 2023:

- Addresses particular concerns for **energy technologies**



"Importance to energy" and "**supply risk**"

- Weighted averages of several factors
- Score from 1 to 4

Source: US DOE, 2023

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The criticality matrix: Dimensions

US Department of Energy - 2023 : Scale from 1 to 4

Importance to energy

- **Energy Demand**: importance of both materials and the technologies that use them to the future of energy, including technologies that produce, transmit, store, and conserve energy
- **Substitutability Limitations**: ability to reduce the use of the material in energy applications through material substitution or substitutions in the energy system itself

Source: US DOE, 2023

The criticality matrix: Dimensions

US Department of Energy - 2023 : Scale from 1 to 4

Availability and Supply Risk

- **Basic availability**: extent to which global supply (including recycling) will be able to meet demand
- **Competing technology demand**: evaluates trends in demand from non-energy sectors
- **Political, regulatory, and social factors**: assesses supply risks associated with these
- **Co-dependence on other markets**: reliance of a material on the production of other products
- **Producer diversity**: market concentration and the ability of producing countries to exert market power over a particular material market

Source: US DOE, 2023

The criticality matrix: Scoring metrics

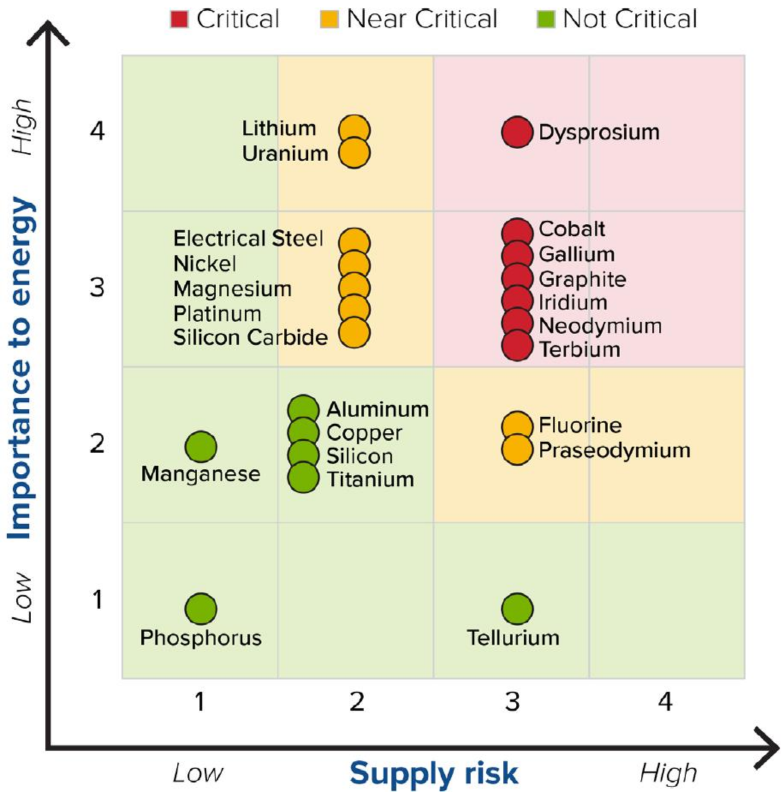
Factor	Metrics	Score = 1	Score = 2	Score = 3	Score = 4
Importance to Energy	***Energy Demand (70%)***	Meets one of the criteria below: (1) Market share of the material for energy applications <10%. (2) Market share of the most dominant specific sub-technology <10%.	Must meet both criteria below: (1) Market share of the material for energy applications ≥10%. (2) Market share of the most dominant specific sub-technology ≥10%.	Must meet both criteria below: (1) Market share of the material for energy applications ≥40%. (2) Market share of the most dominant specific sub-technology ≥25%.	Must meet both criteria below: (1) Market share of the material for energy applications ≥ 70%. (2) Market share of the most dominant specific sub-technology ≥50%.
	Substitutability limitations (30%)	**Perfect or near-perfect** substitutes are available at material and system levels with **little to no limitations or concerns**.	Substitutes are available at either material or system levels with **minor limitations or concerns.**	Substitutes are available either at the material level or systems level with **major limitations or concerns.**	**No substitutes are available** at either the material or system levels.
Supply Risk	***Basic Availability (40%)***	**No concerns** about existing capacity to meet near- and medium-term demand.	**Minor concerns** about capacity to meet near- and medium-term demand.	**Major concerns** about capacity to meet near- and medium-term demand.	**Grave concerns** about capacity to meet near- and medium-term demand.
	Competing Technology Demand (10%)	CAGR of any non-energy application ≤ 3%.	CAGR of any non-energy application ≤ 5%.	CAGR of any non-energy application ≤ 10%.	CAGR of any non-energy application >10%.
	Political, Regulatory, and Social Factors (20%)	Weighted average percentile of Governance Indicators and Environmental Performance Index is greater than 60.	Weighted average percentile of Governance Indicators and Environmental Performance Index is from 45 to 60.	Weighted average percentile of Governance Indicators and Environmental Performance Index is from 30 to 45.	Weighted average percentile of Governance Indicators and Environmental Performance Index is less than 30.
	Co-depend-ence on Other Markets (10%)	Must meet both criteria below: (1) May or may not be produced as a co-product of other metals. (2) Produced as a main product in most circumstances.	Must meet both criteria below: (1) Most (>50%) production is as a co-product or as a by-product of other metals. (2) Produced as a main product in some circumstances OR there is excess by-product supply in the market.	Must meet both criteria below: (1) Significant (>75%) production as a co-product or by-product of other metals. (2) May be produced as a main product in some circumstances AND there is not excess by-product supply in the market.	Must meet both criteria below: (1) 100% of production is as a co-product or as a by-product of other metals. (2) Not produced as a main product anywhere in the world AND there is no excess by-product supply in the market.
	Producer Diversity (20%)	Herfindahl-Hirschman Index (HHI) less than 2500	HHI from 2500 to 3332	HHI from 3333 to 4999	HHI greater than or equal to 5000

Compound Annual Growth Rate (CAGR) - mean annual growth rate of an investment over a specified period of time longer than one year
Herfindahl-Hirschman Index (HHI) - measure of the size of firms in relation to the industry. Used as indicator of the amount of competition among them

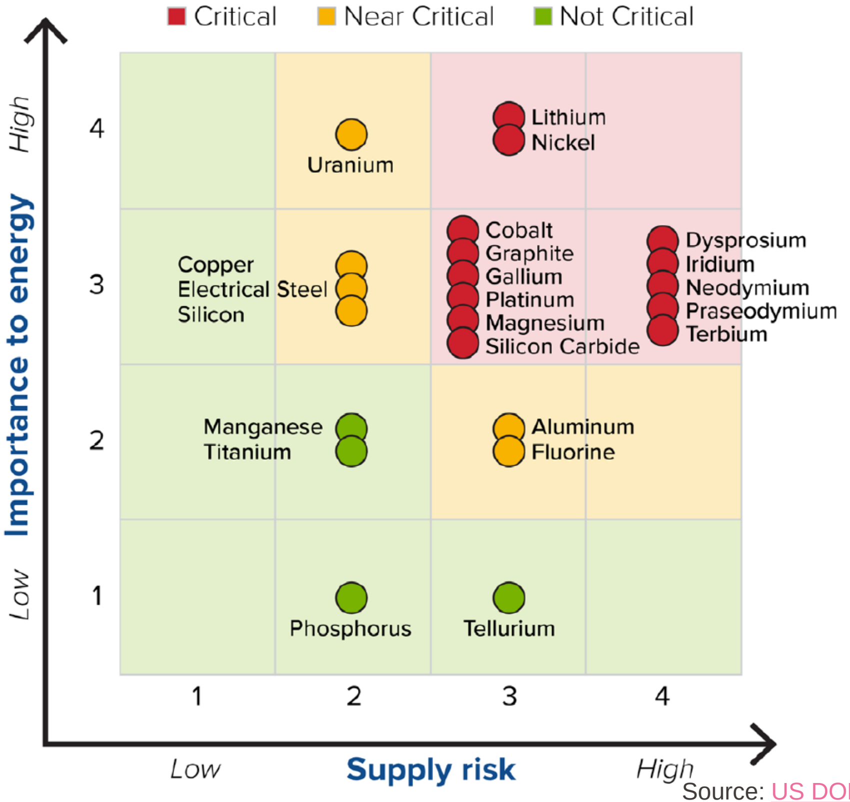
Source: US DOE, 2023; Wikipedia, 2024a, 2024b

The criticality matrix: Scoring metrics

Short-term (2020-2025) criticality matrix



Medium-term (2025-2035) criticality matrix



Source: US DOE, 2023

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Supply chain concentration

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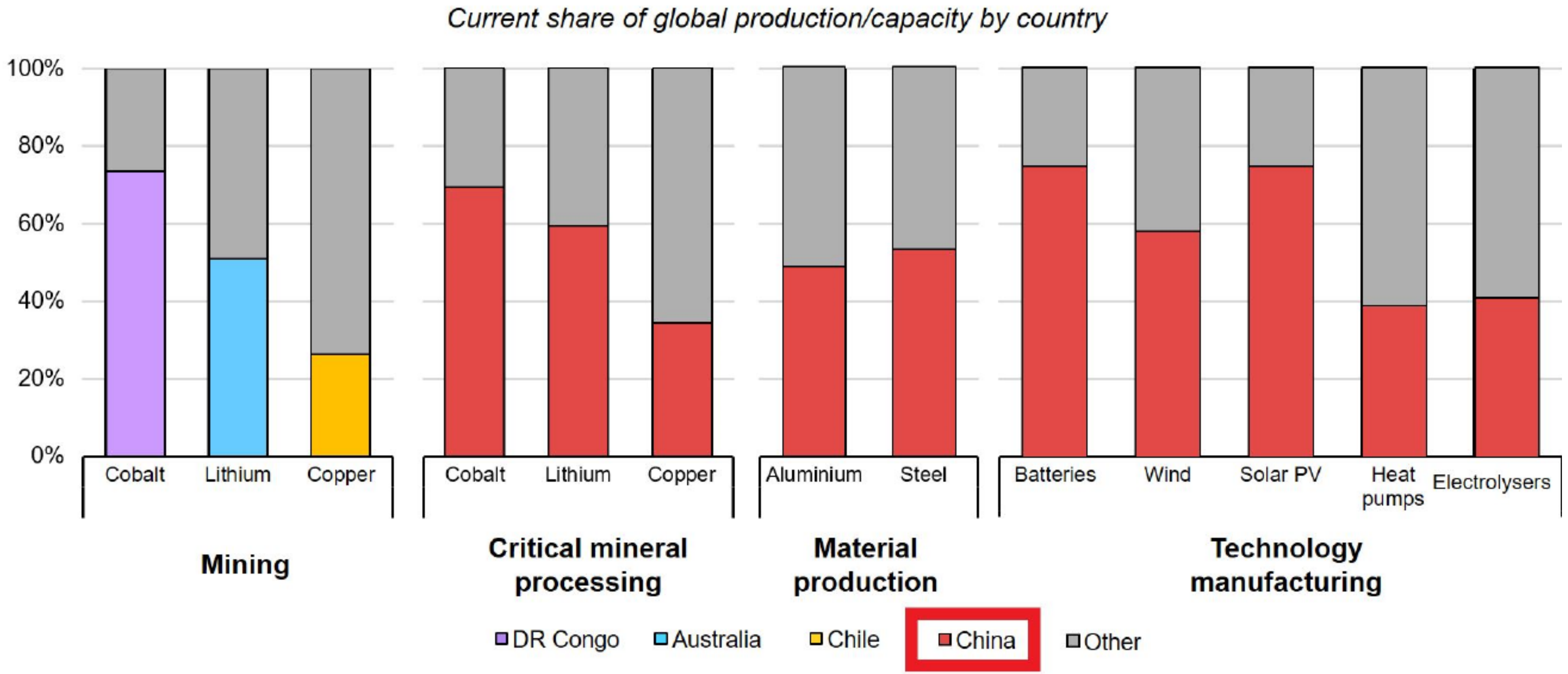
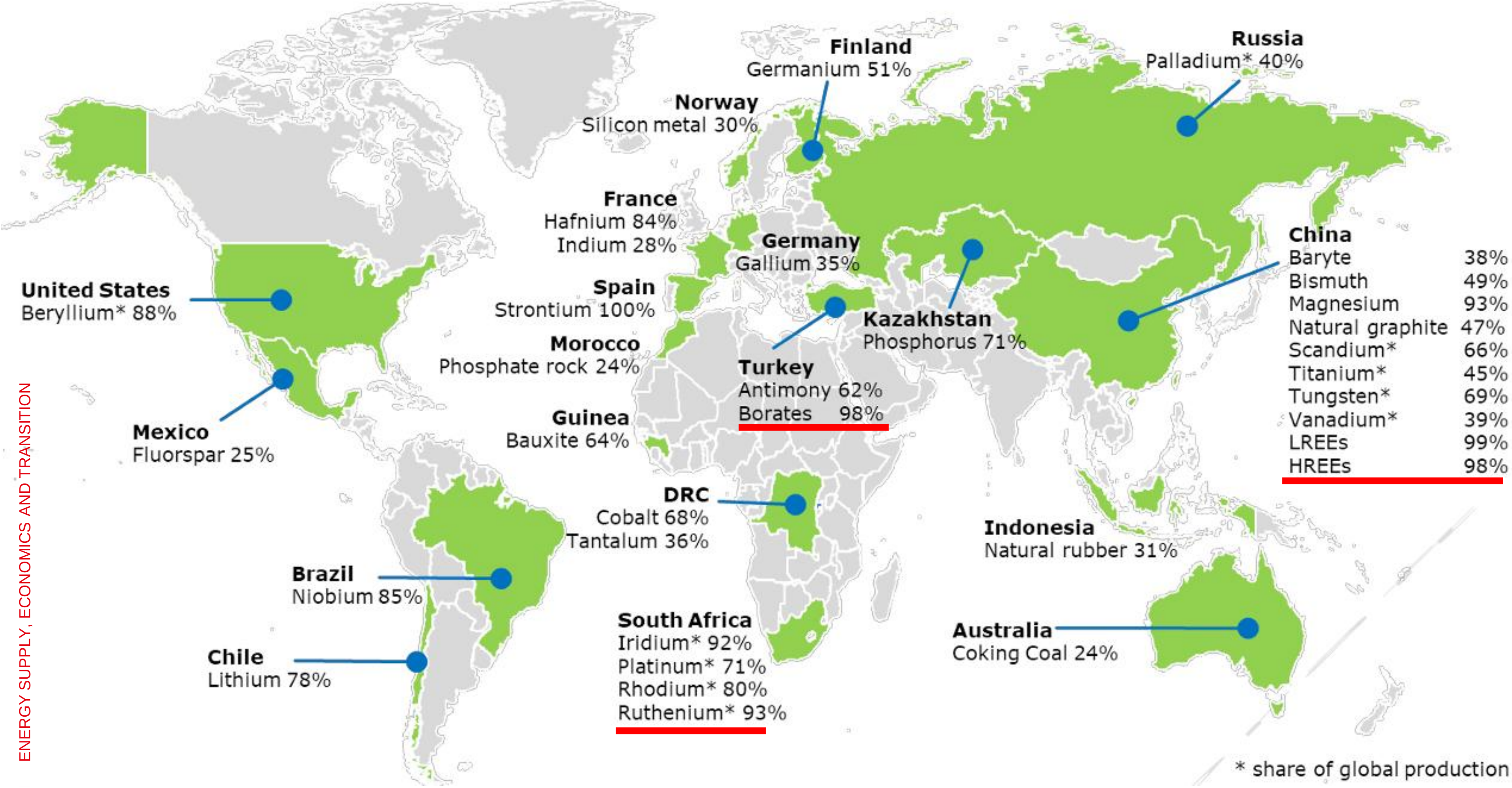


Source: IEA, 2023

EU list of critical raw materials suppliers (2020)



* share of global production

Source: European Commission, 2020

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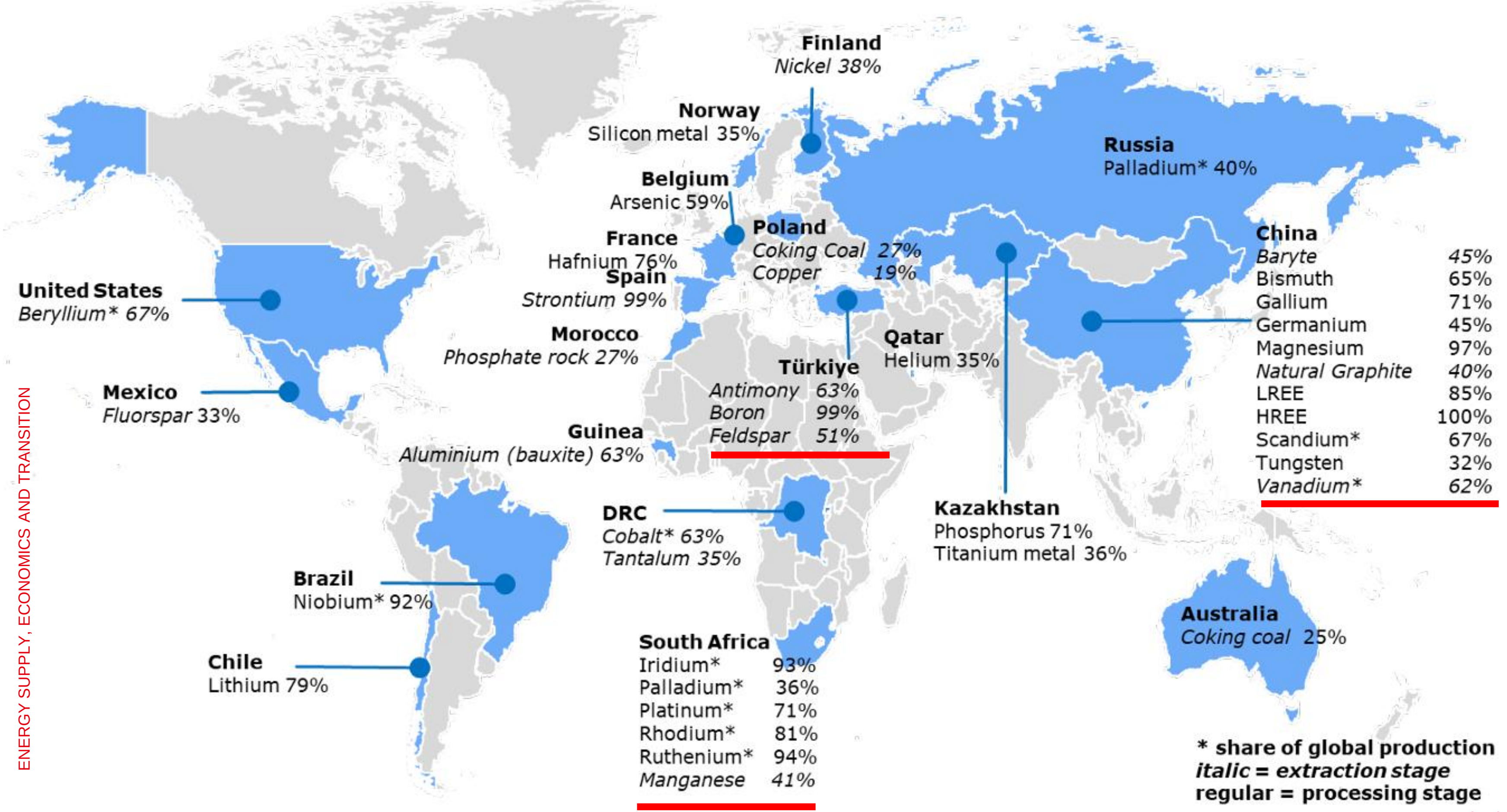
ENERGY SUPPLY, ECONOMICS AND TRANSITION

EU list of critical raw materials suppliers (2023)



Source: European Commission, 2023

Key takeaways – status and trends

- Although some metals are scarce, **a fully renewable energy system is unlikely to deplete metal reserves and resources** up to 2050
- Even if the energy system was fully renewable, **supply constraints** on several elements **would still compel us to reduce our energy demand**
- Shifting from a fossil-based to a RE-based system does not alleviate the problem of resource depletion, it merely shifts it from fuel to metals, however **it allows for substitution and recycling**
- Stocks in use and recycling rates are high, but again, **other uses are competing** for them at a comparative advantage

Key takeaways – critical materials

- Critical with respect to reserves (2050): **Silver** (Ag), **Gold** (Au), **Cadmium** (Cd), **Cobalt** (Co), **Lead** (Pb), **Nickel** (Ni), **Tin** (Sn), **Zinc** (Zn)
- Critical with respect to resources (+2100): **Cadmium** (Cd), **Cobalt** (Co), **Iron** (Fe), **Lithium** (Li), **Molybdenum** (Mo), **Nickel** (Ni), **Zinc** (Zn)
- Relative impact scores are helpful in prioritizing technologies
- The uncertainties remain very high

Key takeaways – Moving forward

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- The energy world is indeed transitioning, and **renewable energy technologies play a key role on material requirements** (e.g.offshore wind vs PVs, large vs small EVs, etc.)

- As per current studies, there is **no scarcity of reserves** for energy transition minerals, but **capabilities for mining** and **refining** them are limited.

- Assessment of the **criticality** of materials is **dynamic** and continuously **changing**

- As **resources** are **geographically concentrated**, the **supply chain** of critical materials **could be exposed to risks**

- At the same time, this **wide distribution** could open opportunities **to innovate**, diversifying the **mining** and **processing of materials**

Research at EPFL - HERUS

An integrated approach for advancing critical raw materials assessment in the renewable energy transition: insights from Switzerland and Italy

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Abstract

The transition to carbon neutrality requires the adoption of renewable energy technologies such as photovoltaic solar panels and wind turbines. These technologies rely on Critical Raw Materials (CRMs) that play an essential role in enabling the energy transition. The criticality of these materials is shaped by two key dimensions: (i) external, encompassing global and regional factors like production volumes, supply concentration, and geopolitical dependencies, and (ii) internal, which relate to national preparedness, including recycling capacity, and national energy transition targets. This study presents a novel methodology for assessing the criticality of raw materials required for renewable energy technologies, incorporating both external and internal contexts. The methodology was tested through case studies in Italy and Switzerland — two countries with distinct energy transition pathways and material dependencies. The approach integrated an analysis of supply risks, material importance, projected material demands, stock availability, and end-of-life recycling potential for two renewable energy technologies: wind turbines and photovoltaic solar panels. The study compiled CRMs lists specific to the energy transition in Italy and Switzerland, as well as a broader perspective for the EU region. Materials such as Rare Earth Elements, gallium, boron, and aluminium emerged as critical due to their potential disruption in the supply chain and growing demand, among other aspects. The results reveal that Switzerland, with its ambitious energy transition targets, faced a broader range of critical materials than Italy, which demonstrated a relatively lower material demand increase. The findings underscore the importance of focalized criticality assessments that account for both global/regional supply dynamics and country-specific circumstances. The methodology provides a framework for policymakers and industry stakeholders to identify material supply risks, support circular economy strategies, and enhance resilience in renewable energy supply chains. This approach is adaptable for use in other national or regional contexts, offering valuable guidance for sustainable energy transitions worldwide.

Keywords: Critical raw materials; Energy transition; Circular economy; Material flow analysis; Criticality assessment

- Assessment of the **criticality** of materials
- Potentials for **circular economy**
- Looking into **global/regional** supply **dynamics** and **country-specific** circumstances

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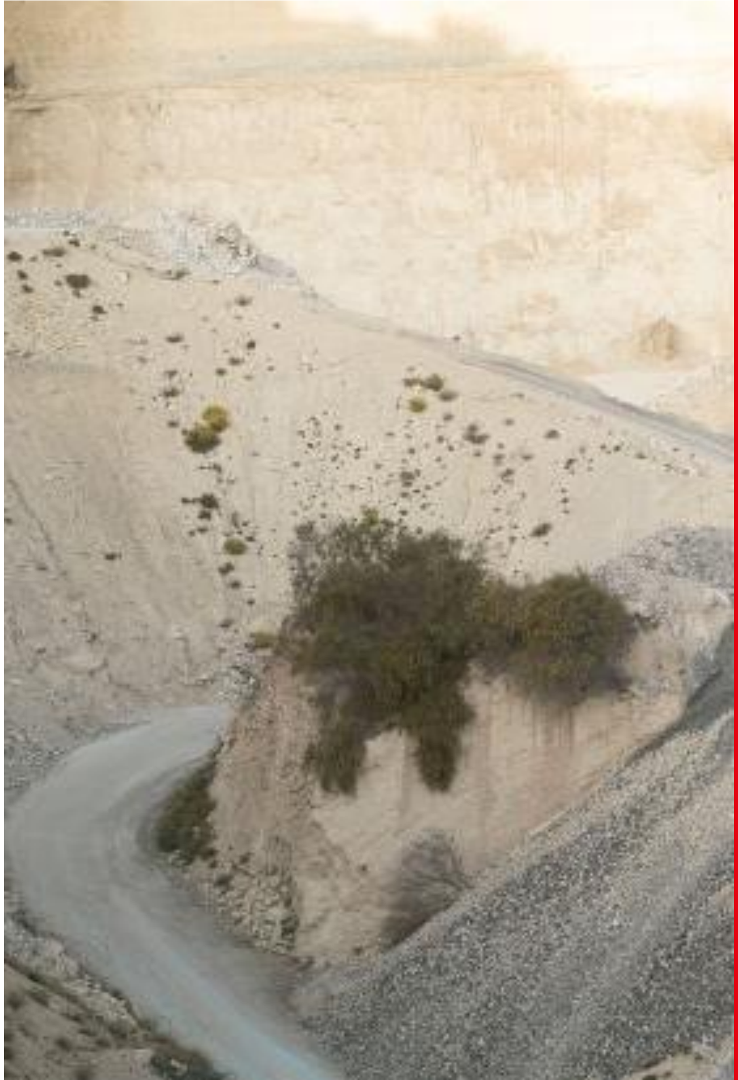

Thanks!

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