Creating Circularity for Critical Raw Materials

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Social Ecology Lecture
BOKU University, Vienna

Photo credits: Ches Mills (artist), Tim T. Werner (data)

Agenda

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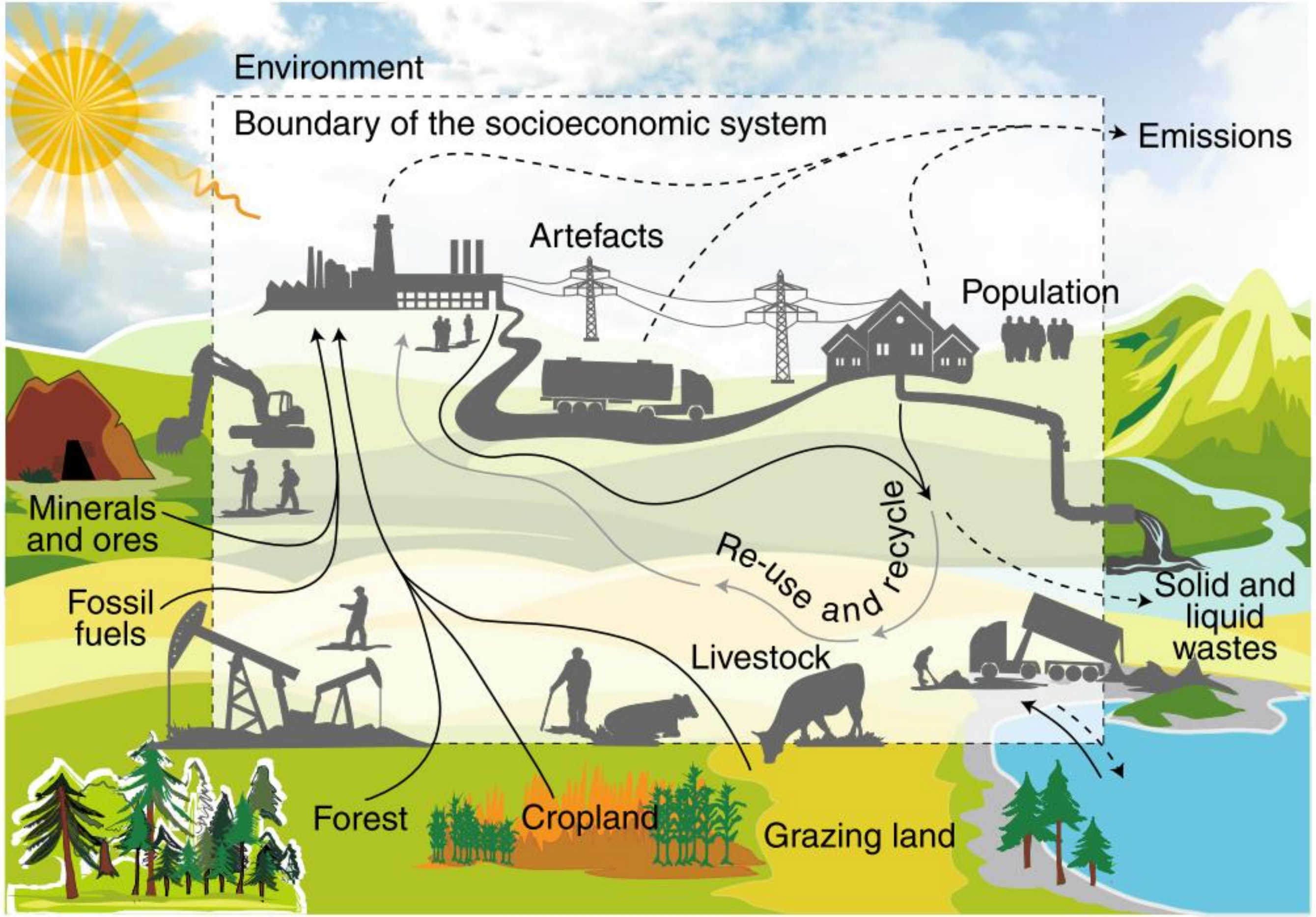
CRITICAL RAW MATERIALS

CIRCULARITY ISSUES

VISION FOR CIRCULARITY

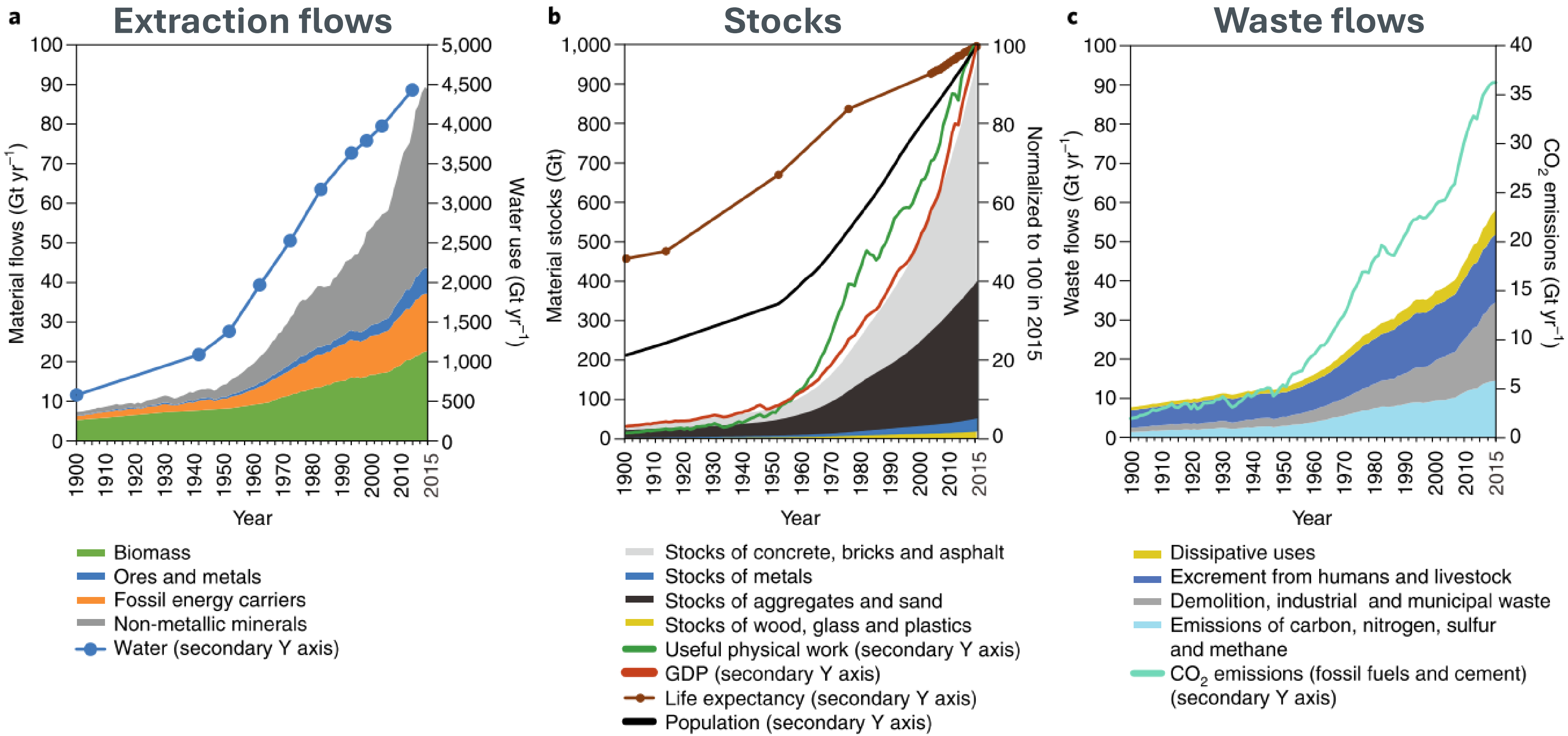
Industrial Ecology: Sustainability and Circular Economy

- Assessment of past, present, and future **material flows** in the anthroposphere.
- **Environmental impacts** of material flows, particularly the **triple planetary crisis**:
  - Climate change
  - Biodiversity loss
  - Pollution
- Impact of **technological development, business decisions, regulation, policy**, and **societal change**.



Haberl et al. 2019, *Nature Sustainability* **2**(3), 173-184

Historic increase of **global** material stocks and flows

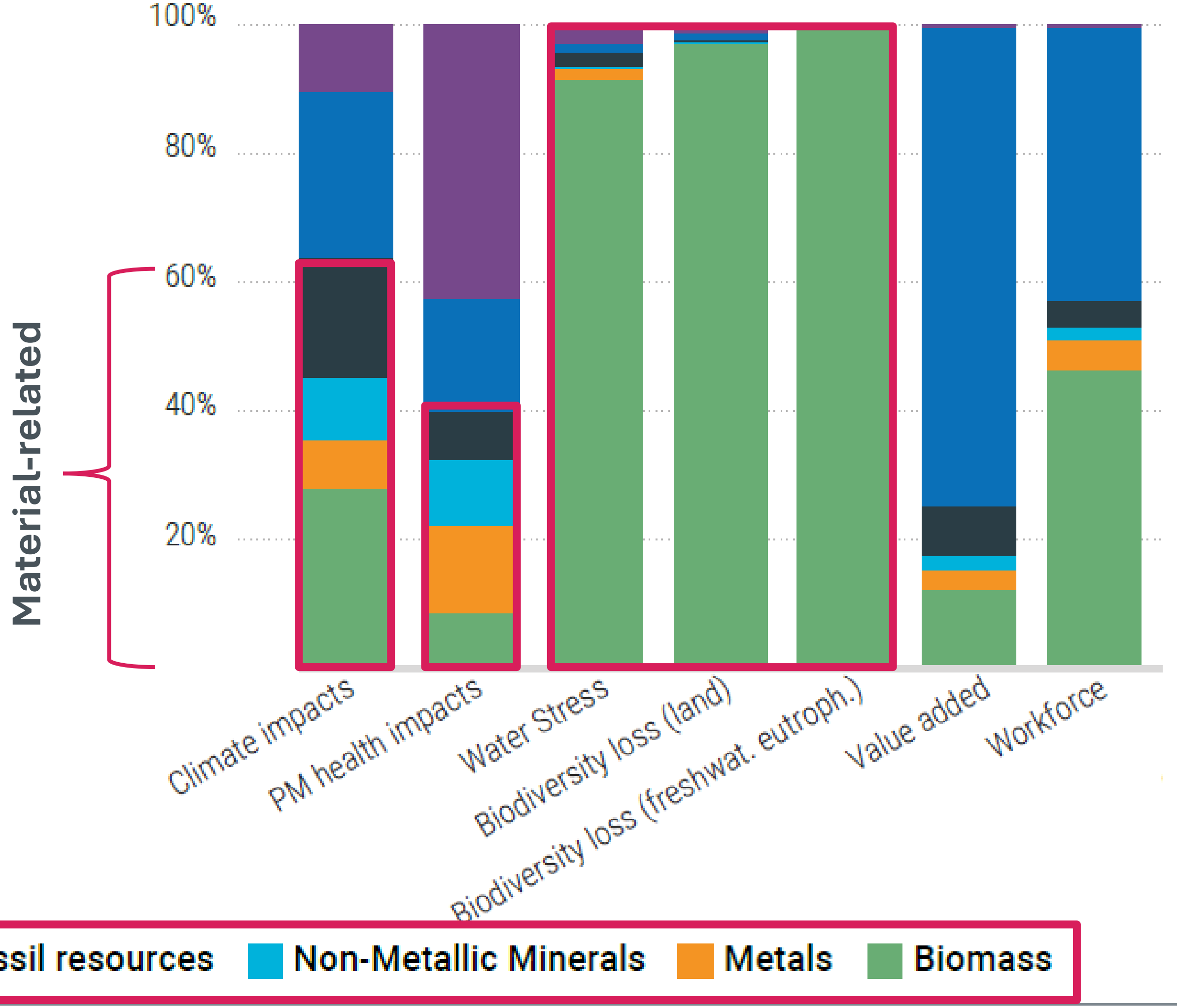


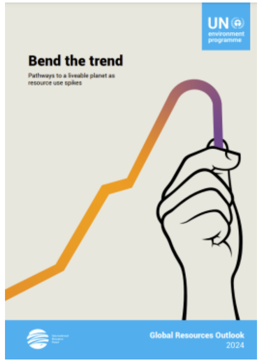
→ we live in a stockpiling society rather than a throwaway society (Krausmann et al. 2017)

Haberl et al. 2019, *Nature Sustainability* **2**(3), 173-184

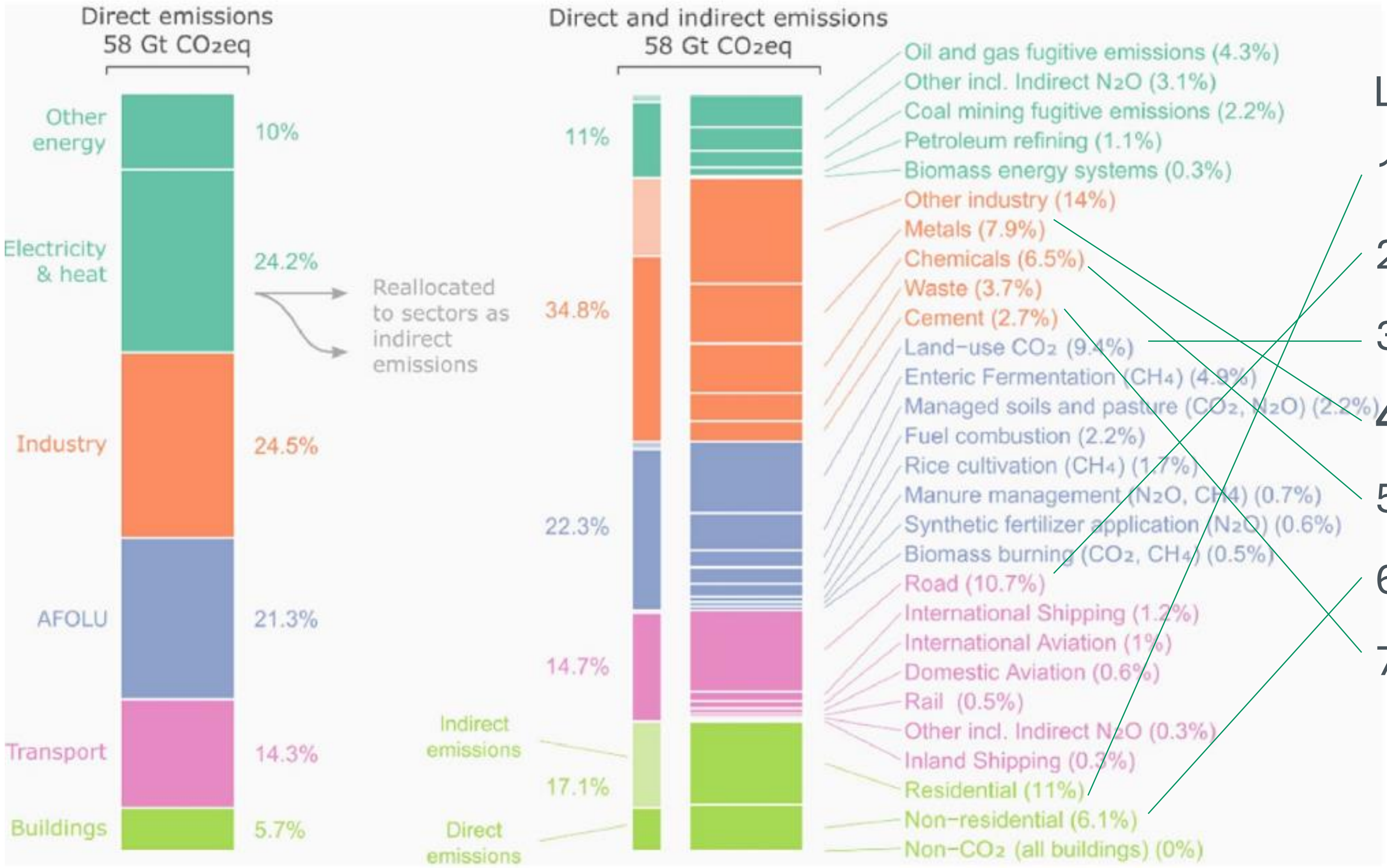
Impacts of resource extraction, processing and use

- Triple planetary crisis
  - We need **net zero global CO_2 emissions**, currently we have about **40 Gt per year**.
  - **Biodiversity loss** is rapid.
  - **Global pollution** with plastic waste, particulate matter, and persistent chemicals is continued.
- Large parts of those impacts are material-related.





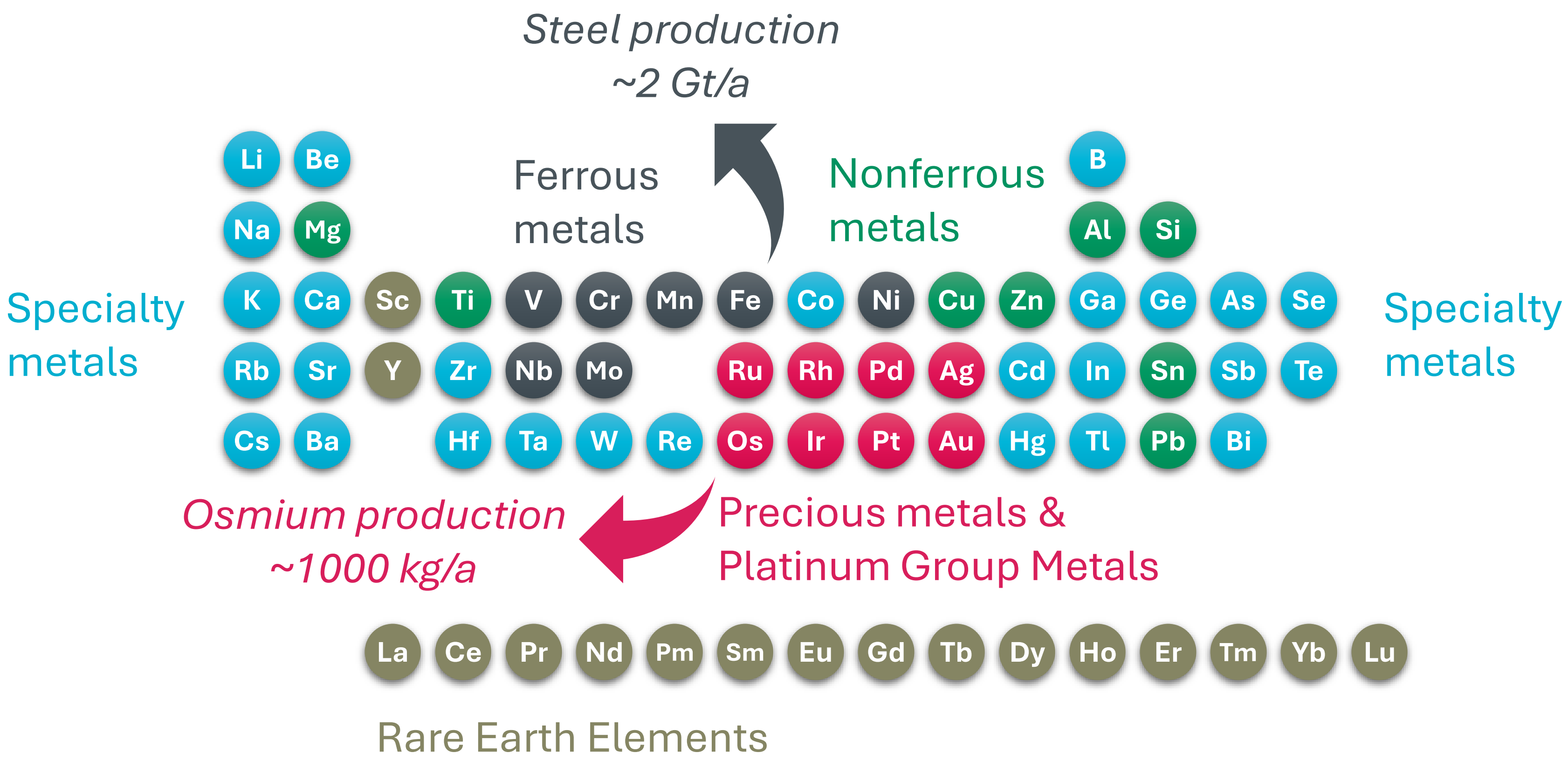
Direct and indirect **GHG emissions** disaggregation 2018



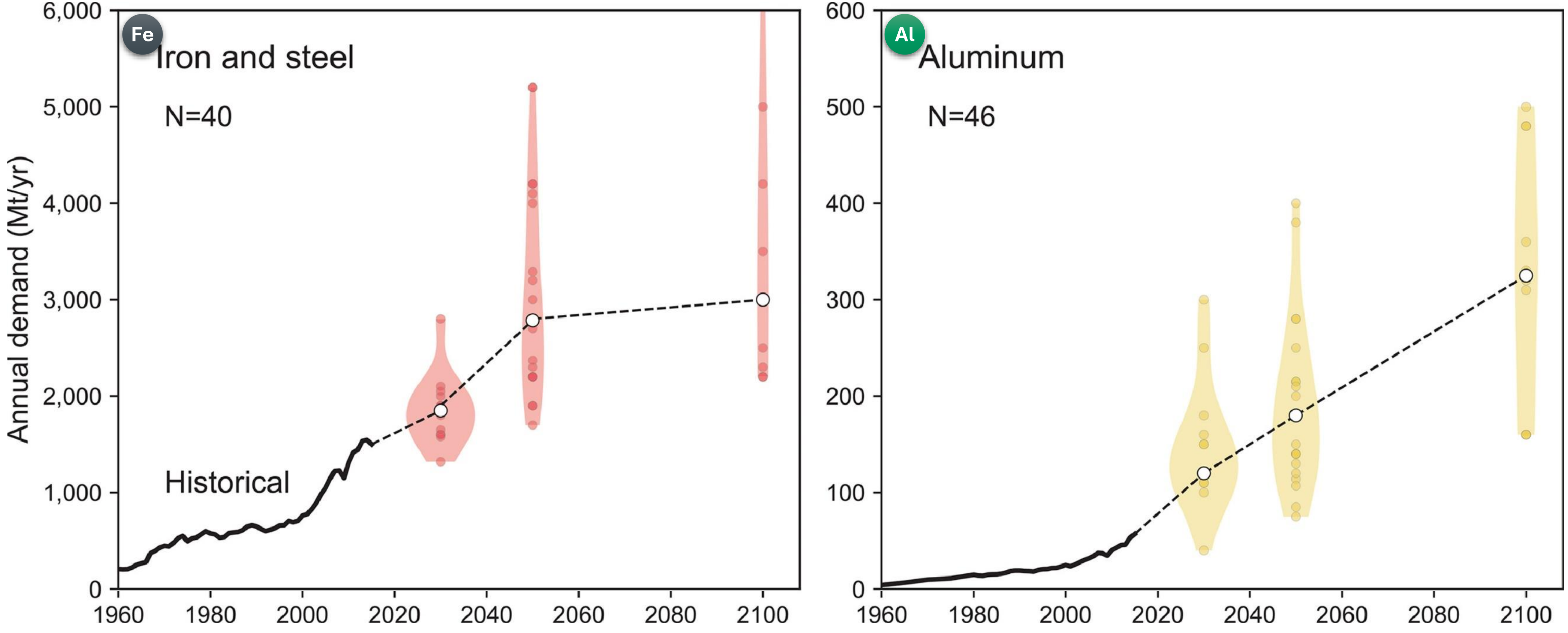
Largest GHG emitting sectors:

1. Residential buildings (11%)
2. Road transport (10.7%)
3. Land use CO_2 (9.4%)
4. **Metals** (7.9%)
5. Chemicals (6.5%)
6. Non-residential buildings (6.1%)
7. Cement (2.7% + heat reqs.)

Metals in the **periodic table**

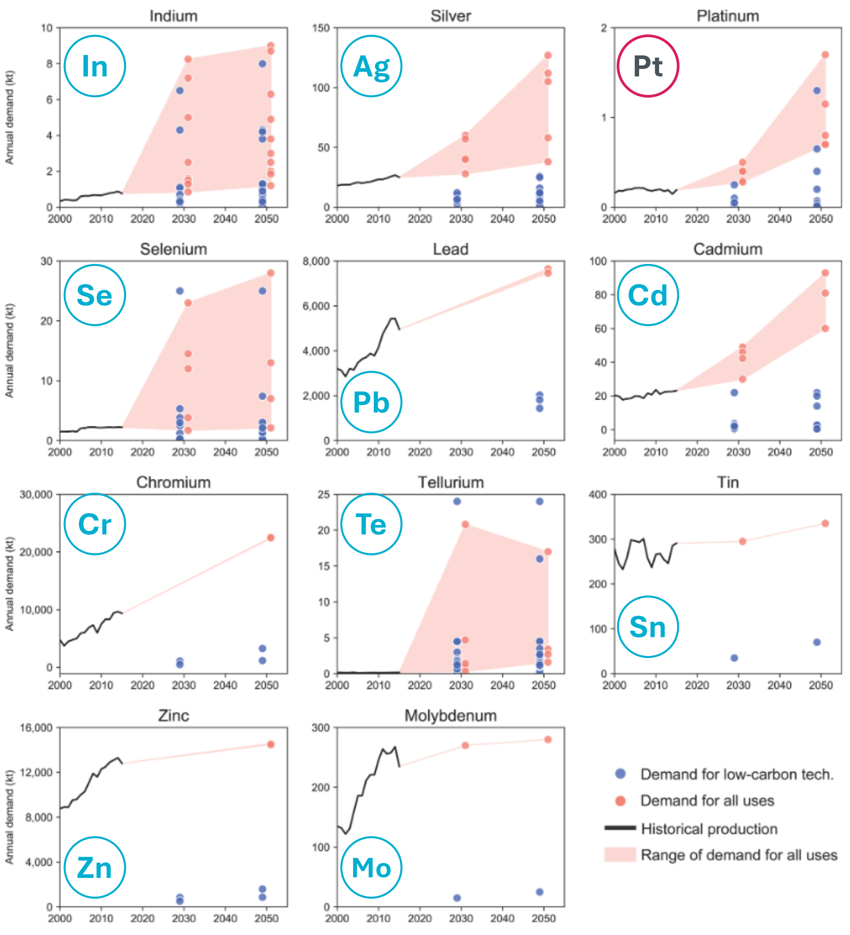


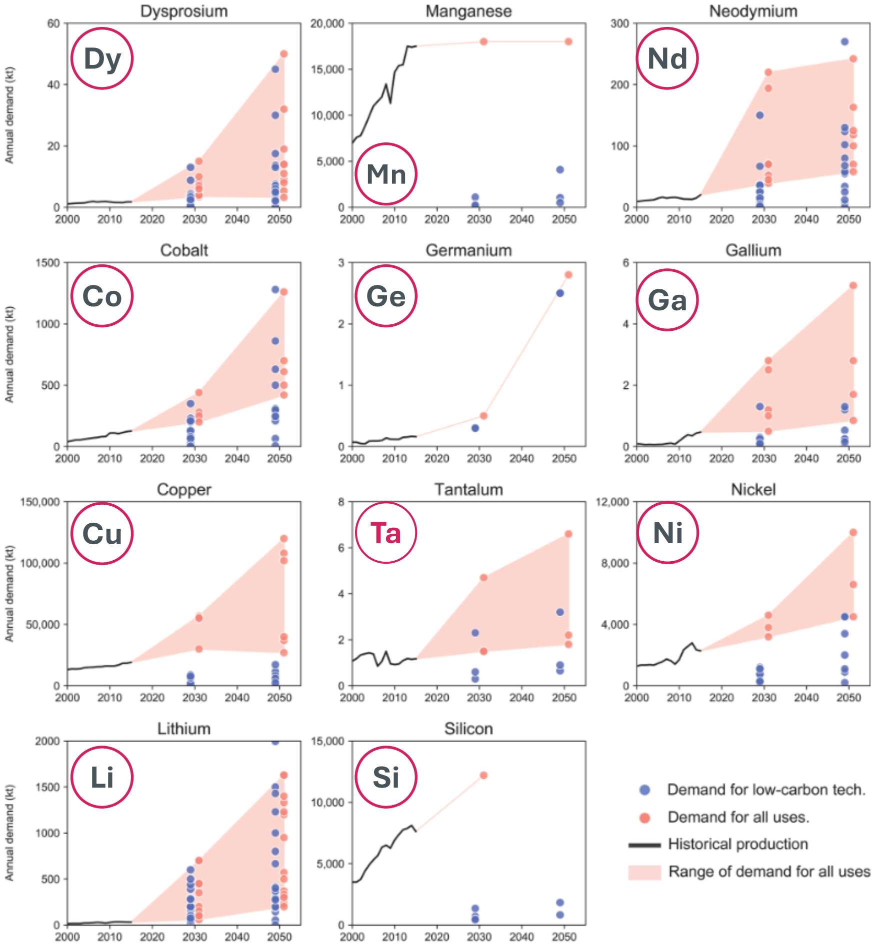
Global annual **demand** projection for Fe and Al



Watari et al. 2021, *Resources, Conservation and Recycling* **164**, 105107

Global annual **demand** projection for various metals





Legend

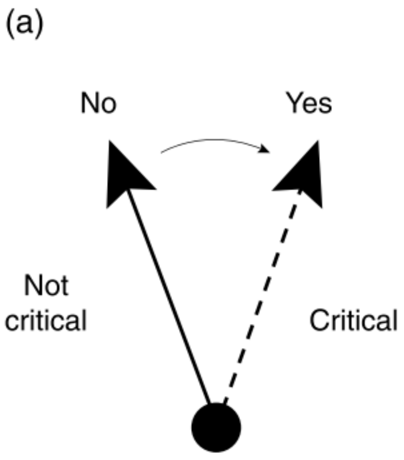
- Li — Critical Raw Material & Strategic Raw Material
- Be — Critical Raw Material
- Na — Not a Critical Raw Material

→ "we can defossilize the economy, but we cannot demetallize it" (Held 2023)

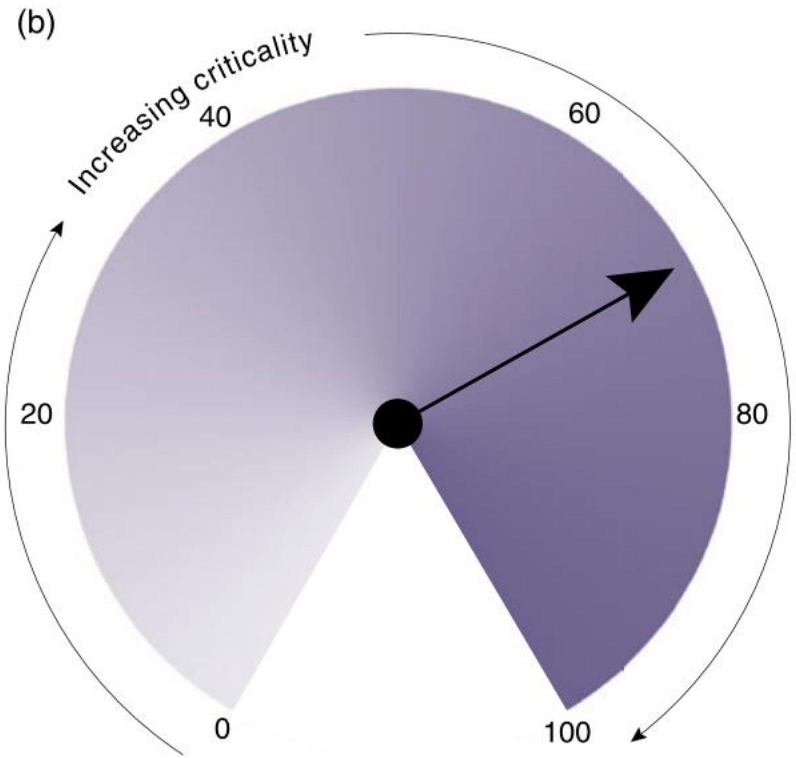
Watari et al. 2021, *Resources, Conservation & Recycling* **155**, 104669

Part 1:
Critical Raw Materials

Preliminary remark: **criticality list** vs. **criticality score**



e.g., EU CRM List

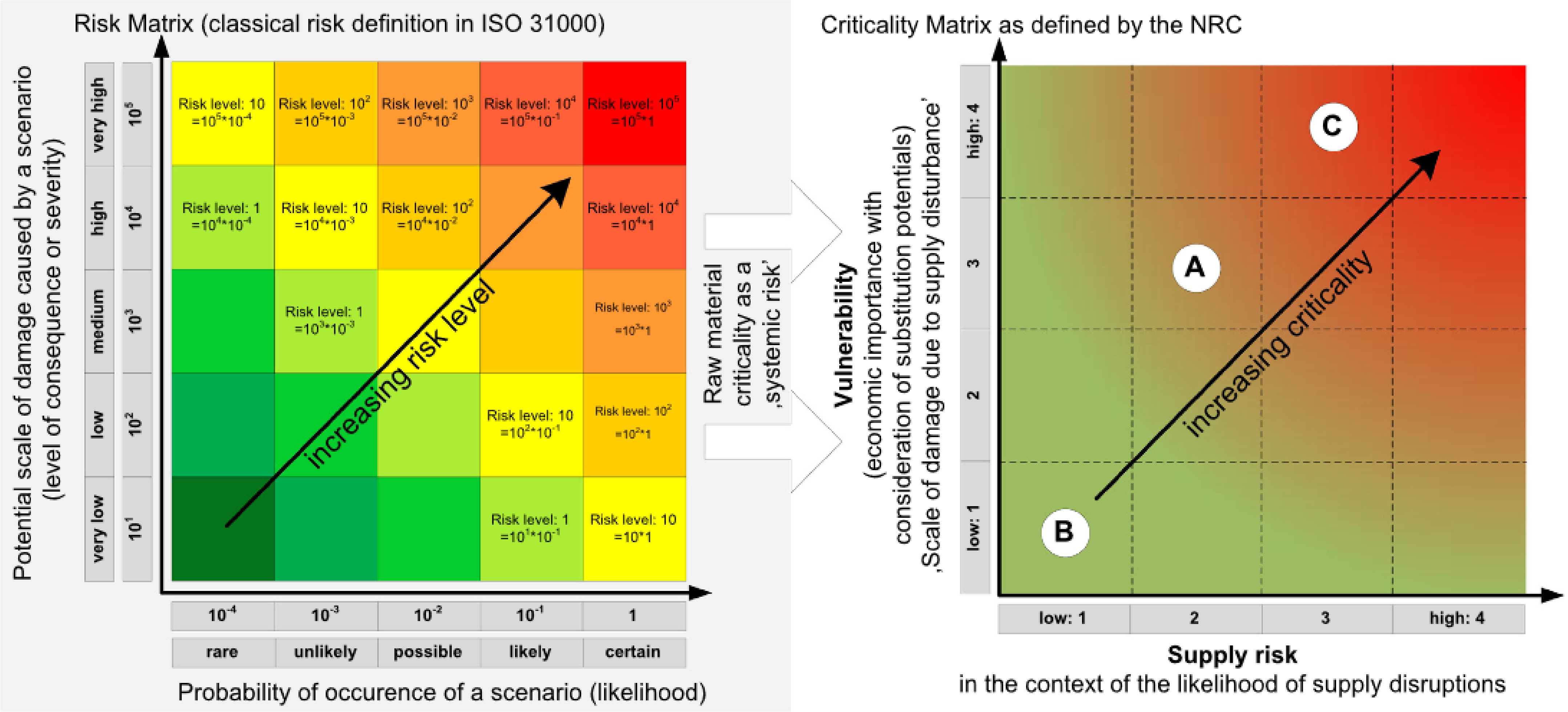


e.g., supply risk assessment

→ we can interpret CRMs either as materials "**on a list**" (good for policymaking) or with "**high scores**" (good for decisionmaking and monitoring/benchmarking)

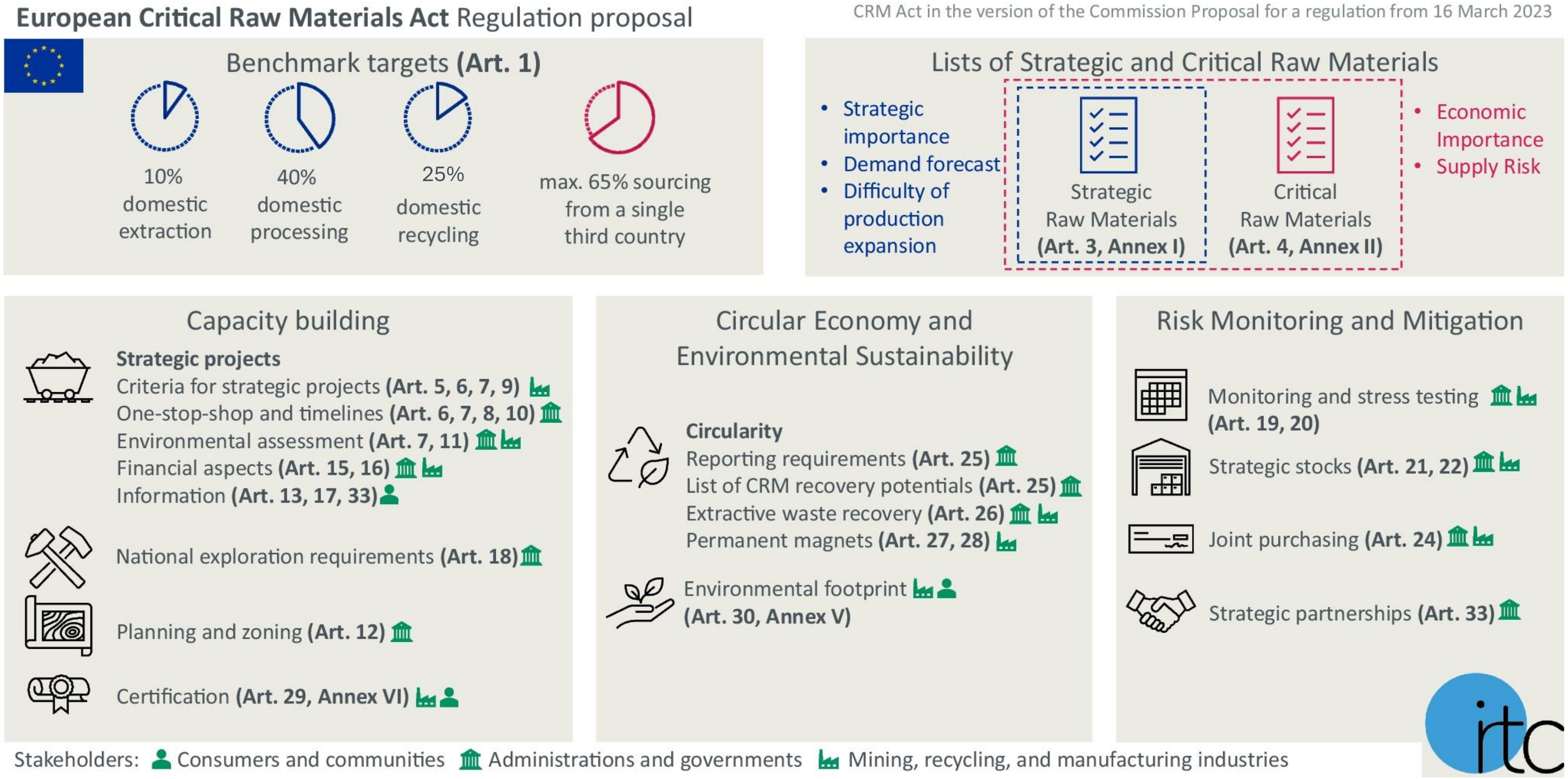
Graedel et al. 2014

Criticality Matrix as an equivalent to the Risk Matrix

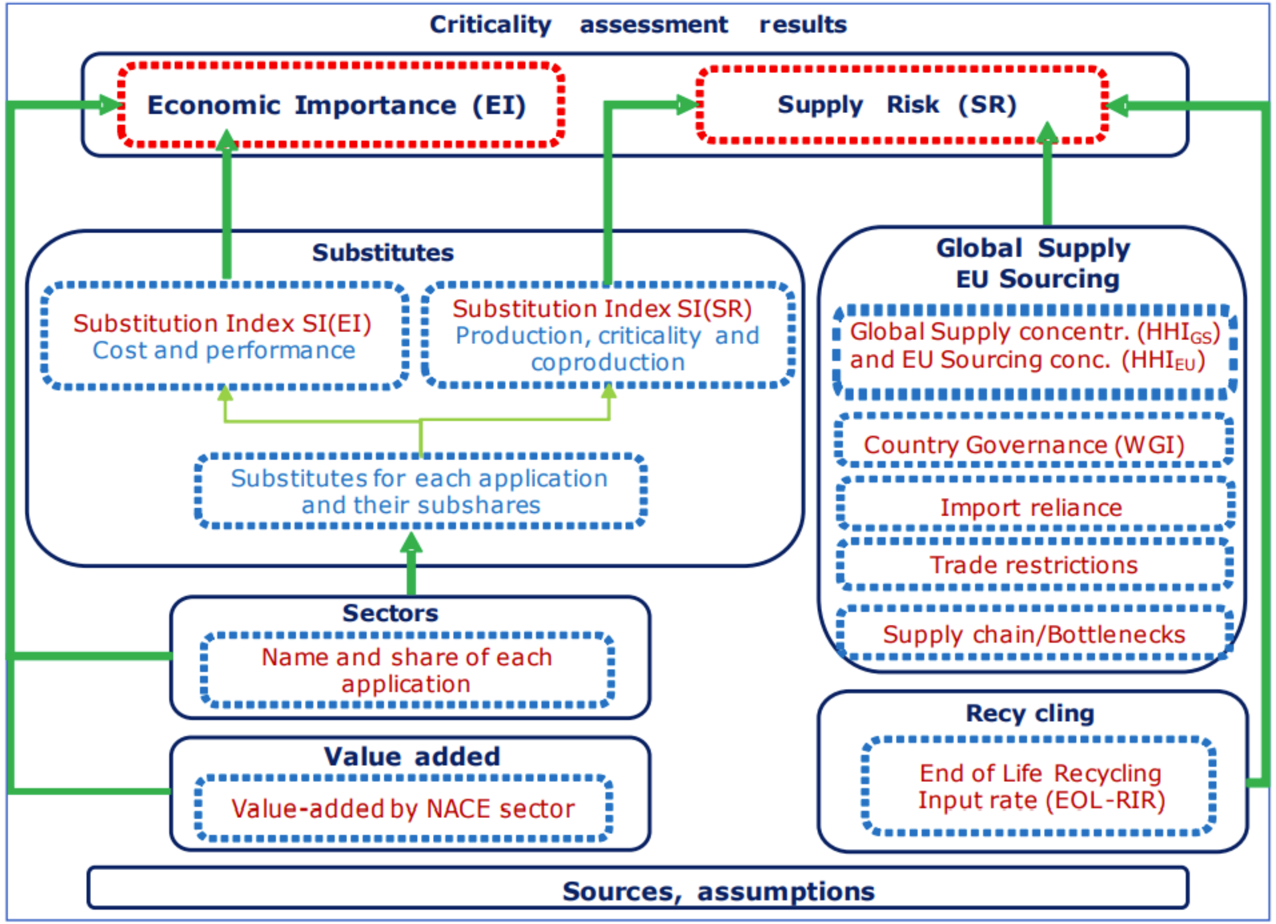


Glöser et al. 2015

European **Critical Raw Materials Act**



Annex II of Critical Raw Materials Act
Critical Raw Materials



Strategic Raw Materials and Critical Raw Materials 2023

Annex I of Critical Raw Materials Act

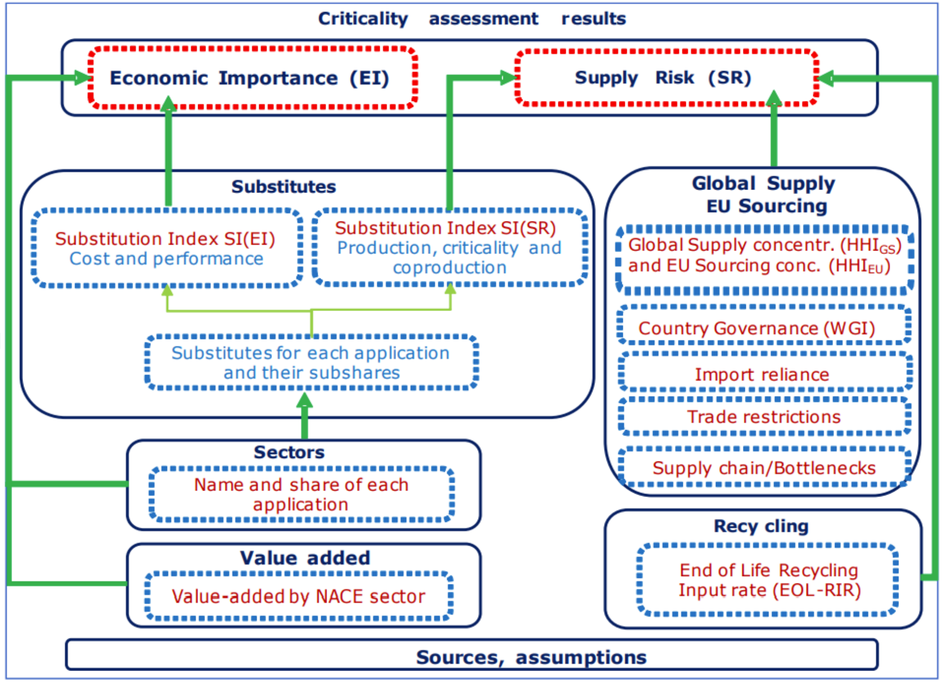
Strategic Raw Materials

- High demand increase due to strategic sectors
- High „production scale“ (log of annual production)
- Low reserve-to-production ratio

(no quantitative publicly reported assessment!)

Annex II of Critical Raw Materials Act

Critical Raw Materials



2023 Critical Raw Materials (*Strategic Raw Materials in italics*)

aluminium/bauxite	coking coal	*lithium*	phosphorus
antimony	feldspar	*LREE*	scandium
arsenic	fluorspar	*magnesium*	*silicon metal*
baryte	*gallium*	*manganese*	strontium
beryllium	*germanium*	*natural graphite*	tantalum
bismuth	hafnium	niobium	*titanium metal*
boron/borate	helium	*PGM*	*tungsten*
cobalt	*HREE*	phosphate rock	vanadium
		*copper**	*nickel**

* Copper and nickel do not meet the CRM thresholds, but are included as Strategic Raw Materials.

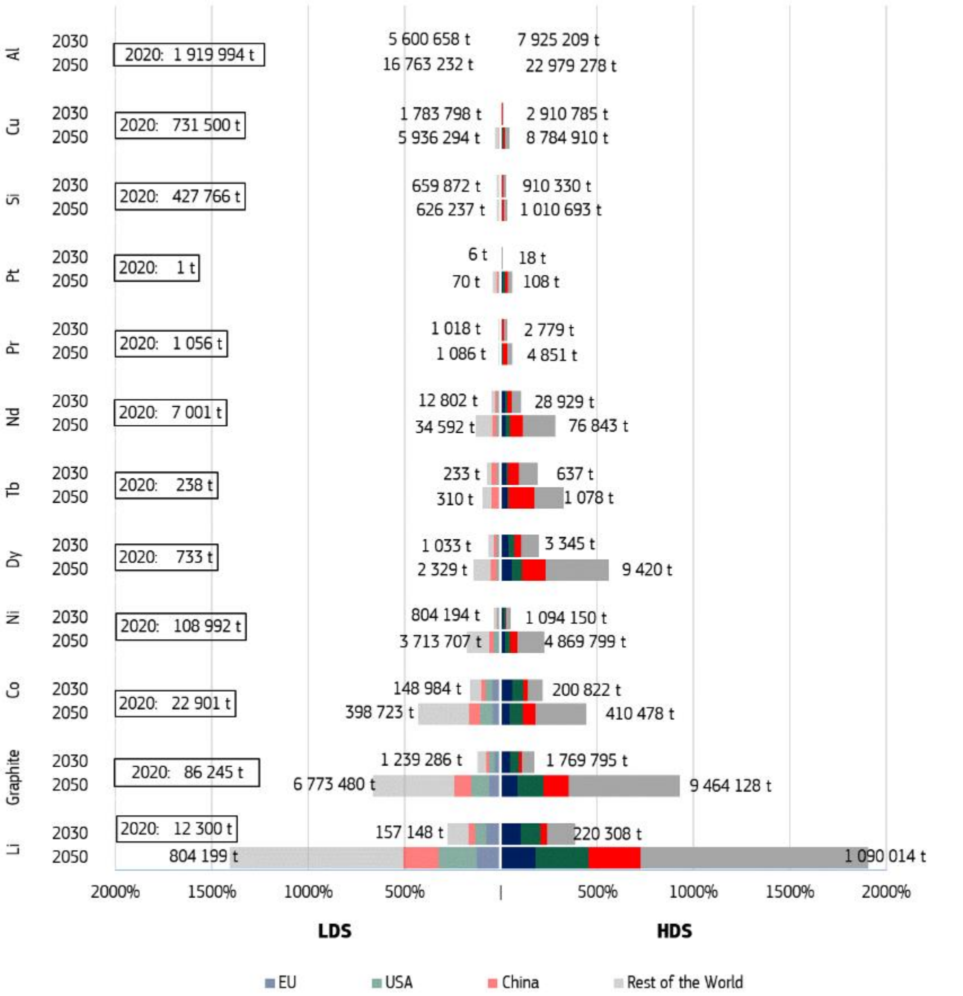
Strategic Sectors and Technologies for the EU

- Li-ion batteries
- Fuel cells
- Electrolysers
- Wind turbines
- Traction motors
- Solar photovoltaics (PV)
- Heat pumps
- Hydrogen direct reduced iron and electric arc furnaces (H2-DRI)
- Data transmission networks
- Data storage and servers
- Smartphones, tablets and laptops
- Additive manufacturing (AM)
- Robotics
- Drones
- Space launchers and satellites

European Commission 2023

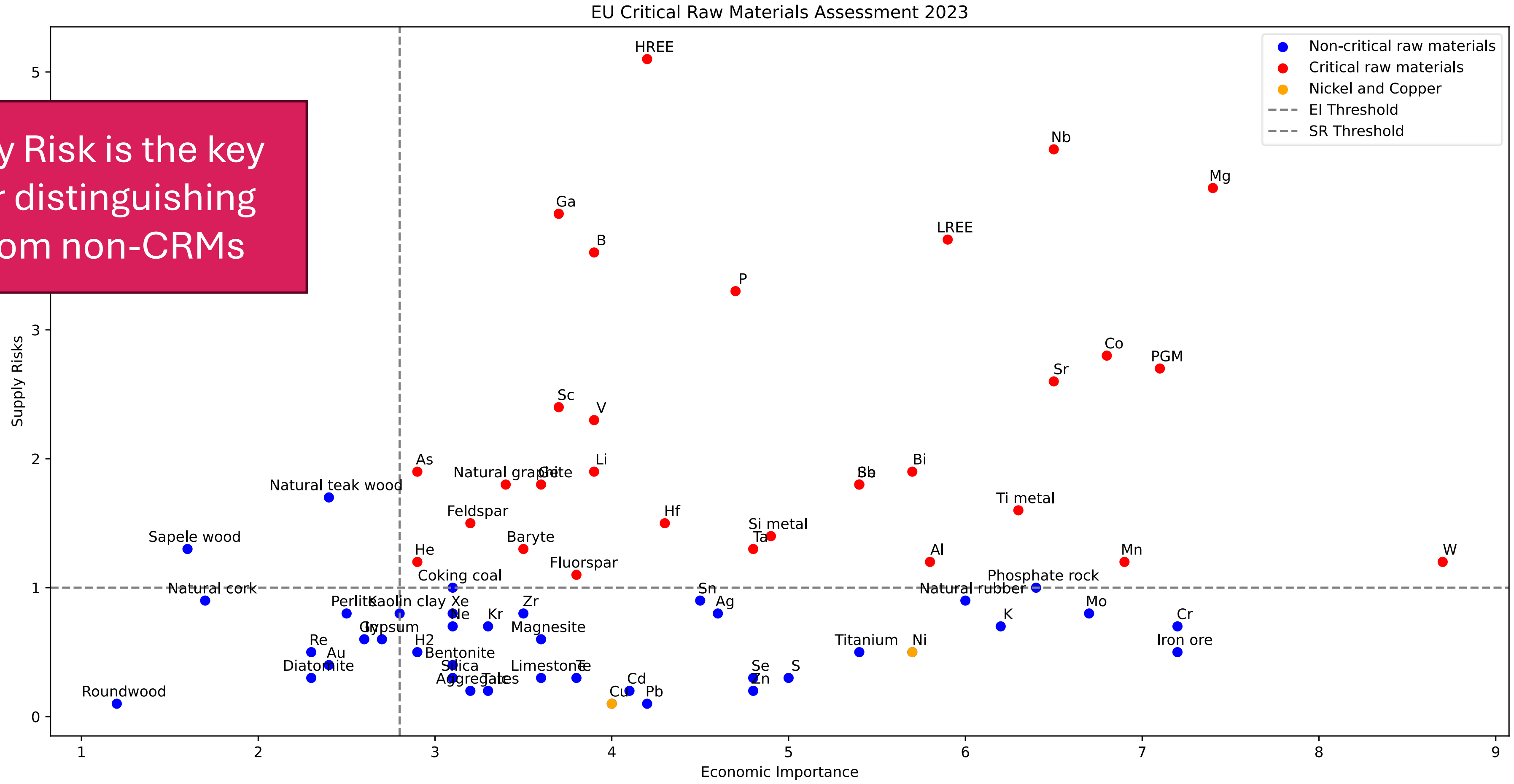
Material demand forecast for strategic sectors

- Material demand forecast for global demand from strategic sectorsin 2030 and 2050 compared to global 2020 annual production (in percent).
- In boxes: 2020 demand from strategic sectors (in t).



EU Critical Raw Materials Assessment Matrix 2023

→ Supply Risk is the key factor for distinguishing CRMs from non-CRMs



→ most raw materials are above the threshold for Economic Importance anyway

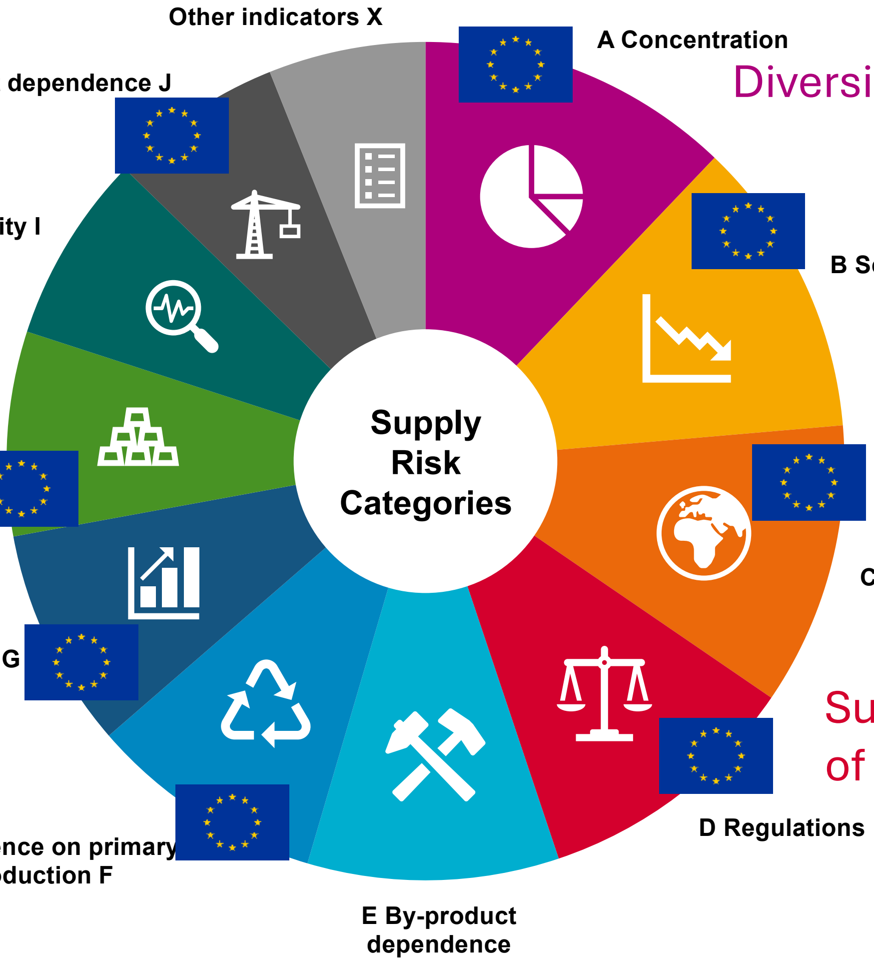
Supply risks can be managed

Indicator included in EU CRM/SRM assessment

Financial hedging und long-term contracts

Research & development of new material substitutes

Investments in recycling and processing technology



Diversification of suppliers

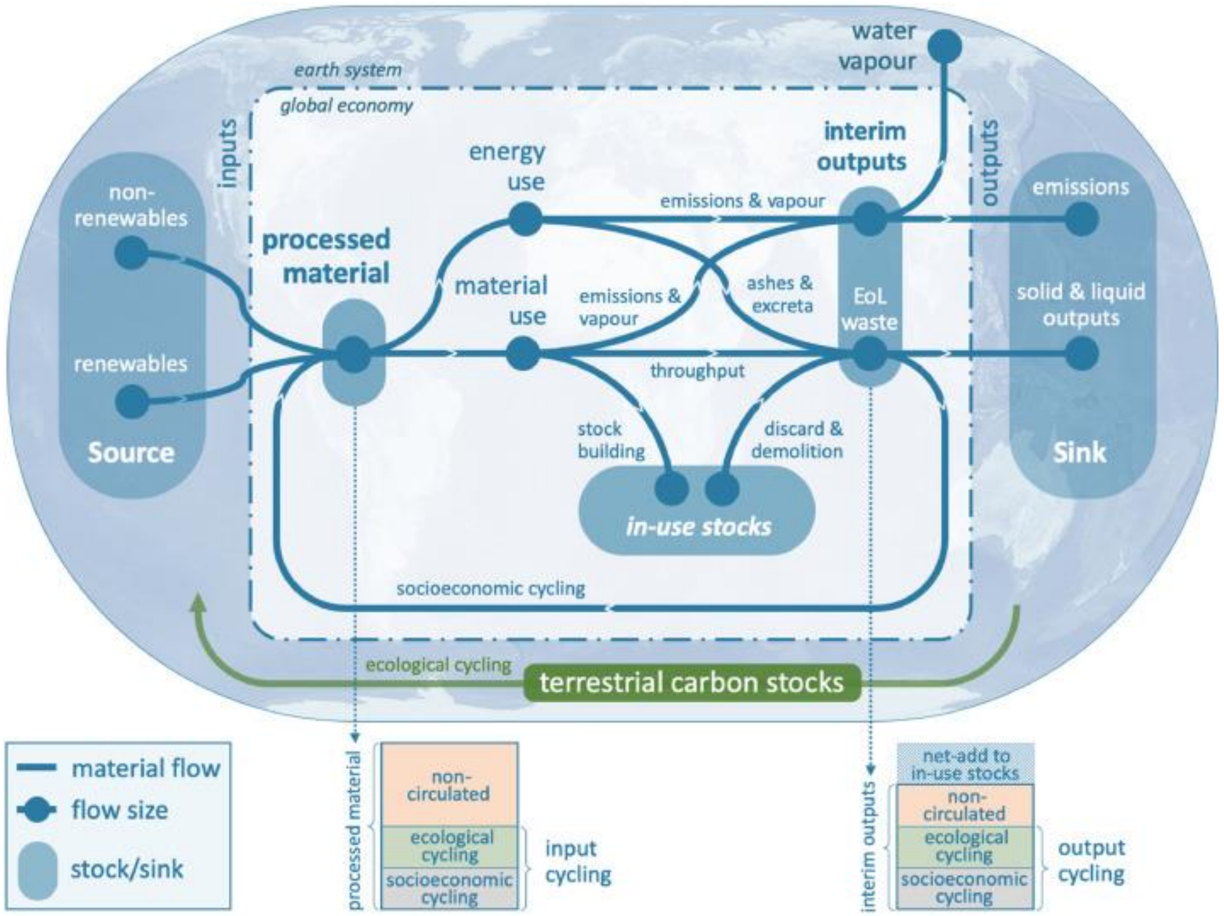
Investments in exploration and mining

Sustainable selection of suppliers

Part 2:
Circularity Issues

Material flows in the global economy (Haas et al. 2020)

- **Input cycling** is the circulated part of processed materials.
- **Output cycling** is the circulared art of end-of-life wastes.
- **Socioeconomic cycling** considers secondary raw materials.
- **Ecological cycling** relies on biogeochemical cycles and plant growth.



Tracing global material flows and losses in the economy

Aluminium body-in-wite

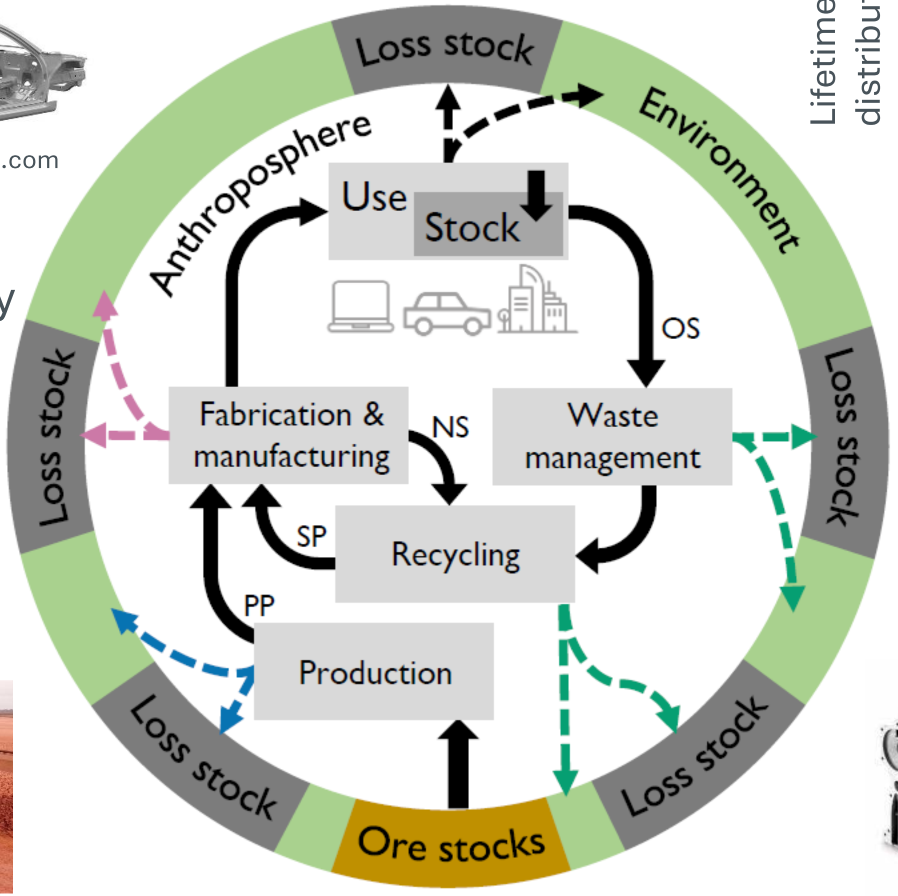
Photo: Hydro.com

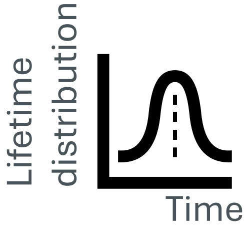
Aluminium wrought alloy

Photo: Hydro.com

Bauxite mining

Photo: Hydro.com





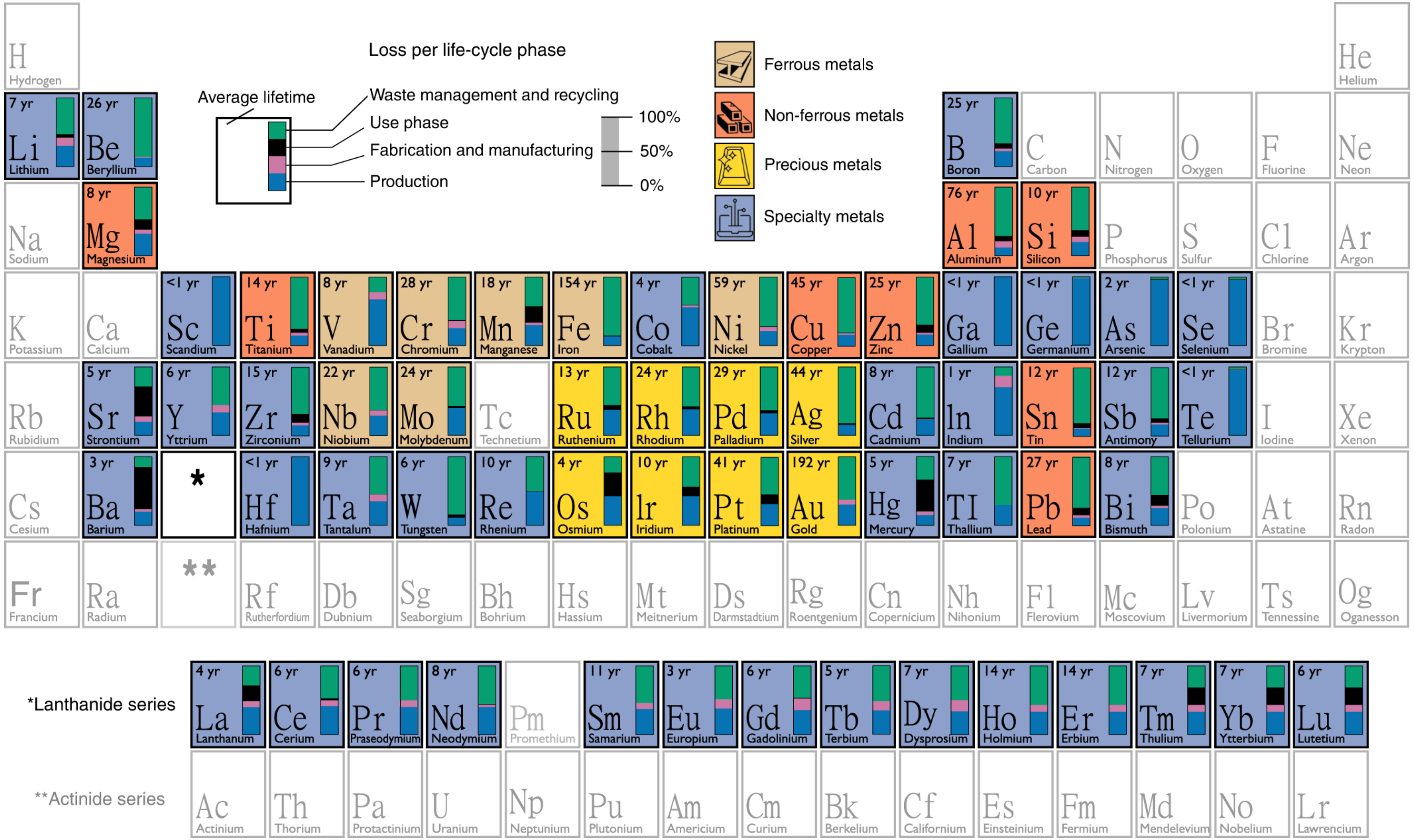
Al scrap from cars

Photo: Hydro.com

Recycled cast Al in motor blocks

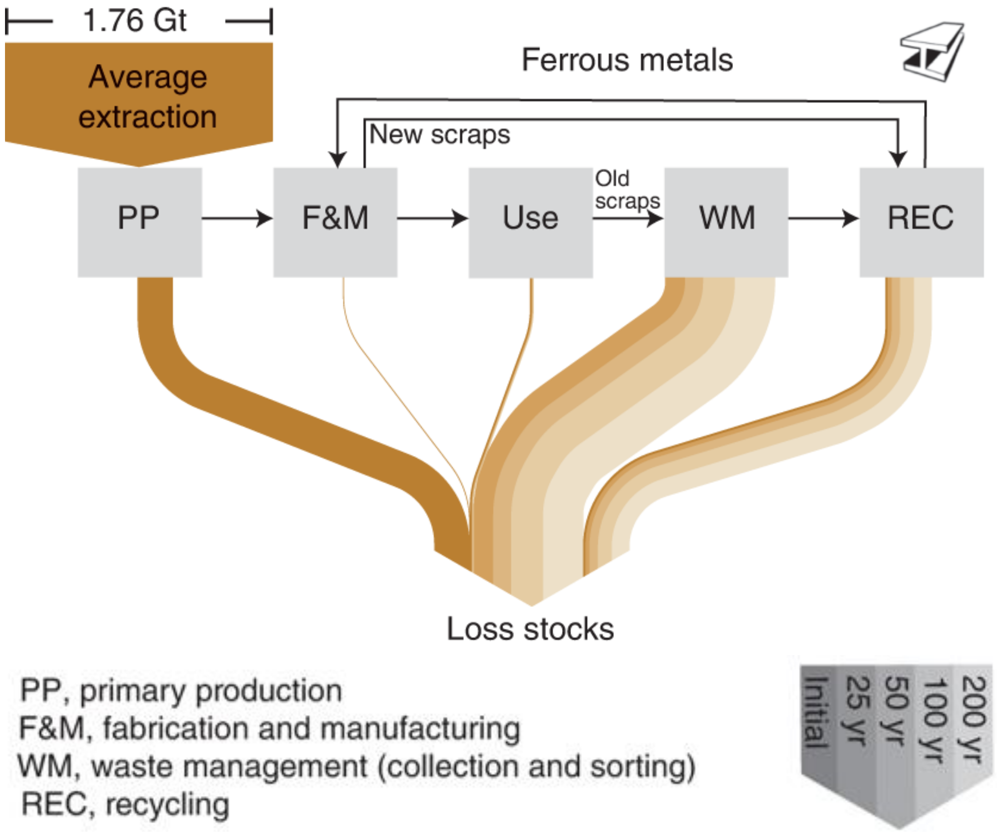
Photo: European Aluminium

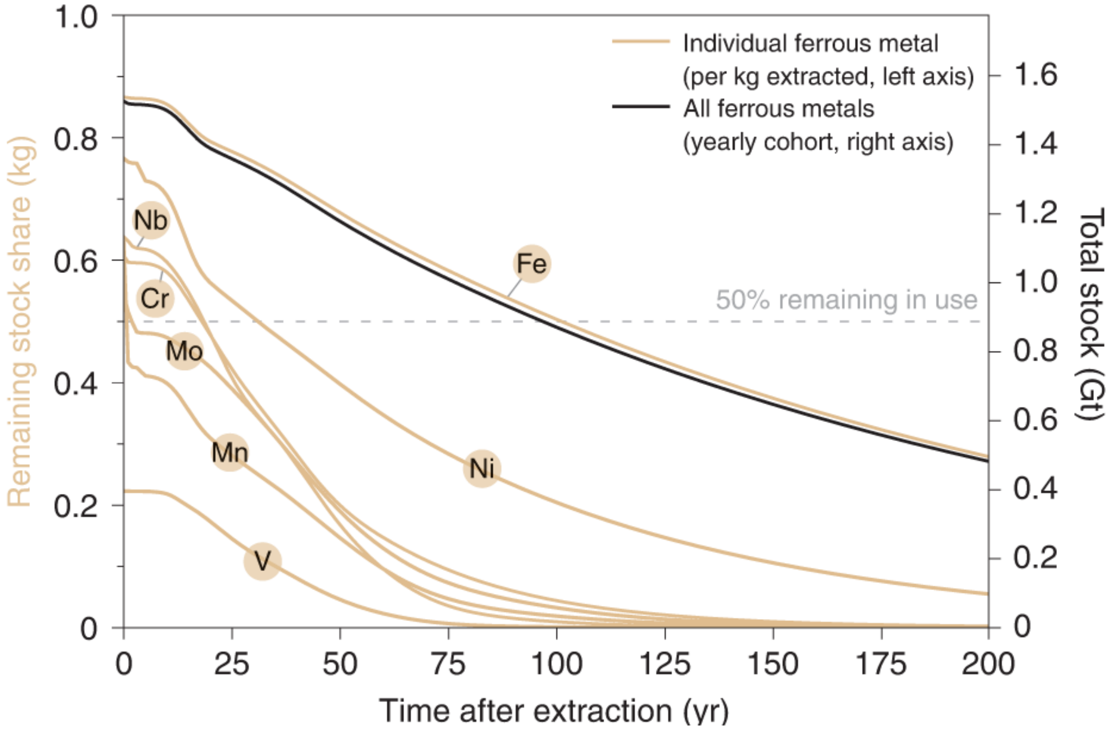
Coverage of the periodic table with MaTrace-dissipation



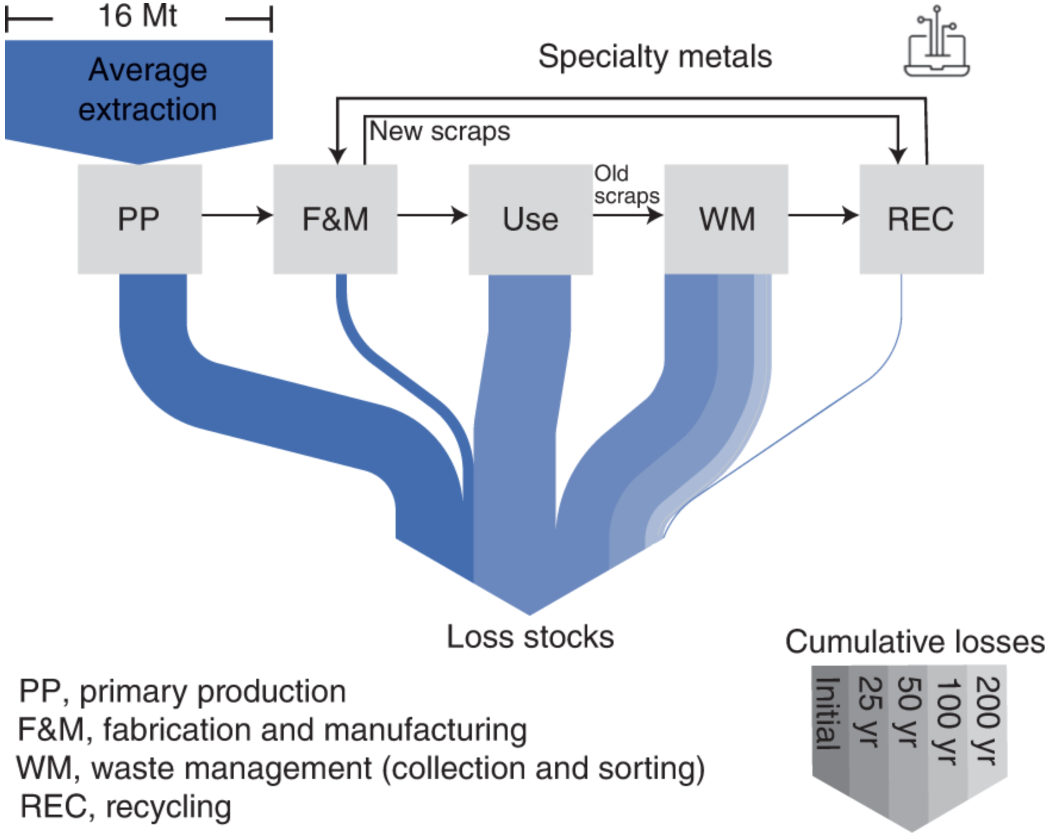
Charpentier Poncelet et al. 2022, *Nature Sustainability* **5**, 717-726

Dissipative losses of ferrous metals

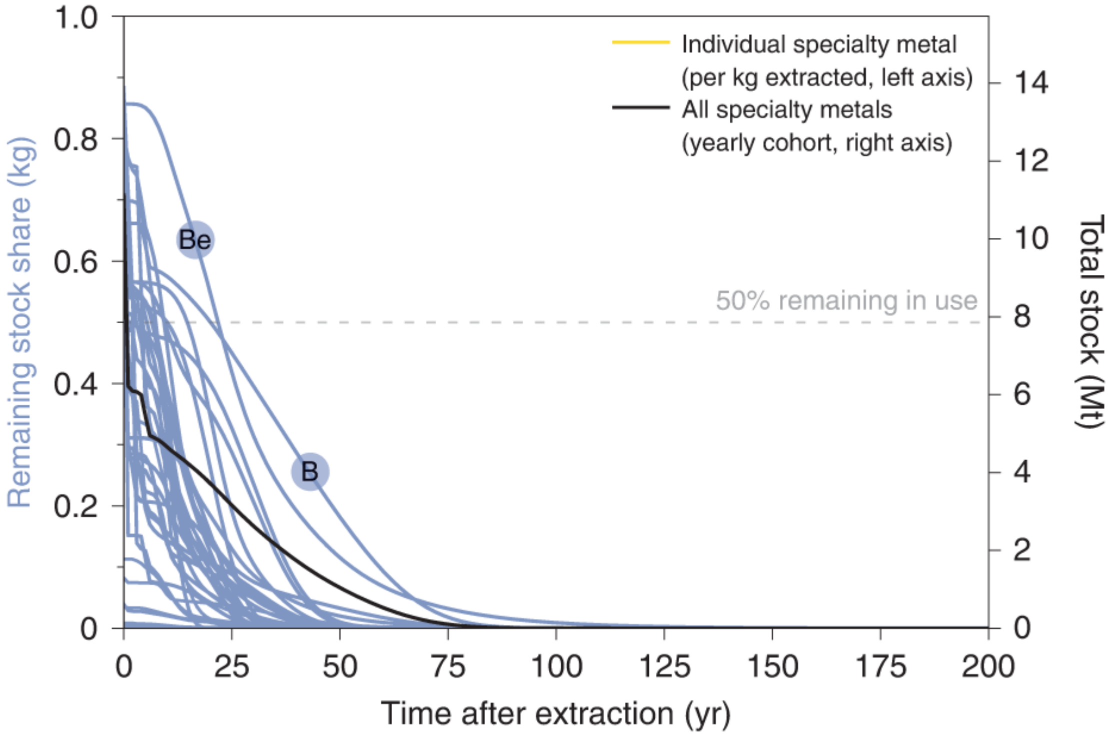




Dissipative losses of specialty metals



PP, primary production
F&M, fabrication and manufacturing
WM, waste management (collection and sorting)
REC, recycling



Charpentier Poncelet et al. 2022, *Nature Sustainability* **5**, 717-726

"Lifetimes" of metals in the global economy

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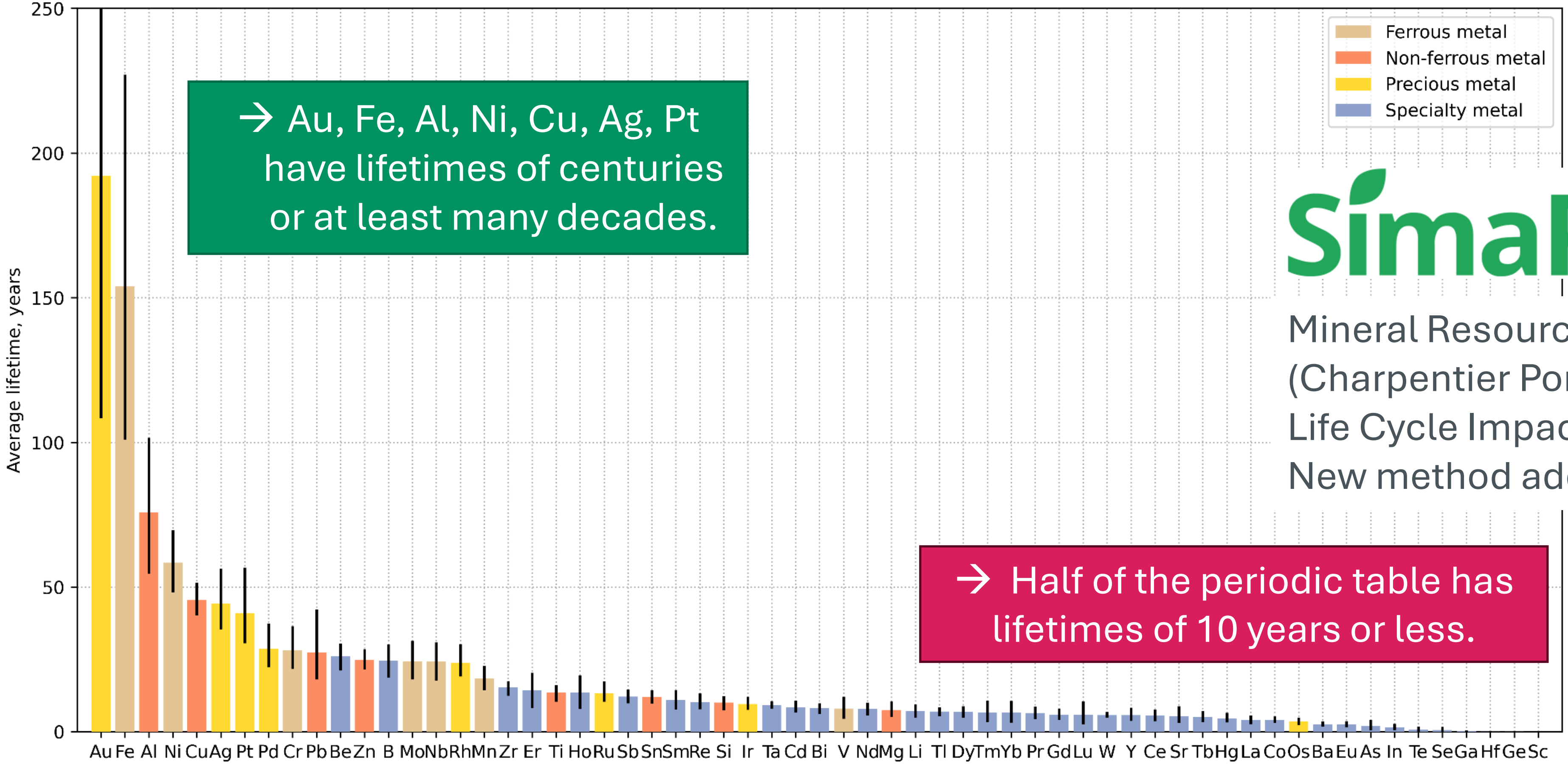

→ Au, Fe, Al, Ni, Cu, Ag, Pt have lifetimes of centuries or at least many decades.

→ Half of the periodic table has lifetimes of 10 years or less.

SimaPro

Mineral Resource Dissipation (Charpentier Poncelet et al. 2022) Life Cycle Impact Assessment New method added in v9.5

Charpentier Poncelet et al. 2022, *Nature Sustainability* **5**, 717-726

Loss rates, end-of-life recycling rates, recycled content

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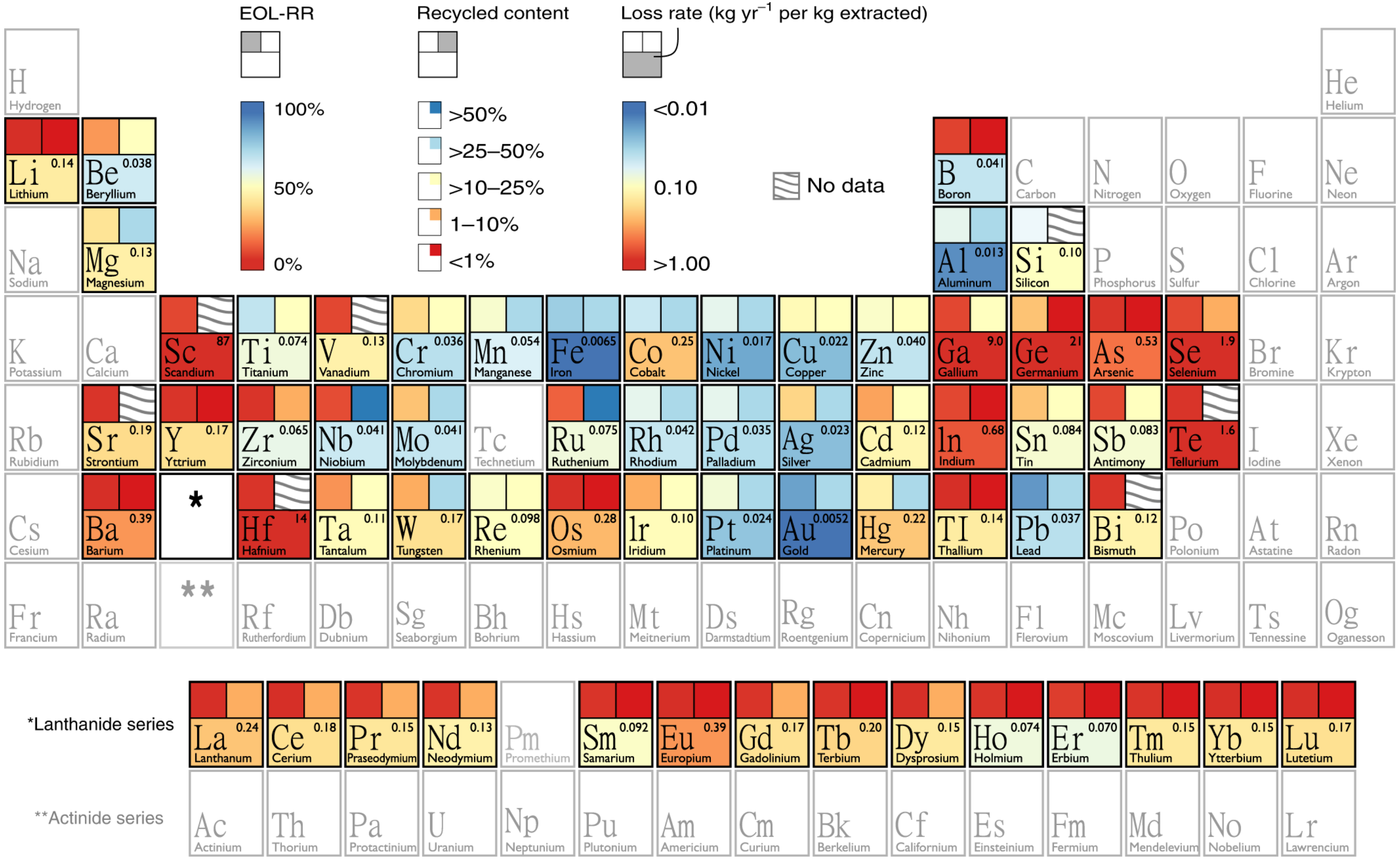

Charpentier Poncelet et al. 2022, *Nature Sustainability* **5**, 717-726

End-of-life recycling input rate in EU Criticality method

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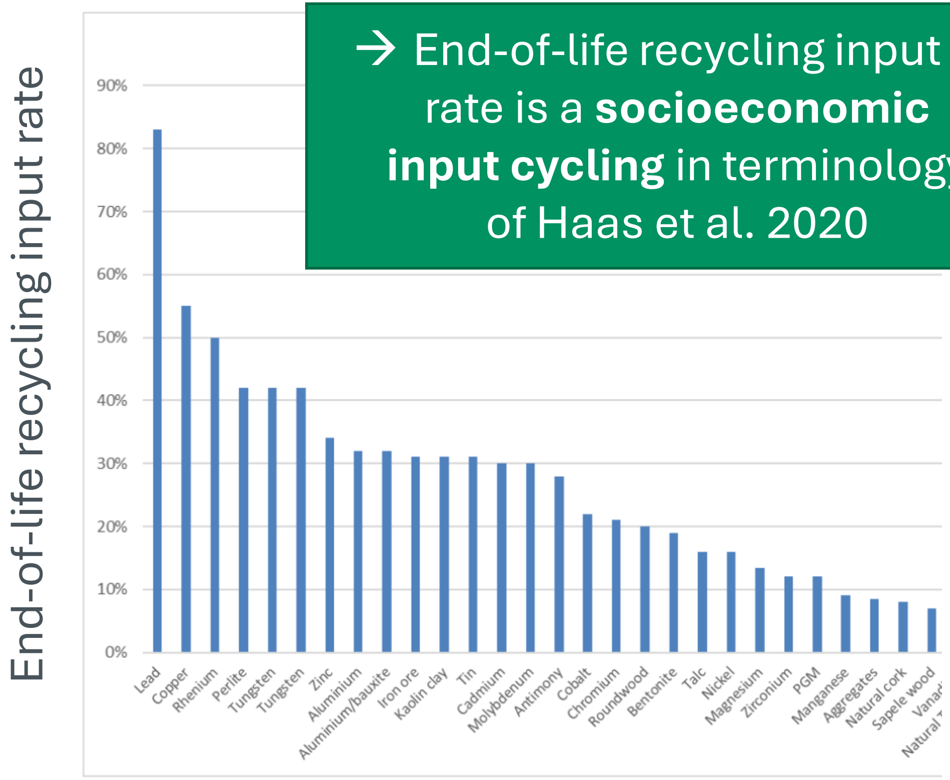
→ EU method assumes recycled materials are supply risk free. Is that so?

- Supply Risk Calculation of the European Commission‘s method:
- $SR = \left[HHI_{WGI,global} \cdot \frac{IR}{2} + HHI_{WGI,EUsourcing} \cdot \left(1 - \frac{IR}{2}\right)\right] \cdot (1 - EoLRIR) \cdot SI_{SR}$
- High EoL-RIR causes supply risk reduction.
  - Lead 83%
  - Copper 55%
  - Rhenium 50%
  - Tungsten 42%
  - Zinc reported 34%, should have been 11% (Bradley et al. 2024)
  - Aluminium 32%
  - Iron 31%
  - Tin 31%
  - Cadmium 30%
  - Molybdenum 30%



→ End-of-life recycling input rate is a **socioeconomic input cycling** in terminology of Haas et al. 2020

Part 4:
Vision for Circularity

Metal-material-component-product composition model

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Metal X Production (e)

Metal Y Production (e)

→ Material Production (m, e) → Component Production (c, m, e) →

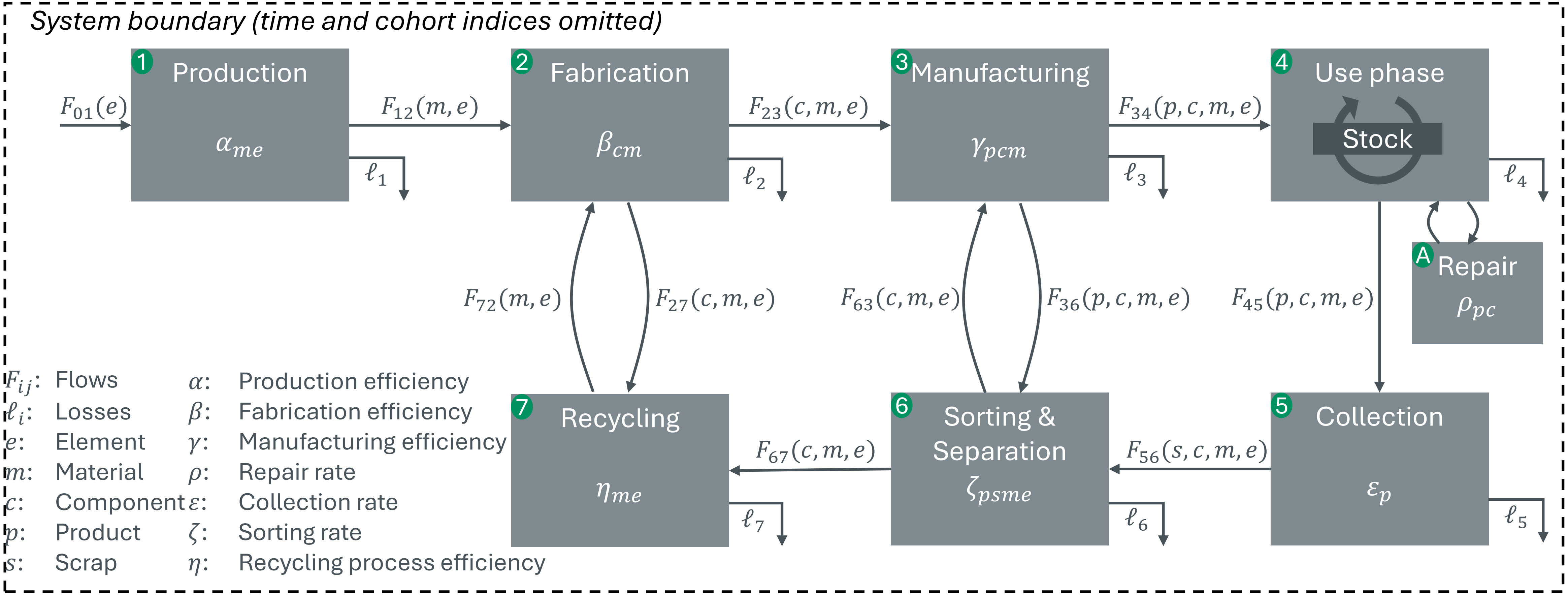
- Product A (p, c, m, e)
- Product B (p, c, m, e)
- Product C (p, c, m, e)
- Product X (p, c, m, e)

- **Typical quality questions**
  - Is it a **homogeneous** material?
  - What is the **purity** of the material?
  - Does it follow a specific **composition**?
  - Are the products **disassemblable**?
  - Are the components **disassemblable**?
  - What are **contaminating** elements?

Example

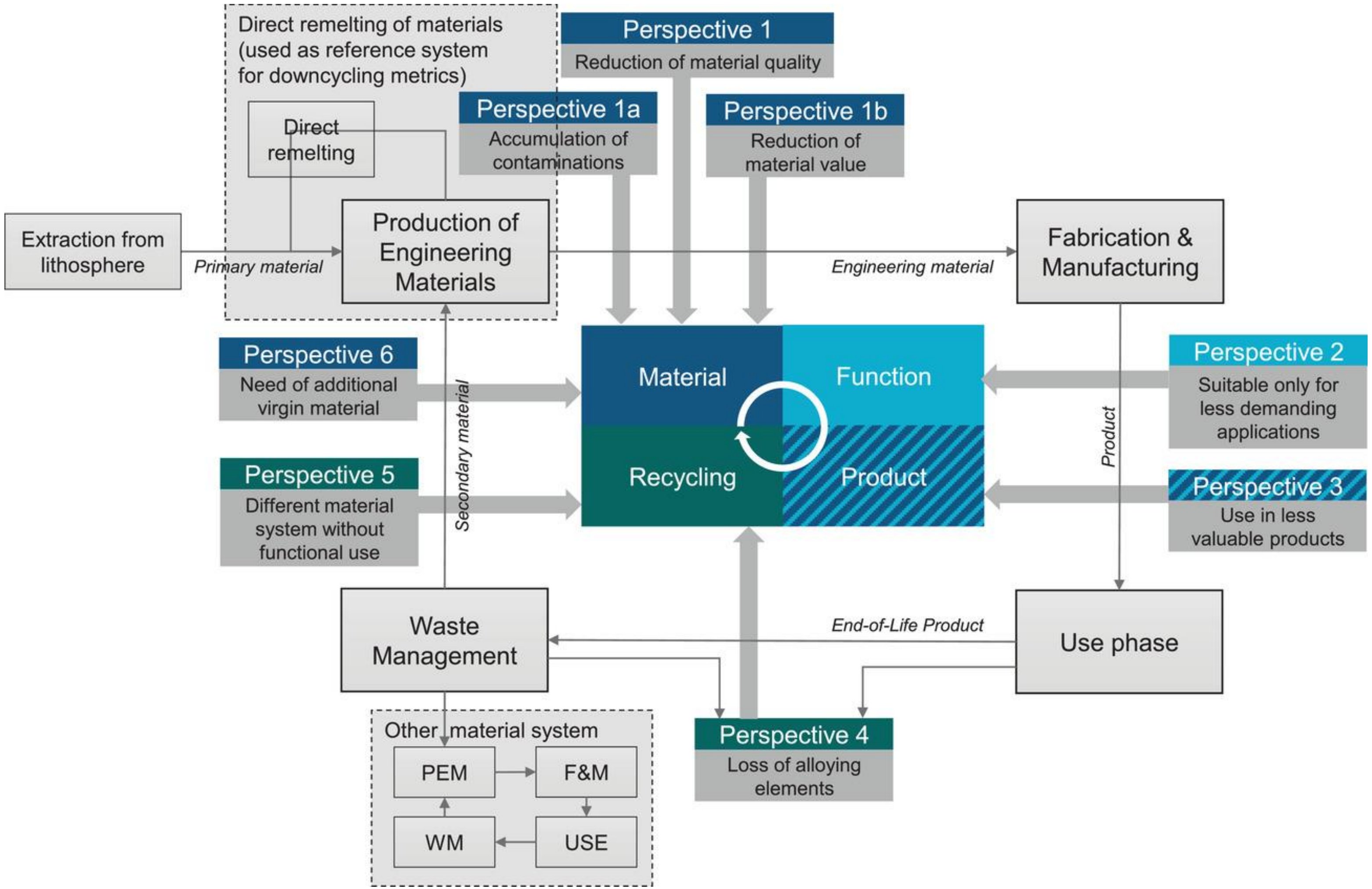
Li, Co → Cathode active material → Lithium-ion battery → Electric vehicle; In-ear headphones

Modeling of metal material flows and losses

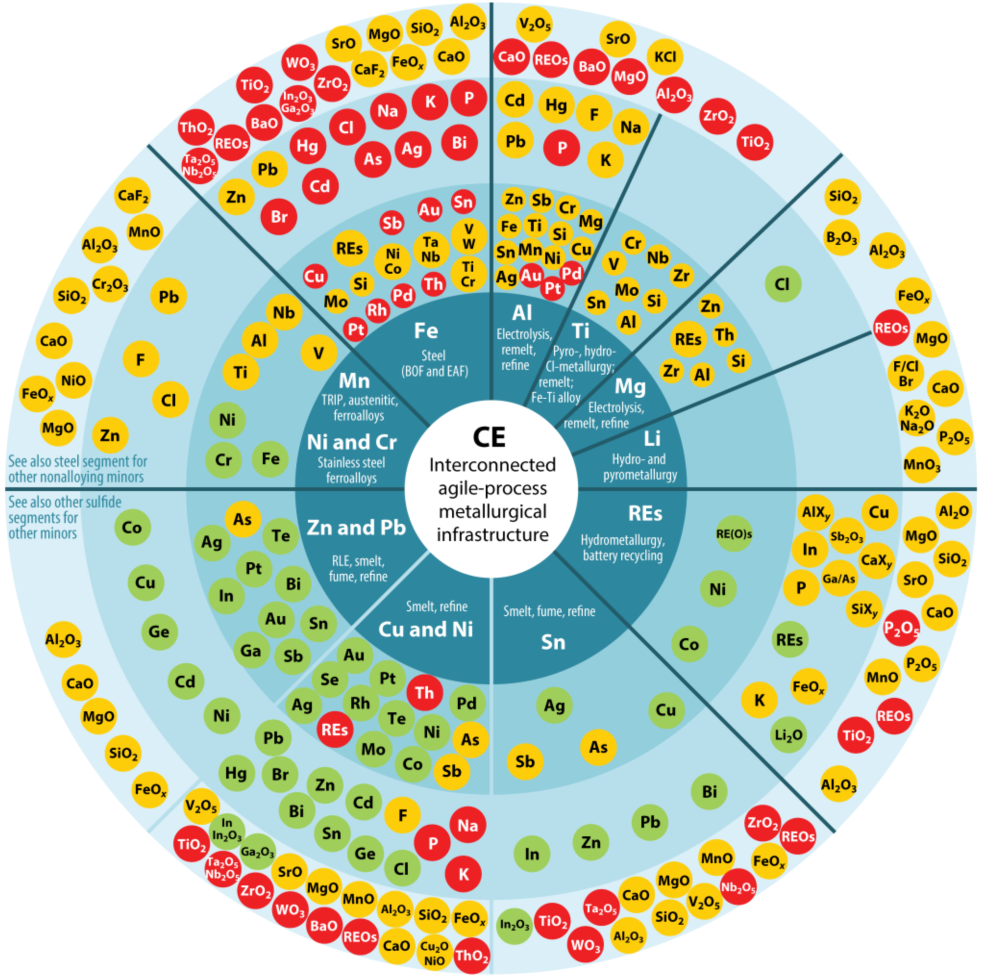


F_{ij}:	Flows	α:	Production efficiency
ℓ_i:	Losses	β:	Fabrication efficiency
e:	Element	γ:	Manufacturing efficiency
m:	Material	ρ:	Repair rate
c:	Component	ε:	Collection rate
p:	Product	ζ:	Sorting rate
s:	Scrap	η:	Recycling process efficiency

Perspectives of downcycling



Metal Wheel (Reuter et al. 2019)



→ All parts of the metal wheel are required for a functional circular economy of metals (Reuter 2023)

Economically viable destinations of complex resources and materials, designed functional material combinations, scrap, residues, etc., to metallurgical processing infrastructure (each segment) to produce refined metals, high-quality compounds, and alloys in the best available technology.

Key

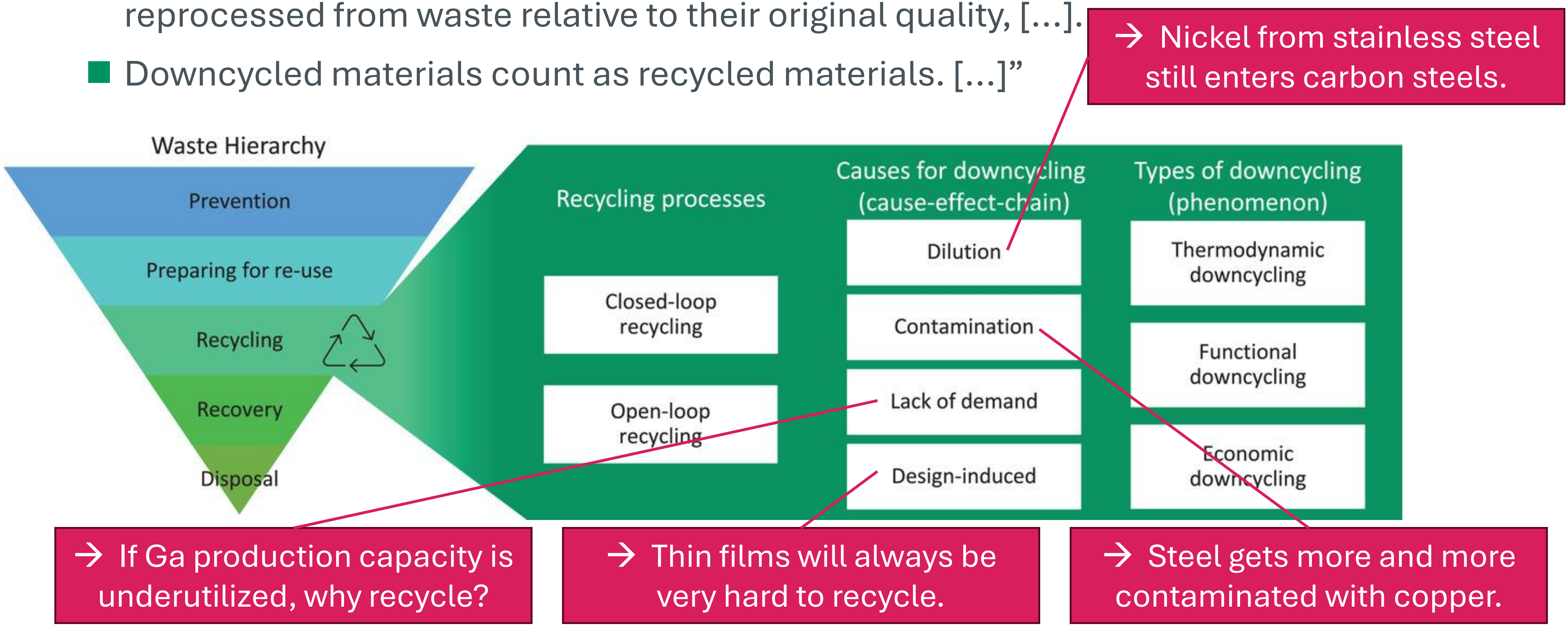
- **R** — **Mainly recovered element**
  Compatible with the base metal as an alloying element or can be recovered in subsequent processing.
- **R/L** — **Recovered in alloy/compound or lost if in the incorrect stream/scrap/module**
  Governed by functionality, if not detrimental to base metal or product (e.g., if refractory metals in EoL product report to slag, and slag is also intermediate product for cement).
- **L** — **Mainly lost element: not always compatible with base metal or product**
  Detrimental to properties and cannot be economically recovered; e.g., Au dissolved in steel or aluminum will be lost.

- **CE's agile base metal processing infrastructure**
  Extractive metallurgy's backbone, the enabler of a CE as it also recovers technology elements used, e.g., in renewable energy infrastructure, IoT, and eMobility, etc.
- **Dissolves primarily in base metal if metallic (mainly pyrometallurgy and smelting route)**
  Valuable elements recovered or dissipatively lost (metallic, speiss, compounds, and alloys in EoL also determine the destination). Linked hydro- and pyrometallurgical infrastructure determines percent recovery.
- **Compounds primarily to dust, slime, speiss (mainly hydrometallurgy and refining route)**
  Collectors of valuable minor elements as, e.g., oxides, sulfates, and chlorides, and mainly recovered in appropriate predominantly hydro-metallurgical infrastructure if economical. Often separate infrastructure.
- **Primarily lost to benign, lower-value building material products; also contributing to dissipative loss**
  Relatively lower value but an inevitable part of society and material processing. A sink for metals and loss from the CE system as oxides/compounds. Usually linked but separate infrastructure.

Reuter MA, et al. 2019.
Annu. Rev. Mater. Res. 49:253–74

Causes and types of downcycling

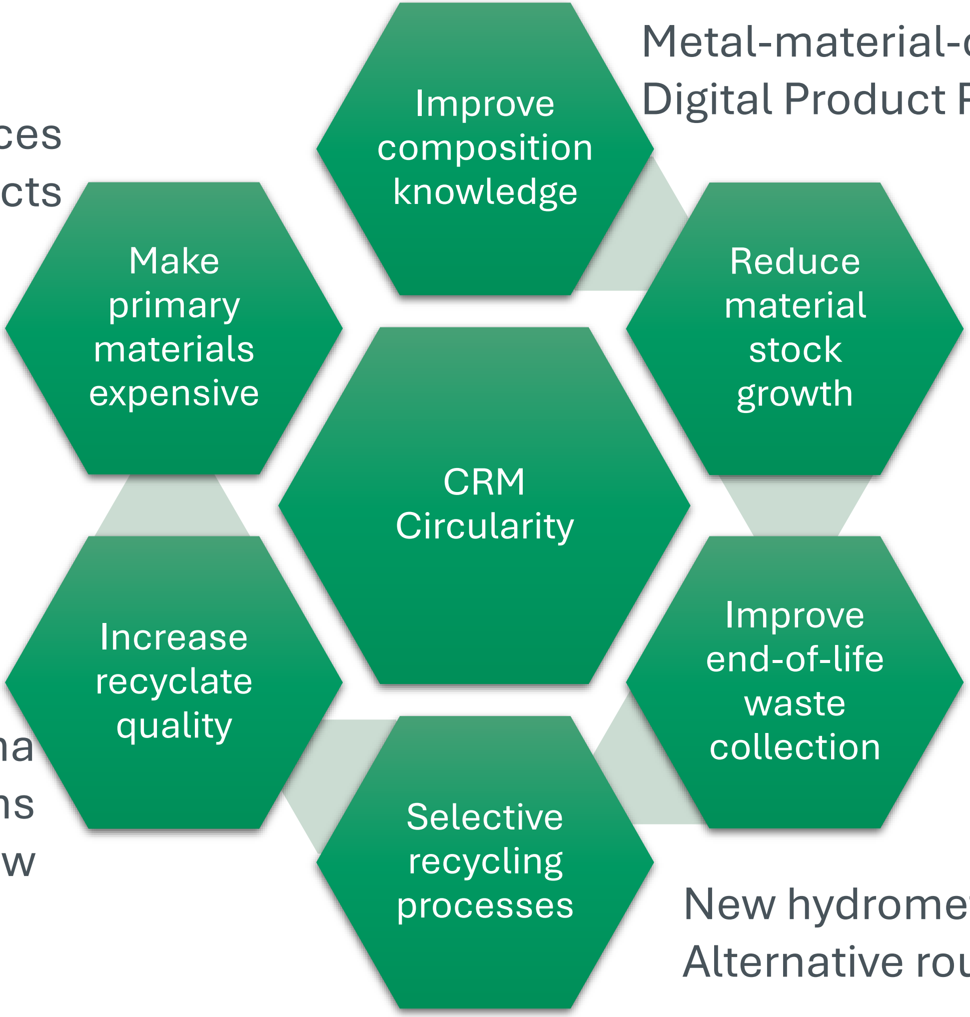
- "Downcycling is the phenomenon of quality reduction of materials reprocessed from waste relative to their original quality, […].
- Downcycled materials count as recycled materials. […]"



Checklist for CRM Circularity

GHG taxes and allowances
Regulate environmental impacts

Avoid downcycling phenomena
Avoid contaminations
Make cascades slow



Metal-material-component-product composition
Digital Product Passport / Battery Pass / Catena-X

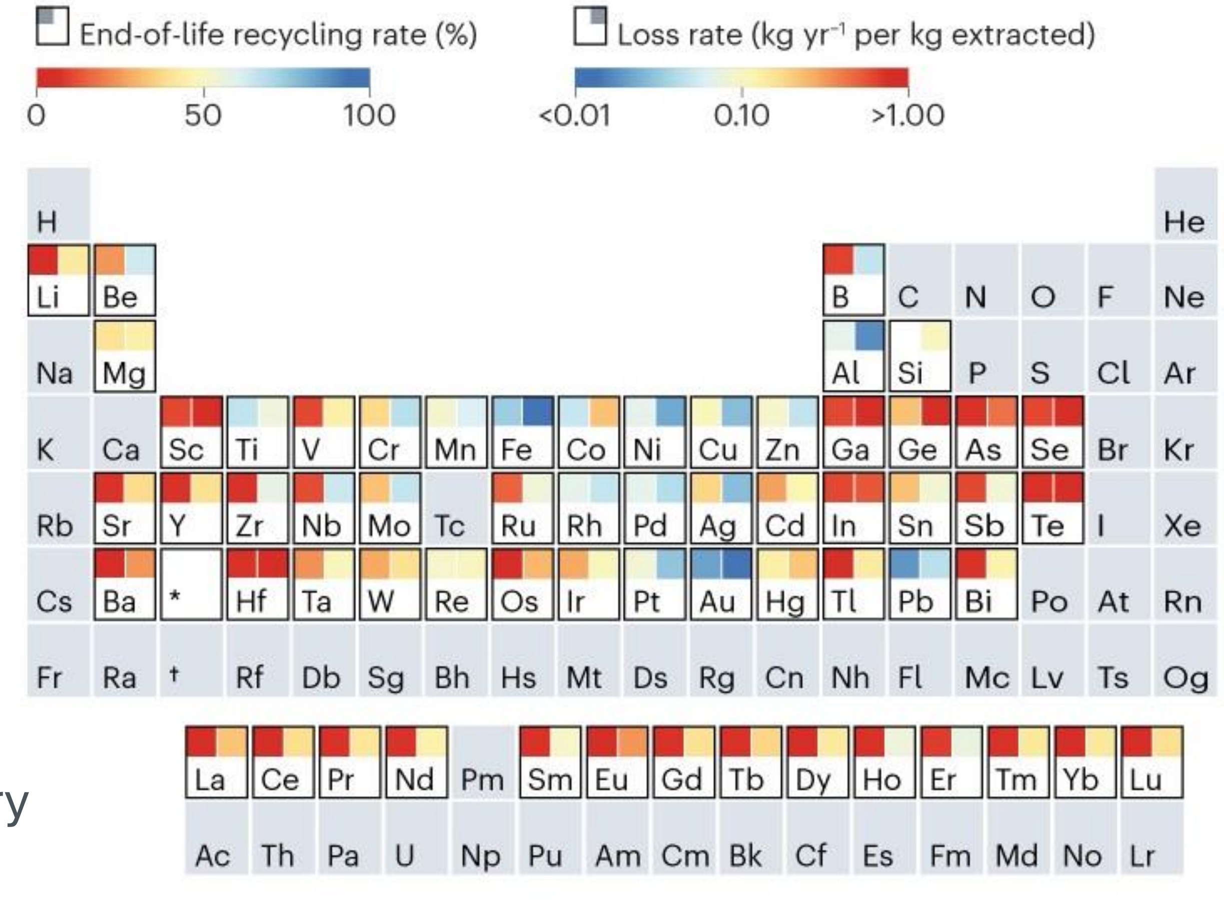
More intensive product and infrastructure utilization

Take-back mechanisms
Extended producer responsibility
Product-as-a-service (PaaS)

New hydrometallurgic process routes
Alternative routes (deep eutectic, direct recycling)

Summary

- Primary raw material demand is a major driver over environmental impacts and the triple planetary crisis.
- **Critical Raw Materials** are (ideally) materials with high **Supply Risks** and high **Vulnerability to Supply Reduction**.
- EU CRM list of 2023: **32 “true CRMs”**, plus **Ni** and **Cu**, which are strategic raw materials.
- Increasing recycled content is a core measure to decrease supply risks in the **Critical Raw Materials Act**.
- Circularity takes inter- and transdisciplinary efforts for material information, waste collection, and recycling technology.



*Lanthanide series; †Actinide series.