Material Feasibility of European Energy System Models

EnInnov2026 – 19. Symposium Energieinnovation

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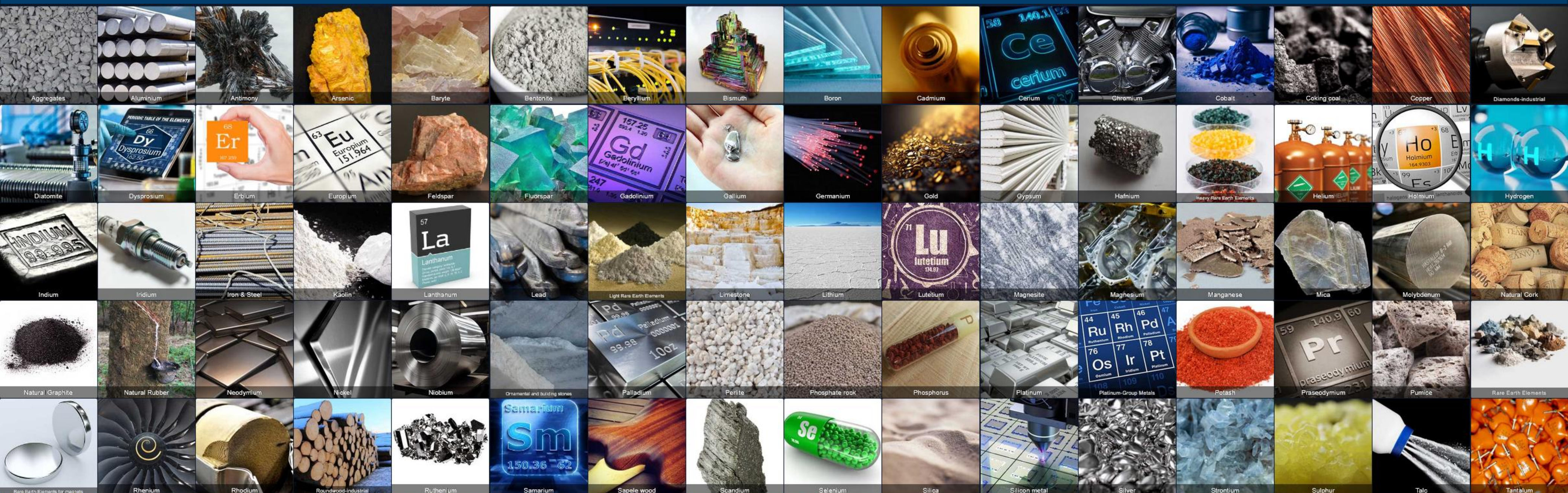

Jülich Systems Analysis

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Image: European Commission (JRC), RMIS – Raw Materials Profiles, cropped screenshot (16.01.26)

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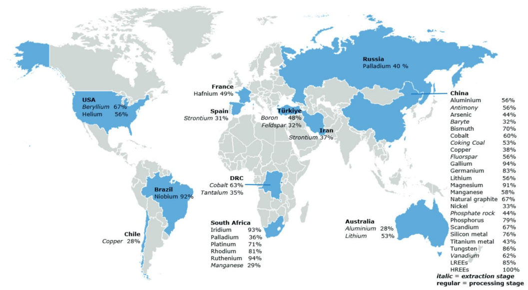
Why Materials are Critical to the Energy Transition

Economic Importance

Clean technologies induce a **growing demand** in **critical minerals**

Supply Risk

Geographically **concentrated resources** lead to **high dependencies**



Complex supply chains may **conceal supply risks** and disruptions

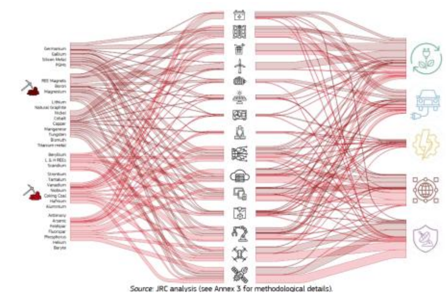


Image center: European Commission (2023): Study on the critical raw materials for the EU 2023 – Final report, Publications Office of the European Union (30.01.26)
Image left & right: Carrara, S. et al. (2023): Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study, Publications Office of the European Union, JRC132889. (30.01.26)

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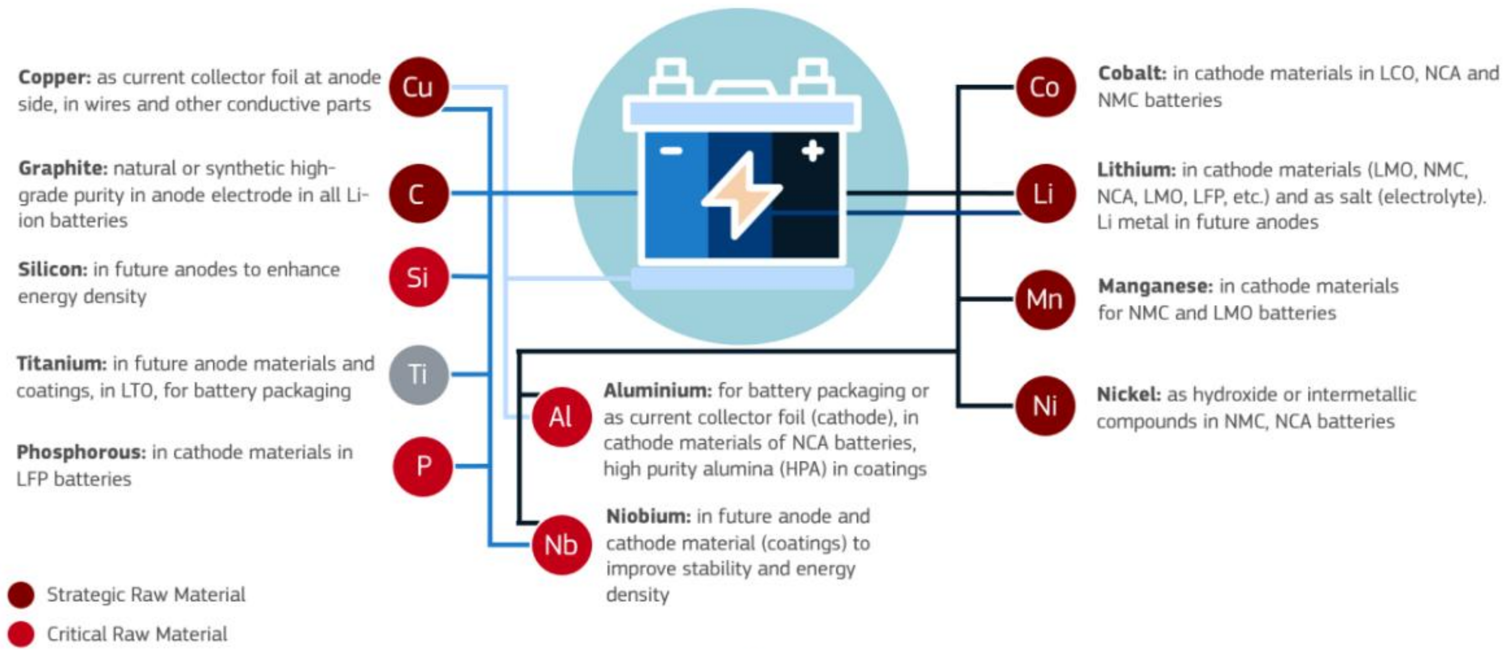

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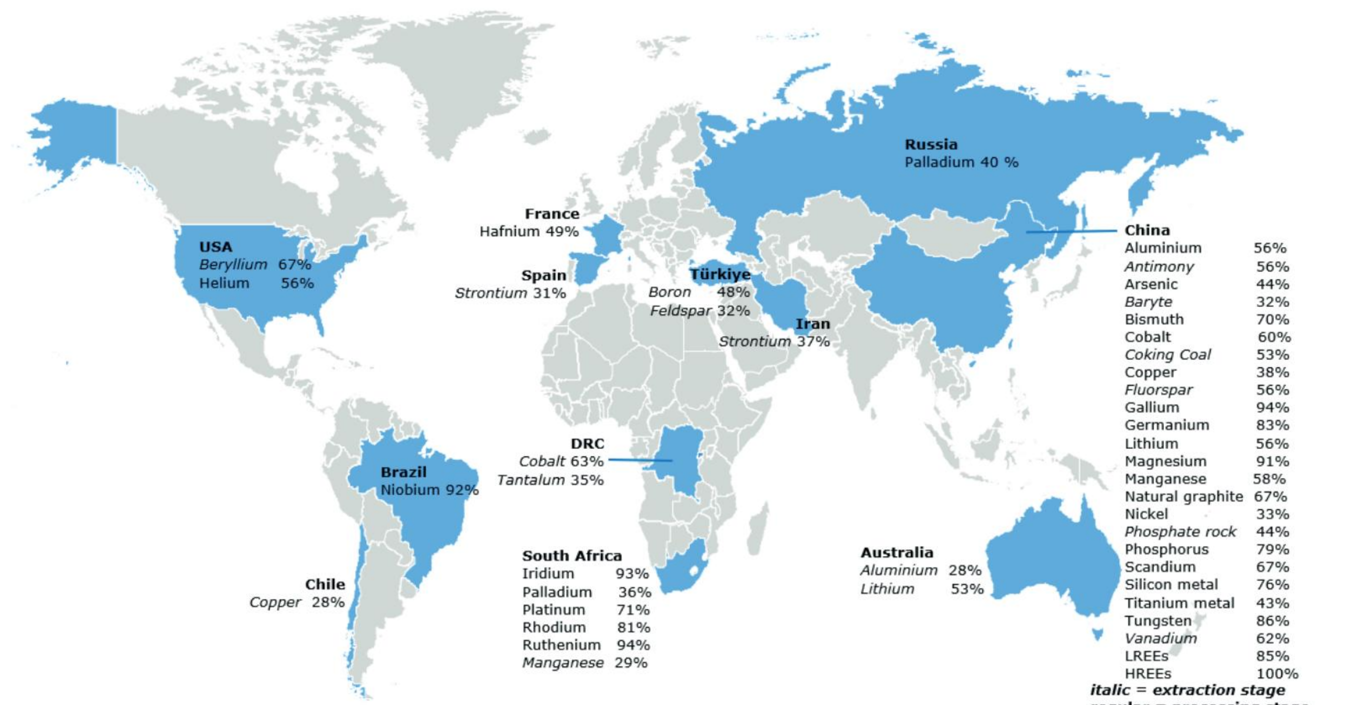

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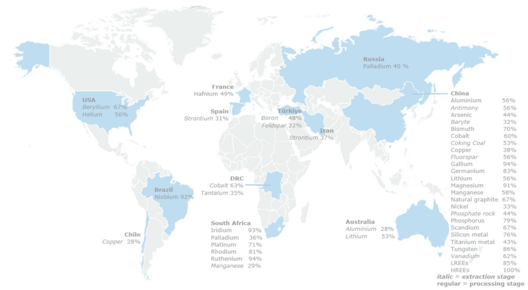

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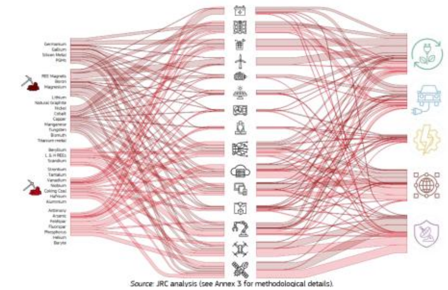

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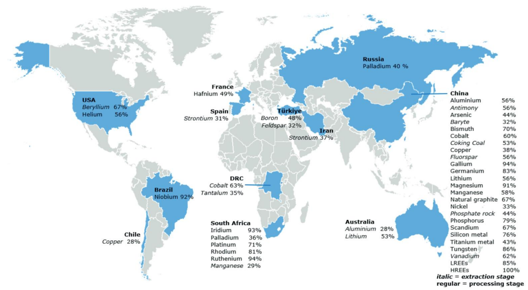

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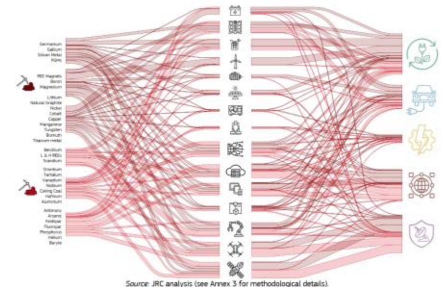
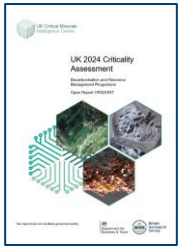
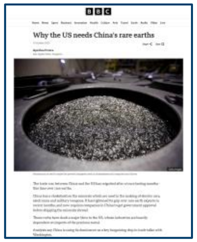


➔ **Policy response**





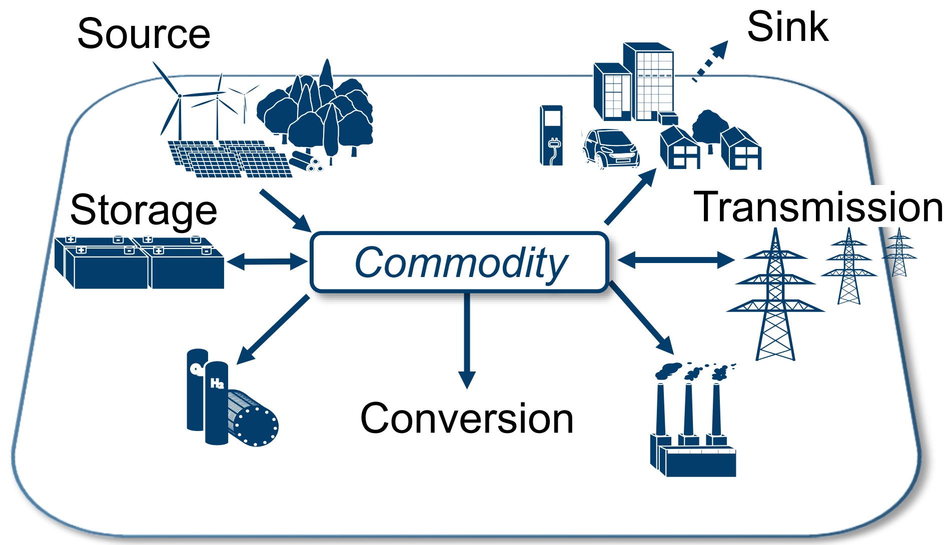
- ➔ **Economic importance** of **Critical Raw Materials (CRM)** is **rising** due to modern technology usage
- ➔ **Supply risk** and dependence on other country's is **rising**
- ➔ **Decision making** for **future energy systems** has to **consider CRM** and its **supply**

Research Question

State of the Art

- Energy System **Models** do **not consider material constraints** sufficiently
- A very **few** are **hard-linked** to **material constraints**[1]
- **Decision making** is **based** on potentially **infeasible models** results.

Energy System Models

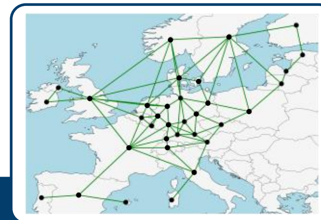


Are existing **European Energy Systems** proposed by Models **feasible** from a **material perspective**?

[1]Schulze, K. et. al. (2024): Overcoming the challenges of assessing the global raw material demand of future energy systems. Joule, Vol. 8, Iss. 7, 1936 – 1957.

Image right: Klütz et al. (2025). ETHOS.FINE: A Framework for Integrated Energy System Assessment. Journal of Open Source Software, 10(105), 6274.

Methodology – Ex Post Assessment



Calculate material Demand to Reserve Ratio (DRR):

$$\mathbf{DRR}_{\mathrm{mat}} = \frac{\mathbf{Demand}_{\mathrm{mat}}}{\mathbf{Reserve}_{\mathrm{mat,EU}}}$$ **> 100 % ➔ infeasible**

Calculate the **demand per material** over all considered technologies

$$\mathbf{Demand}_{\mathrm{mat}} = \mathbf{Capacity}_{\mathrm{subtech}} * \mathbf{Material\ Intensity}_{\mathrm{subtech}}$$

Allocate reserves to the EU using a **fair population key** or **GDP**

$$\mathbf{Reserve}_{\mathrm{EU}} = \mathbf{Reserve}_{\mathrm{global}} * \mathbf{Key}_{\mathrm{allocation}}$$

$$= \frac{\mathbf{Population}_{\mathrm{EU}}}{\mathbf{Population}_{\mathrm{global}}}$$

$$= \frac{\mathbf{GDP}_{\mathrm{EU}}}{\mathbf{GDP}_{\mathrm{global}}}$$

Extract capacity data from European System Models & apply **roadmaps** of future **sub technology market shares**

$$\mathbf{Capacity}_{\mathrm{subtech}} = \mathbf{Capacity}_{\mathrm{tech}} * \mathbf{Market\ Share}_{\mathrm{subtech}}$$

Extracted from **literature review**

DRR – Demand to Reserve Ratio
mat – material
tech – technology
subtech – subtechnology

Multiple material cases

Methodology – Multiple Material Cases

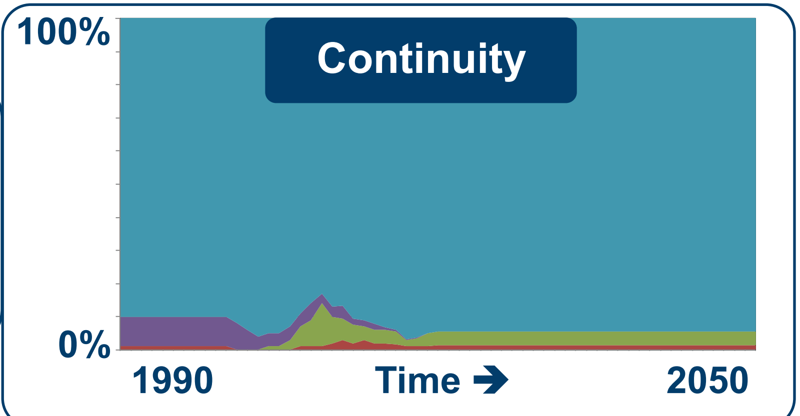
Material Intensity

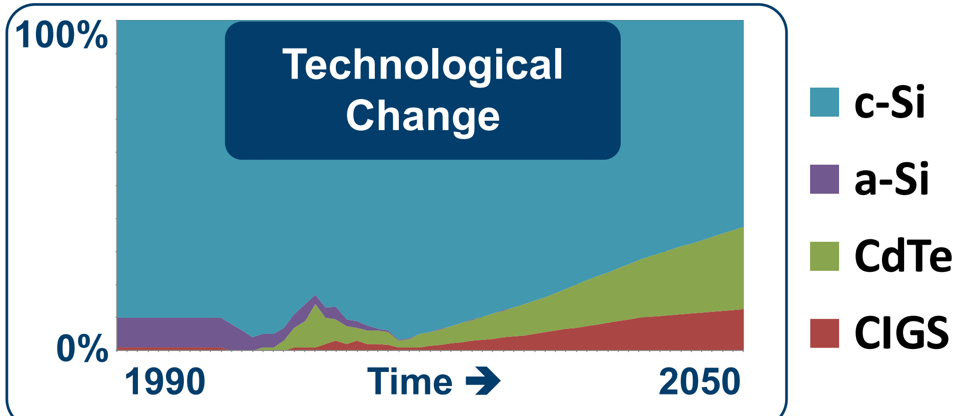
- **Material requirements** of technologies change due to **technological progress**[1]

Market Shares

- **Future market shares** of technologies are subject to uncertainties
- Apply a **conservative** (“*continuity*”) and one **progressive** (“*change*”) **roadmap**[2]

PV Subtech Market-share





Allocation Keys

- Fair **allocation** of **global reserves** according to the EU’s share global **population and economic share (GDP)**

[1] Carrara, S. et. al. (2020): Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system, Publications Office of the European Union. JRC119941. (30.01.26)
[2] Schlichenmaier et al. (2022): May material bottlenecks hamper the global energy transition towards the 1.5 °C target. Energy Reports. Vol. 8. 14875-14887.

Methodology – Multiple Material Cases

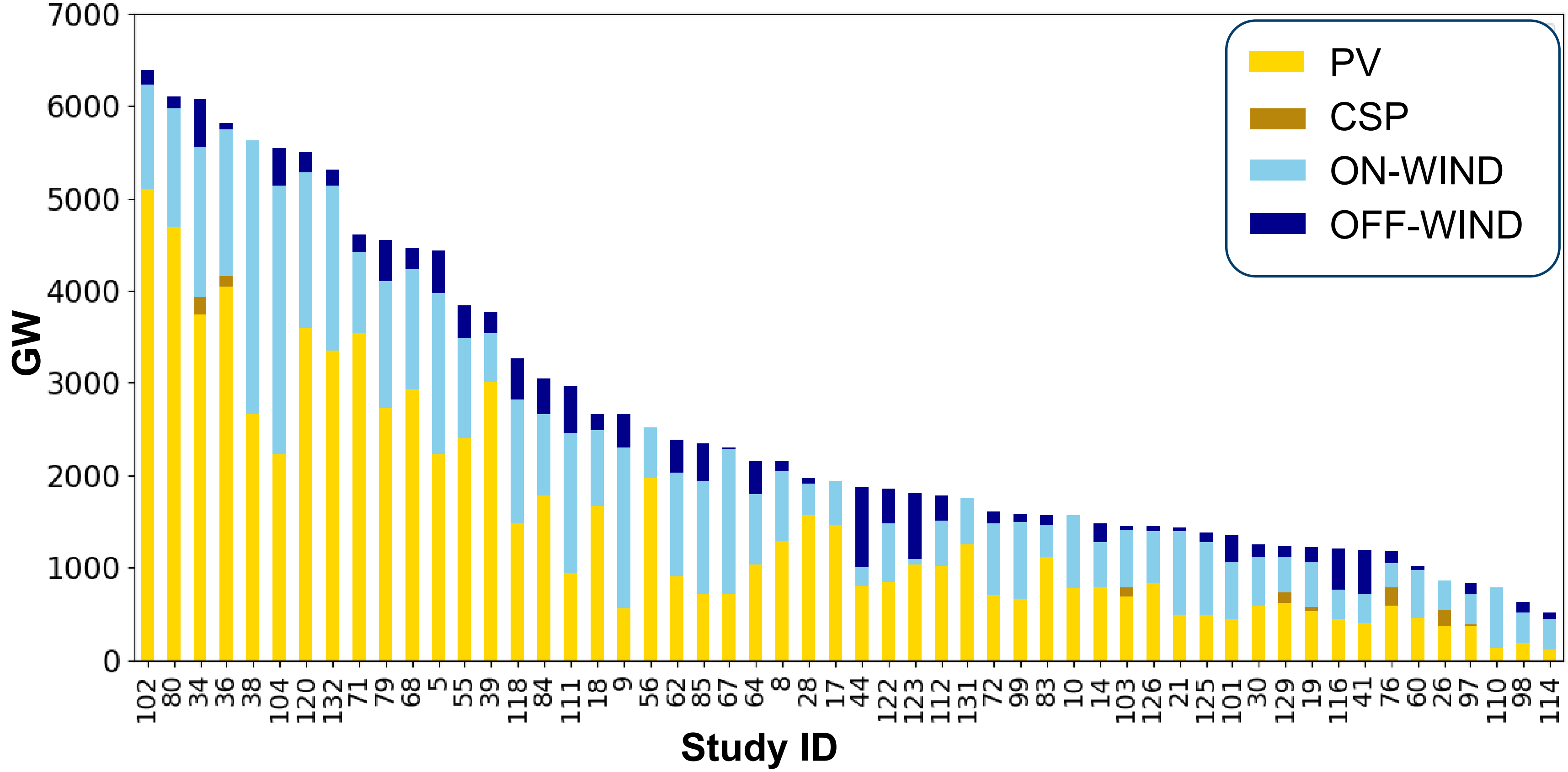
	Continuation	Change
Population	MI_{Low} MI_{Med} MI_{High}	MI_{Low} MI_{Med} MI_{High}
GDP	MI_{Low} MI_{Med} MI_{High}	MI_{Low} MI_{Med} MI_{High}

Set of **Pessimistic** assumptions

Set of **Optimistic** assumptions

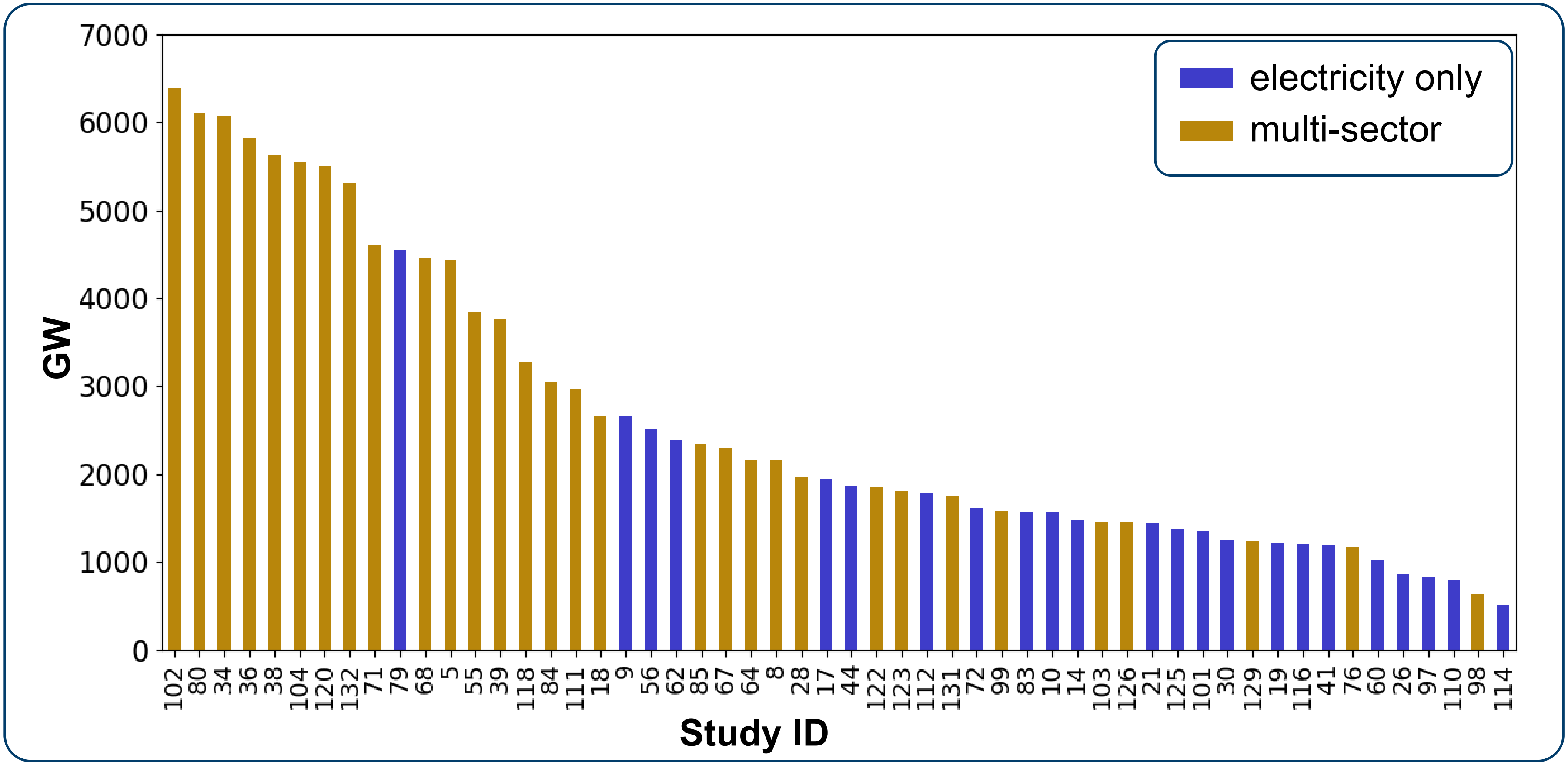
MI: Material Intensity

Results – Capacity Expansion



- ➔ Capacity expansion **data extractable** in **60/132 eligible studies**
- ➔ **Focus** on **main technologies** to check a **lower boundary** of **material feasibility**
- ➔ Even though the **geographic scope** is **similar** within the studies, the **capacity expansion differs**

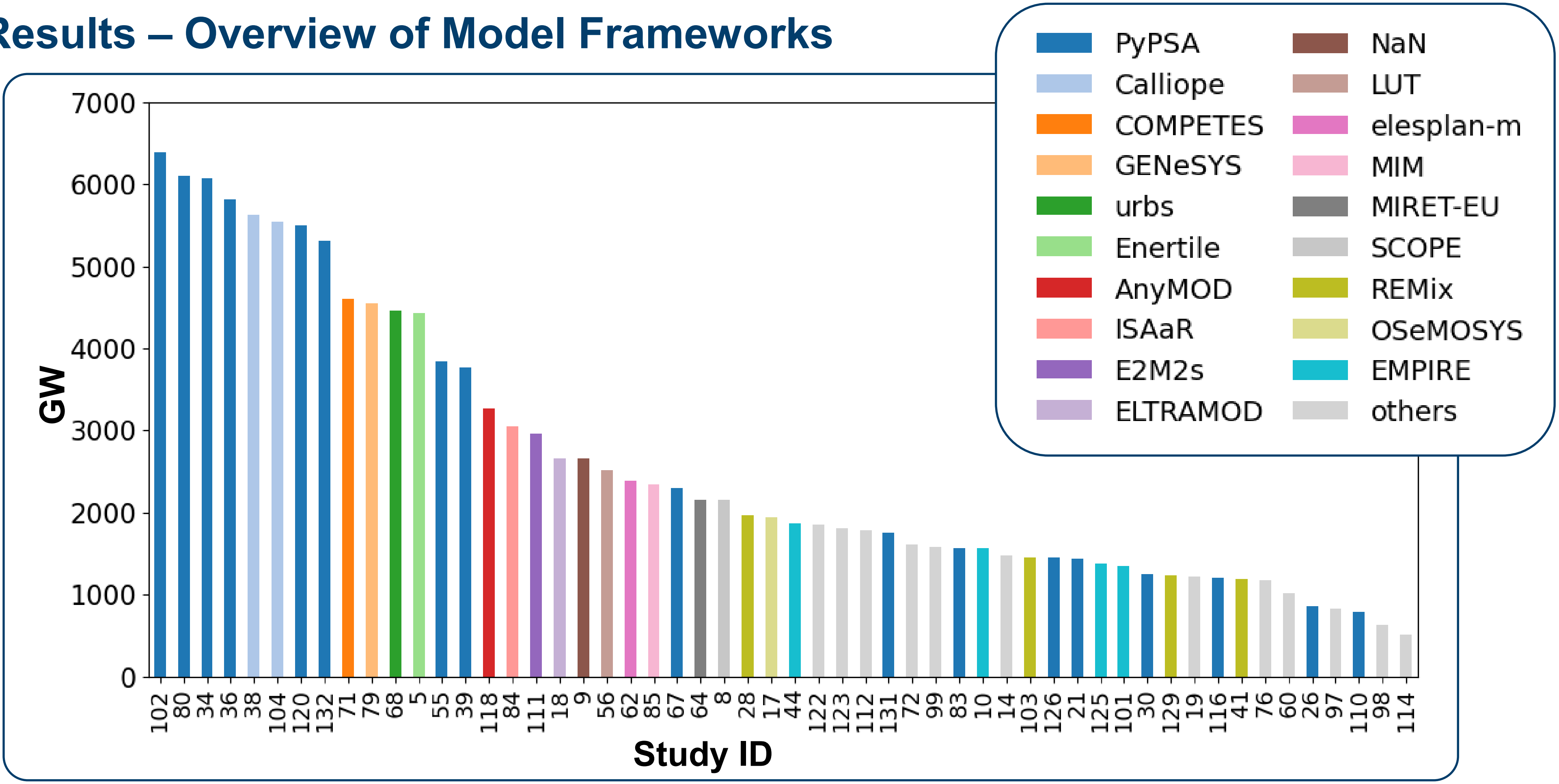
Results – Scope of studies



➔ **Studies differ** in their sectoral **scope** (and decarbonization level, techno-economic assumptions)

➔ Especially **different sector** scopes (additional demands) lead to **deviating capacities**

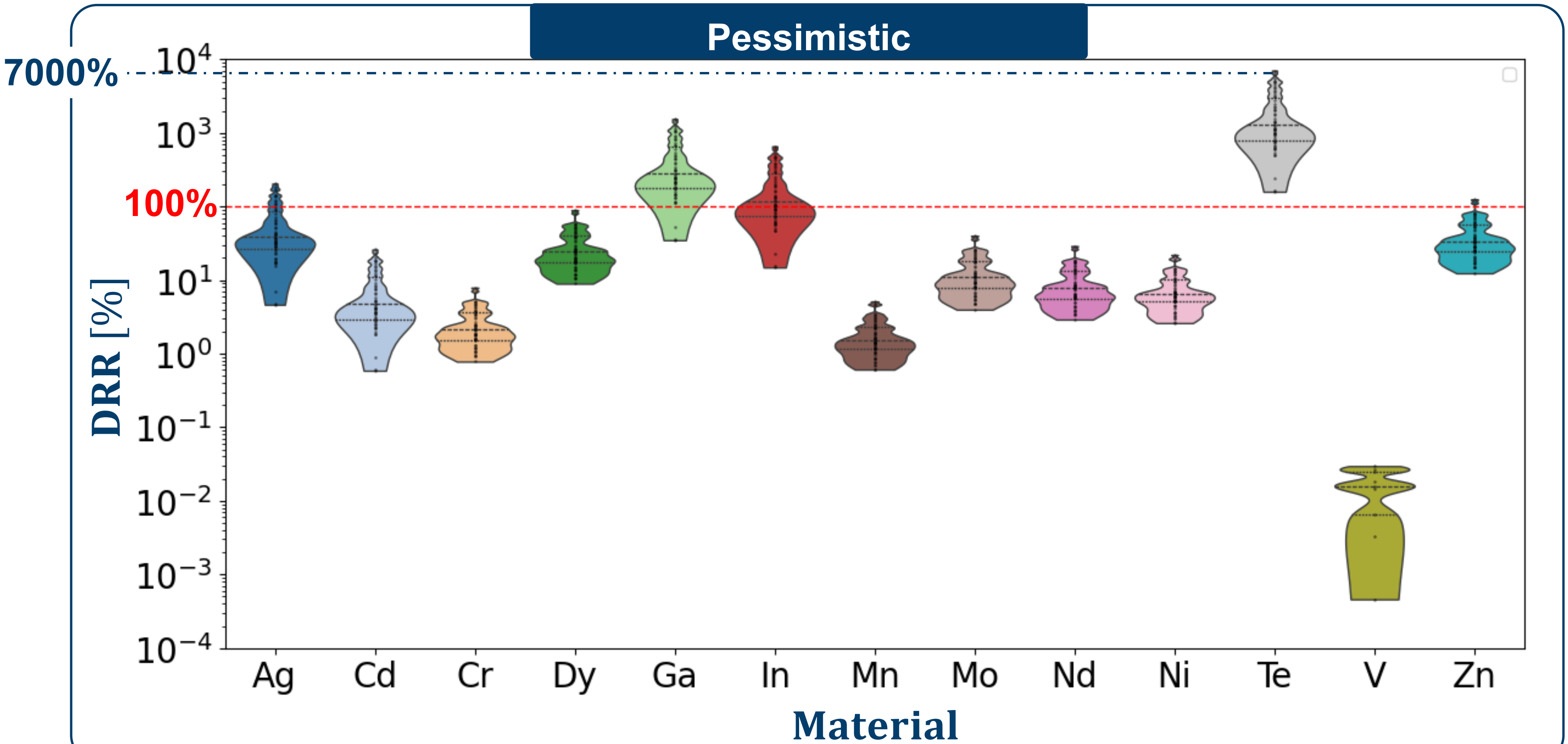
Results – Overview of Model Frameworks



➔ The studies we investigate include **almost 30 models**

➔ **PyPSA** takes the **Lion Part** in European Energy System Modelling studies

Results – Material shortages in future EU Systems for Solar and Wind



- **Shortages** in **Tellurium** (Cu byproduct), **Gallium** (Zn byproduct), **Indium** (Zn byproduct)
- Mainly **induced by usage** of **innovative PV technologies**
- **Not** any material **shortages** found for **Wind** deployment

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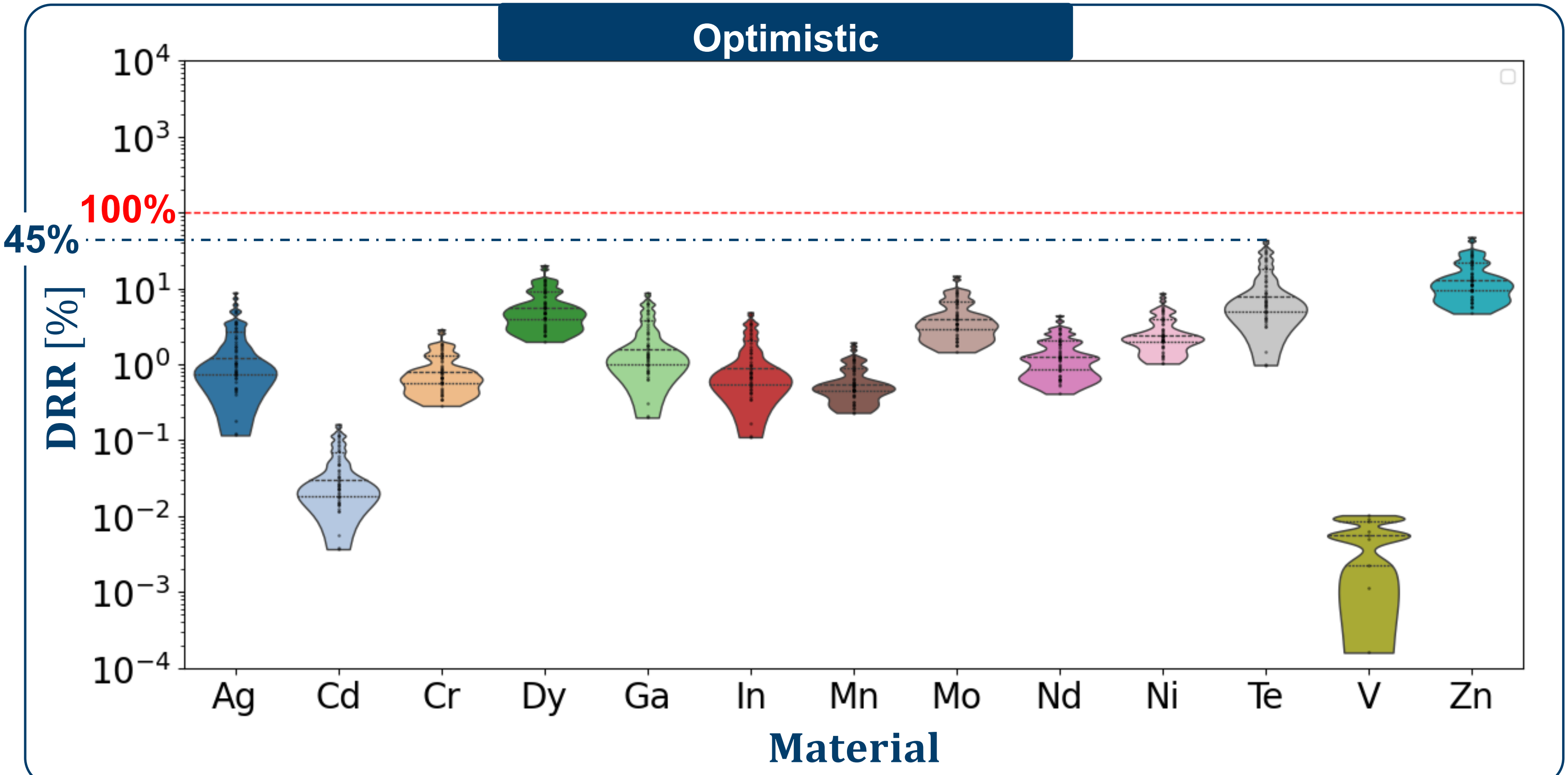

- ➢ **No material shortages**
- ➢ **GDP reserve allocation** leads to **less shortages**
- ➢ **Conservative PV** sub-technology **deployment eases** material **bottlenecks**

Discussion

- RE Capacities have to be built entirely new
- No recycling considered
- No competing demand considered
- Limited selection of technolgies

Key Take Aways

European energy systems proposed by Energy System **Models exceed** material **reserves** that may be available to the EU

Deployment of **innovative PV technologies (CdTe & CIGS cells)** may lead to **material shortages**

Energy System Models should consider material constraints to ensure (physically) feasible results

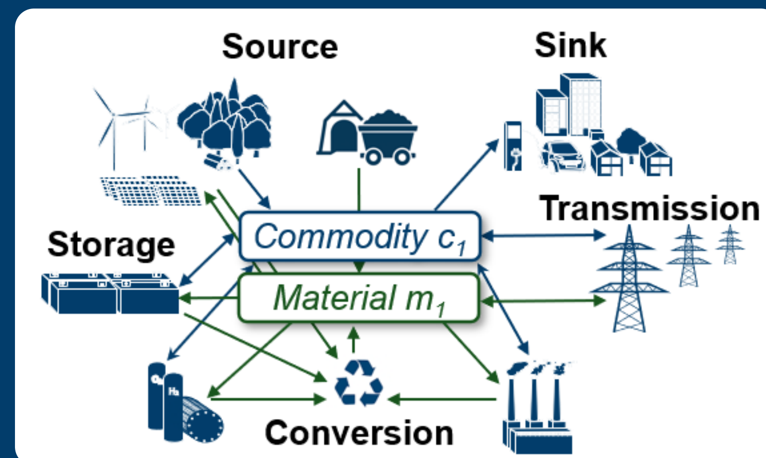

Image Top: Generated with ChatGPT.

Thank you for your attention!

For further questions, please contact:

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go.fzj.de/JuelichSystemsAnalysis

Publications
go.fzj.de/ice2_publications

GHG net zero scenario
go.fzj.de/ksg45

Project DacStorE
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H2 Atlas Africa
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