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ENV 501 / GR A3 30

# Material Flow Analysis and resource management


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**Fall 2024**

# Last session

- Approaches to solving MFA systems
- Sensitivity analysis
- Error propagation in MFA system models
- How to present results and uncertainty ranges

# Course outline

| Block | Week | 8:15 - 9:00 and 9:15 - 10:00 | | 13:15 - 14:00 | 14:15 - 15:00 |
|---|---|---|---|---|---|
| Block I: EW-MFA global / national | W1 - Sep 12 | Introduction to the course and general concepts | All | Exercise | Project |
| | W2 - Sep 19 | EW – MFA and EW – MFA in different countries | FMC | Exercise | Project |
| | W3 – Sep 26 | EW – MFA in the Swiss context, Urban Metabolism | External Guest – Florian Kohler | Exercise | Project |
| | W4 - Oct 03 | EW – MFA in the Swiss context: Cantons and Circular Economy | FMC | Exercise | Project |
| Block II: MFA regional / urban | W5 - Oct 10 | The Service-Stock-Flows Nexus | FMC | Exercise | Project |
| | W6 - Oct 17 | Dynamic MFA | External Guest – Stefan Pauliuk | Exercise | Project |
| | Oct 24 | Autumn break | | | |
| | W7 - Oct 31 | Spatial MFA | FMC | Exercise | Project |
| | W8 - Nov 07 | Input-Output Analysis and Material Flow Cost Accounting | External Guest – Vincent Moreau | Exercise | Project |
| | W9 - Nov 14 | MFA and Uncertainty | E[illegible]ernal guest – [illegible]an Pauliuk | Exercise | Project |
| | W10 - Nov 21 | Case studies: Waste management in Indonesia / Critical Raw Materials in the Swiss context | GF & FMC | Exercise | Project |
| Block III: Social sciences and public policy | W11 - Nov 28 | Social Metabolism | CRB | Exercise | Project |
| | W12 - Dec 05 | Agent-based model | CRB, FMC, MAH, SLC | Past exam | Project |
| | W13 - Dec 12 | Group Project Presentation | CRB, FMC, MAH | Project | Project |
| | W14 - Dec 19 | Group Project Presentation | CRB, FMC, MAH | Project | Project |

# Content of lecture

- Examples of MFA application in resource management and sustainability
- Methods for conducting MFA, with unique considerations based on specific issues
  - The energy transition in Switzerland
  - Waste management in Indonesia
- Insights gained from MFA methods that are replicable or provide inspiration for other case studies
- Insights for integrating MFA findings into policy and decision-making

Binder, Félix Martín del Campo, Hecher, Campfens

# MFA in practice – Applications (recap)



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***"You can't manage what you can't measure."***

- Urban planning
- Energy planning
- Economic and environmental performance
- Development of industrial symbiosis and eco-industrial parks
- Closing material loops and circular economy
- Pollution control
- Material and energy supply security

# MFA in practice – Applications (recap)



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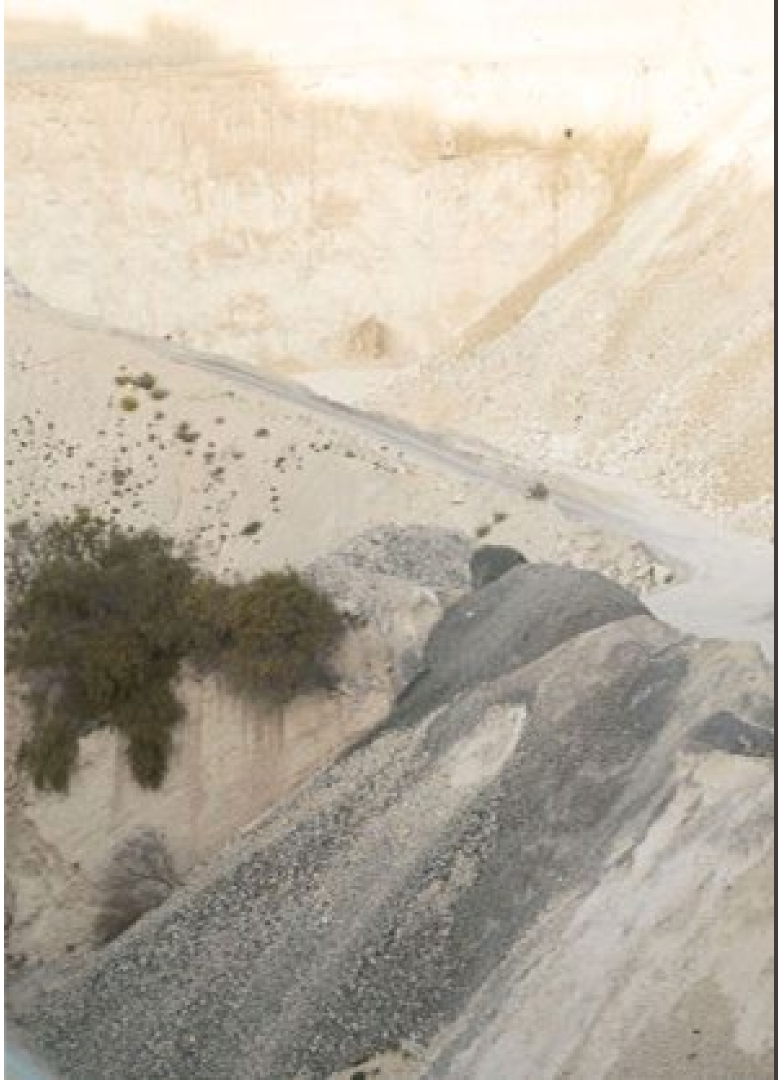
- **Early detection** of harmful/useful material accumulation or depletion in anthropogenic/natural subsystems.
- **Prediction of future** quantities in anthropogenic/natural subsystems.
- **Identification** of the need for action in the areas of environmental, resource, waste and policy management.
- **Evaluation** of the effectiveness of current/planned measures.
- **Design** of ecologically-optimized products, processes and systems (e.g. green design, eco-design, circularity).



# Case study: The energy transition in the Swiss context

Laboratory on Human-Environment Relations in Urban Systems

# The issue at hand: The Swiss Energy Strategy





*« The science is clear: to ensure sufficiently high probability of global warming remaining below 1.5°, global $CO_2$ emissions must be reduced to* ***net zero by the middle of this century*** *at the latest »*

***- Federal Council***

- Increase **energy efficiency** (buildings, mobility, industry, etc.)
- Develop **renewable energies** (promotion, ease the legal framework, etc.)
- Phase out **nuclear energy** (no more construction of nuclear power plants, security concerns, etc.)



Source: Swiss Federal Office of Energy (2018)

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# Current Swiss Energy Landscape



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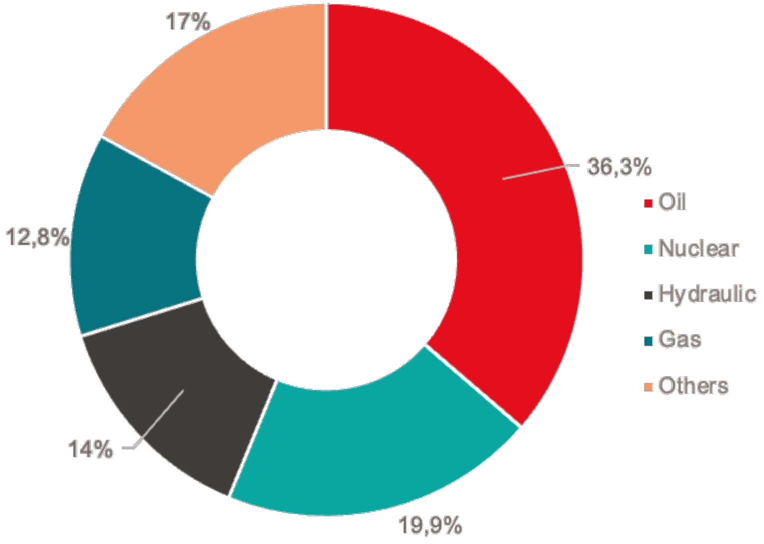
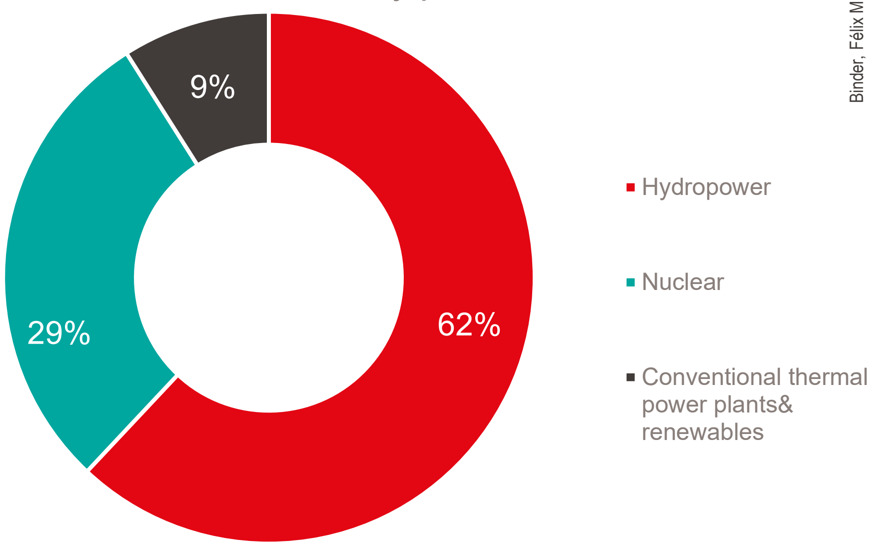
National energy consumption




National electricity production




**Energy supply:** 70% imported

Source: Swiss Federal Office of Energy (2021)

# Observations

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- **Long-term goal:** Net-zero GHG by 2050
- **Intermediate goal:** 50% reduction by 2030 based on 1990 levels

- To achieve the Swiss energy strategy goals:
  - Need to replace 70% of current energy consumption by renewables
  - Increase national production (also to reduce foreing dependency)

- Reduction in GHG emissions ➔ increase in renewable energies
- Increase in renewable energies ➔ increase in materials required to manufacture renewable energy technologies (including critical raw materials)



Source: Swiss Federal Office of Energy (2018)

# Observations

- **Long-term goal:** Net-zero GHG by 2050
- **Intermediate goal:** 50% reduction by 2030 based on 1990 levels

- However, no mention of:
  - Material requirements
  - Material depletion
  - Material impacts
  - Supply chain

- Focus is on GHG emissions and how to reduce them

**How could MFA help in this situation? What would be your approach?**

Source: Swiss Federal Office of Energy (2018)

Binder, Félix Martín del Campo, Hecher, Campfens

# The Swiss Energy Transition

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Master's Degree in Environmental Sciences and Engineering

Master Thesis

Critical Raw Materials (CRMs) in the Context of the Energy Transition and Beyond

(Considering Time, Space, and Geopolitics)

EPFL

**Supervisor:**
Prof. Claudia Binder

**Cosupervisors:**
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**Candidate:**
Matilde Spinello

Spring Semester 2024

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SIE individual project

**Circular economy strategies for the renewable energy transition in Switzerland**

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**Supervisors**
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Prof. Claudia R. Binder

05.02.2024

HERUS - Human-Environment Relations in Urban Systems

- Studies focused on renewable energy technologies:
  - Solar panels
  - Wind turbines
  - Electric vehicles (EV)

- Steps:
  - Determine the type/amount of materials needed to manufacture each technology
  - Assess the total number of solar panels, wind turbines and EV's necessary for the energy transition
  - Estimate total quantity of materials

Source: HERUS Laboratory, 2024

# Critical raw materials (CRMs)



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- Definition of the European Commission: “*Those raw materials that are most important economically and have a high supply risk are called critical raw materials. Critical raw materials are essential to the functioning and integrity of a wide range of industrial ecosystems*”

| 2020 Critical Raw Materials (new as compared to 2017 in bold) | | |
|---|---|---|
| Antimony | Hafnium | Phosphorus |
| Baryte | Heavy Rare Earth Elements | Scandium |
| Beryllium | Light Rare Earth Elements | Silicon metal |
| Bismuth | Indium | Tantalum |
| Borate | Magnesium | Tungsten |
| Cobalt | Natural Graphite | Vanadium |
| Coking Coal | Natural Rubber | **Bauxite** |
| Fluorspar | Niobium | **Lithium** |
| Gallium | Platinum Group Metals | **Titanium** |
| Germanium | Phosphate rock | **Strontium** |

Source: European Commission (2020)

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# Renewable energy technologies - Solar

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**SOLAR PANELS**

c-Si

Si, Ag

Concrete, Steel, Plastic, Glass, Al, Cu

Thin Film

CdTe

Cd, Te

CIGS

In, Ga, Se

a-Si

Si, Ge

Concrete, steel, plastic, glass, Si, Ag, Al, Cu, Cd, Te, In, Ga, Se, Ge...

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Source: European Commission (2020)

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# Renewable energy technologies - Wind

**WIND TURBINE**

Direct Drive

- Electrically Excited Synchronous Generator (DD-EESG)
- Permanent Magnet Synchronous Generator (DD-PMSG)

Gearbox

- Permanent Magnet Synchronous Generator (GB-PMSG)
- Doubled-Fed Induction Denerator (GB-DFIG)

Steel, Plastic, Glass, Al, B, Cr, Dy, Fe, Mn, Mo, Nd, Ni, Pr, Tb, Zn...

Source: European Commission (2020)

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# Renewable energy technologies – E-mobility

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**ELECTRIC VEHICLES**

| Batteries | Fuel cells | Traction motors |
|---|---|---|
| Co, Li, Ni, Mn, C | Pt | Al, B, O, Cu, Dy, Nd, Pr, Si, Fe |

Co, Li, Ni, Mn, C, Pt, Al, B, O, Cu, Dy, Nd, Pr, Si, Fe...



Source: European Commission (2020)

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# Renewable energy technologies



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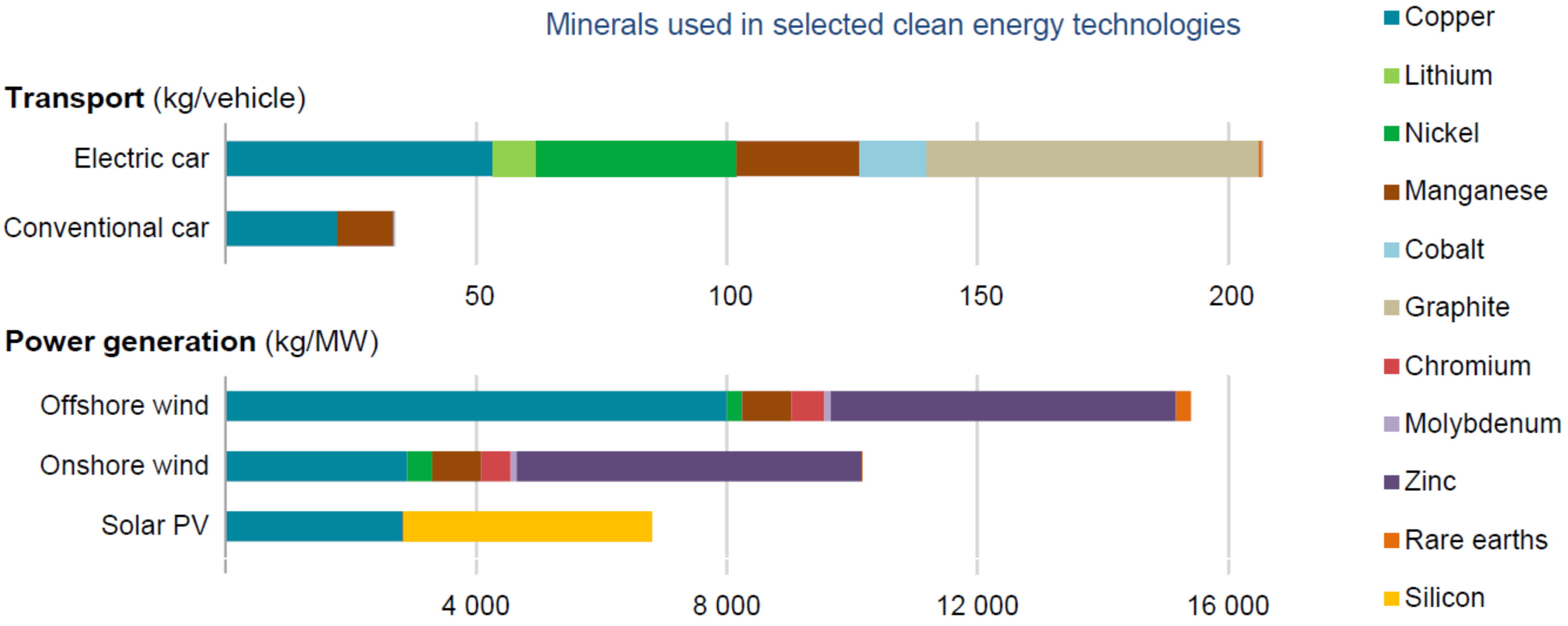


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Source: IEA 2021 - The Role of Critical Minerals in Clean Energy Transitions

# The Swiss Energy Transition



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| Scenario | Description | Switzerland in 2050 |
|---|---|---|
| CLI | Full implementation of the energy agreements | - Environmental policies and practices put in place.<br>- Energy demand reduced in end-hand sectors.<br>- European level $CO_2$ grids. |
| ANTI | Low international cooperation in mitigating climate change | -Limited technological progress leads to high capital costs for low carbon solutions.<br>- 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.<br>- Domestic renewable energies exploited at their maximum potential.<br>- Annual net energy imports as close to 0 as possible. |
| MARKETS | High global cooperation | -Increased availability of imported resources leads to more affordable energy<br>-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



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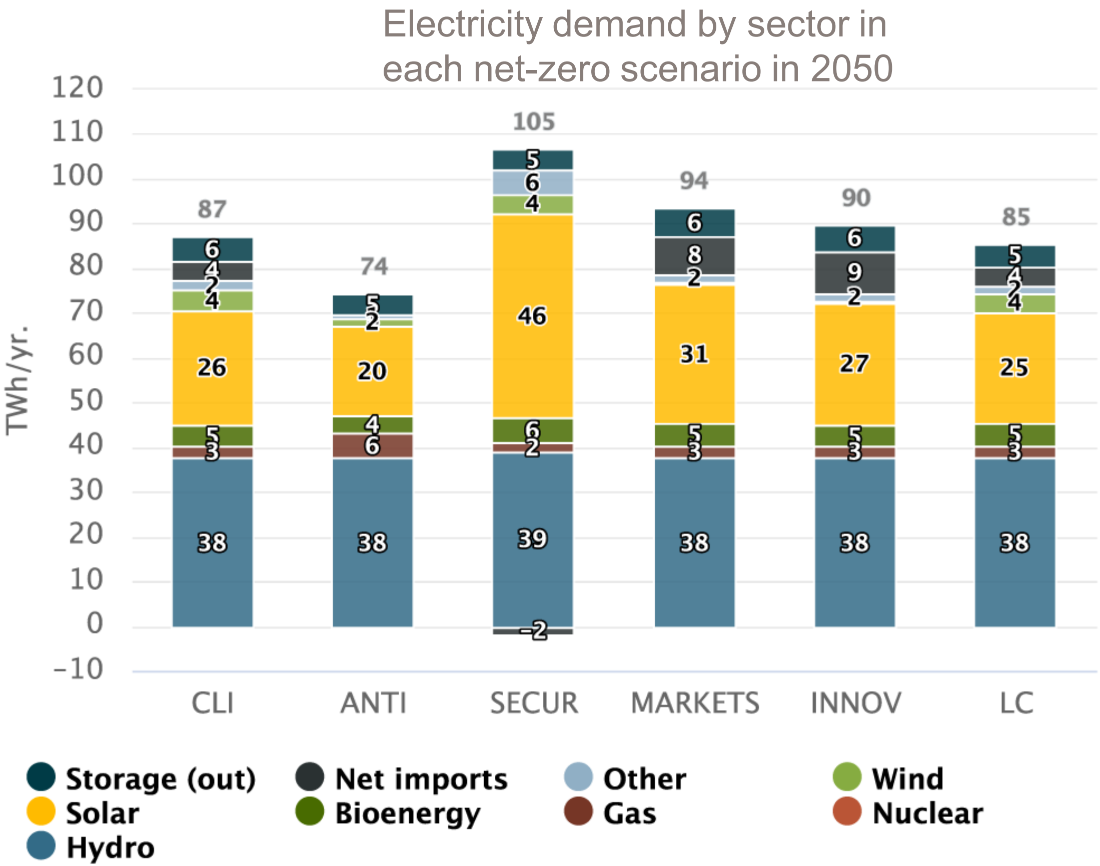


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Source: Panos et al, 2023

# The Swiss Energy Transition



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Forecasted installed capacities to 2050

| | CLI | ANTI | SECUR | MARKETS | INNOV | LC | TARGET* |
|---|---|---|---|---|---|---|---|
| Solar panels (GW) | 26.8 | 20.8 | 47.4 | 32.4 | 28.2 | 28.2 | 37.5 |
| Wind turbines (GW) | 2.6 | 1.0 | 2.6 | 0.1 | 0.1 | 0.1 | 2.2 |
| EV (millions of vehicles) | 4.8 | 4.6 | 3.5 | 4.9 | 5.3 | 5.3 | N.A. |



Source: Panos et al, 2023; Swiss Federal Office of Energy, 2022

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# The Swiss Energy Transition

| Photovoltaic solar panels | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | All technologies | | | | | | c-Si | | CdTe | | CIGS | | | | a-Si | |
| | Concrete (t/MW) | Steel (t/MW) | Plastic (t/MW) | Glass (t/MW) | Al (t/MW) | Cu (t/MW) | Si (t/MW) | Ag (t/GW) | Cd (t/GW) | Te (t/GW) | Cu (t/GW) | In (t/GW) | Ga (t/GW) | Se (t/GW) | Si (t/GW) | Ge (t/GW) |
| 2010 | 60.7 | 67.9 | 8.6 | 46.4 | 7.5 | 4.6 | 7.0 | 84.0 | 116.0 | 132.0 | 25.3 | 43.0 | 11.0 | 107.0 | 163.0 | 73.0 |
| 2018 | | | | | | | 4.0 | 20.0 | 85.0 | 95.0 | 24.0 | 27.0 | 7.0 | 60.0 | 150.0 | 48.0 |
| 2020 | | | | | | | 3.9 | 18.0 | 77.0 | 87.0 | 23.0 | 22.0 | 6.0 | 51.0 | 145.0 | 48.0 |
| 2030 | | | | | | | 3.5 | 11.0 | 60.0 | 70.0 | 17.5 | 17.0 | 4.5 | 40.0 | 130.0 | 32.0 |
| 2040 | | | | | | | 3.5 | 6.0 | 44.0 | 50.0 | 16.2 | 12.0 | 3.0 | 25.0 | 120.0 | 24.0 |
| 2050 | | | | | | | 3.0 | 5.0 | 35.0 | 40.0 | 15 | 10.0 | 2.5 | 20.0 | 110.0 | 20.0 |

| Wind turbines | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Concrete (t/GW) | Steel (t/GW) | Polymers (t/GW) | Glass (t/GW) | Al (t/GW) | B (t/GW) | Cr (t/GW) | Cu (t/GW) | Dy (t/GW) | Fe (t/GW) | Mn (t/GW) | Mo (t/GW) | Nd (t/GW) | Ni (t/GW) | Pr (t/GW) | Tb (t/GW) | Zn (t/GW) |
| DD-EESG | 369000 | 132000 | 4600 | 8100 | 700 | 0 | 525 | 5000 | 6 | 20100 | 790 | 109 | 28 | 340 | 9 | 1 | 5500 |
| DD-PMSG | 243000 | 119500 | 4600 | 8100 | 500 | 6 | 525 | 3000 | 17 | 20100 | 790 | 109 | 180 | 240 | 35 | 7 | 5500 |
| GB-PMSG | 413000 | 107000 | 4600 | 8400 | 1600 | 1 | 580 | 950 | 6 | 10800 | 800 | 119 | 51 | 440 | 4 | 1 | 5500 |
| GB-DFIG | 355000 | 113000 | 4600 | 7700 | 1400 | 0 | 470 | 1400 | 2 | 18000 | 780 | 99 | 12 | 430 | 0 | 0 | 5500 |

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Source: HERUS Laboratory, 2024

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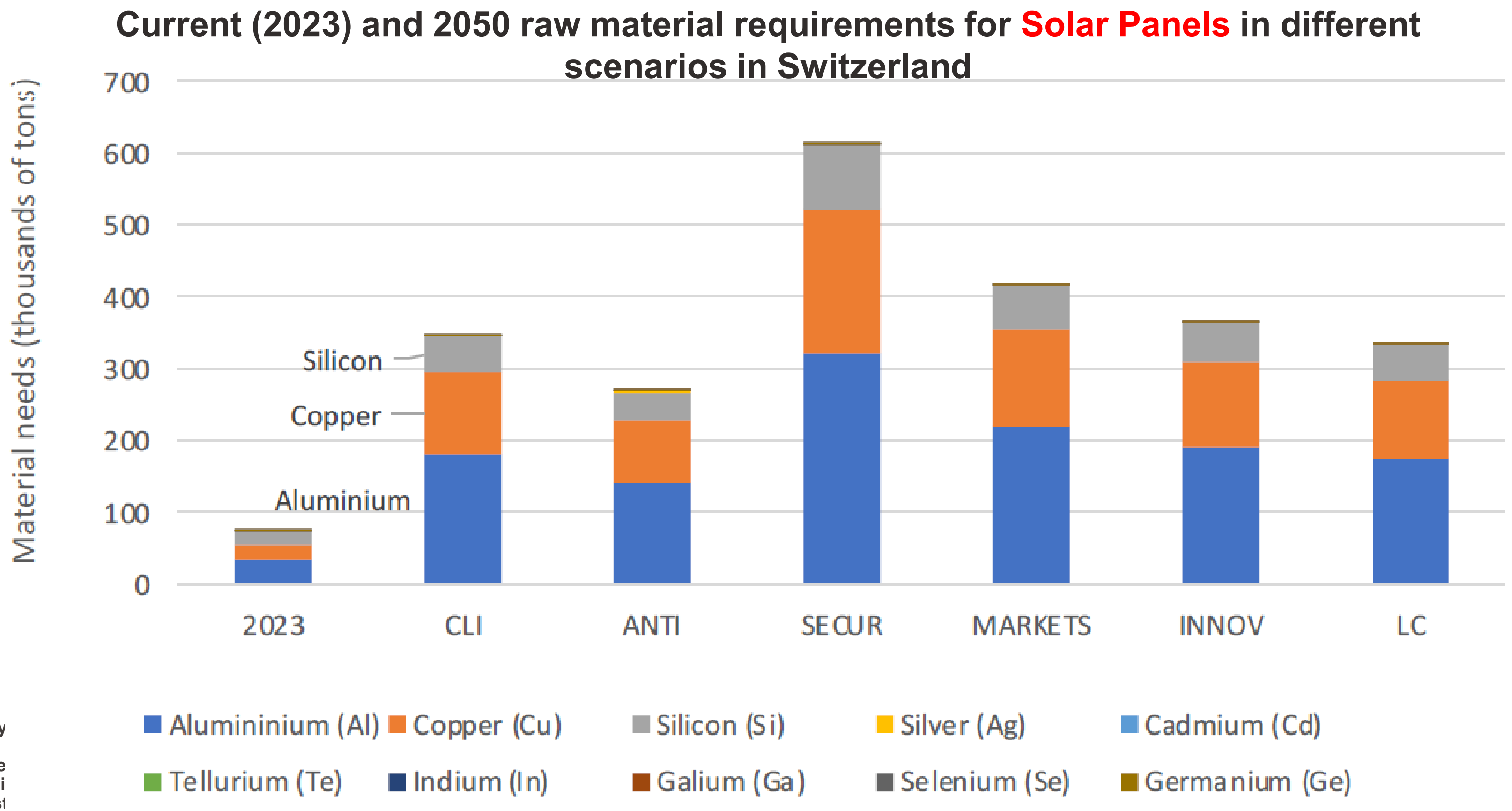
# Technology: Solar

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Source: HERUS Laboratory, 2024

# Technology: Solar



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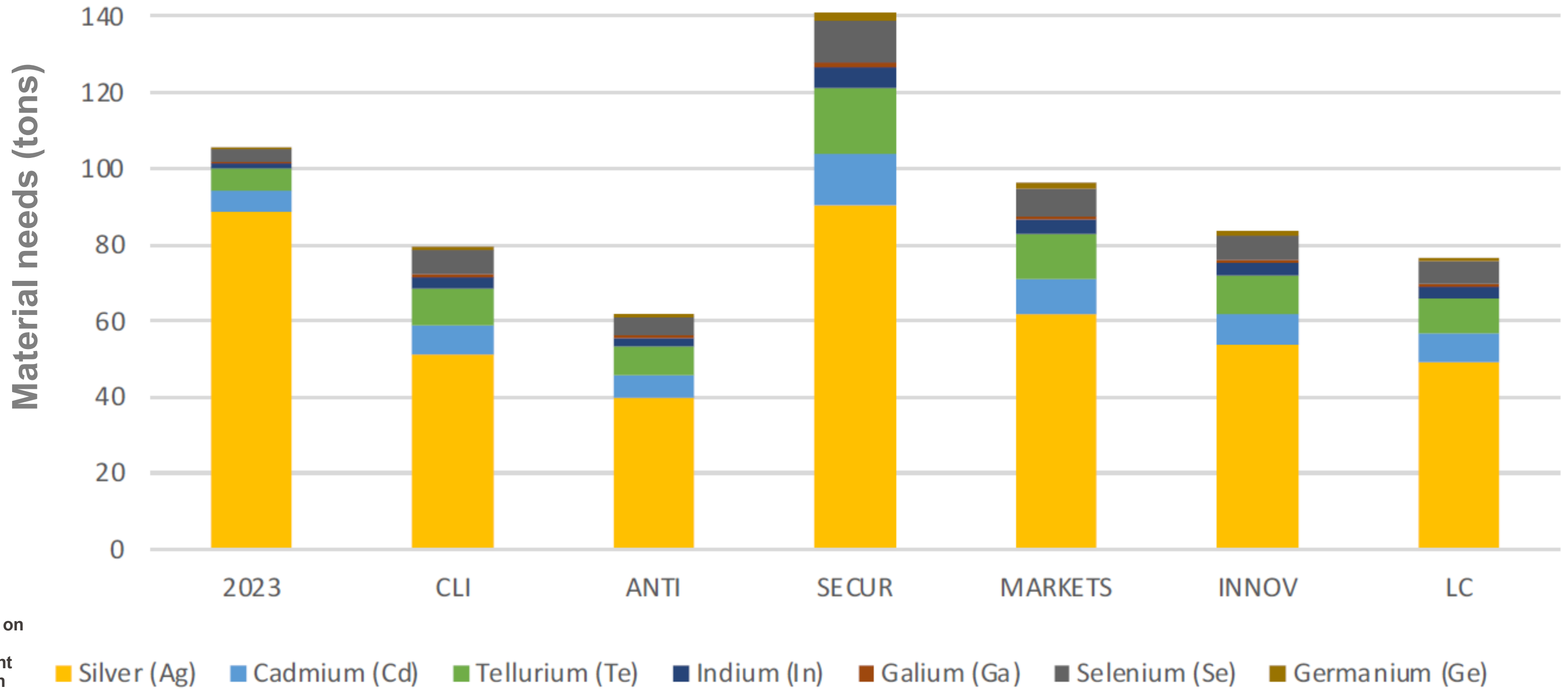
Current (2023) and 2050 raw material requirements for Solar Panels in different scenarios in Switzerland

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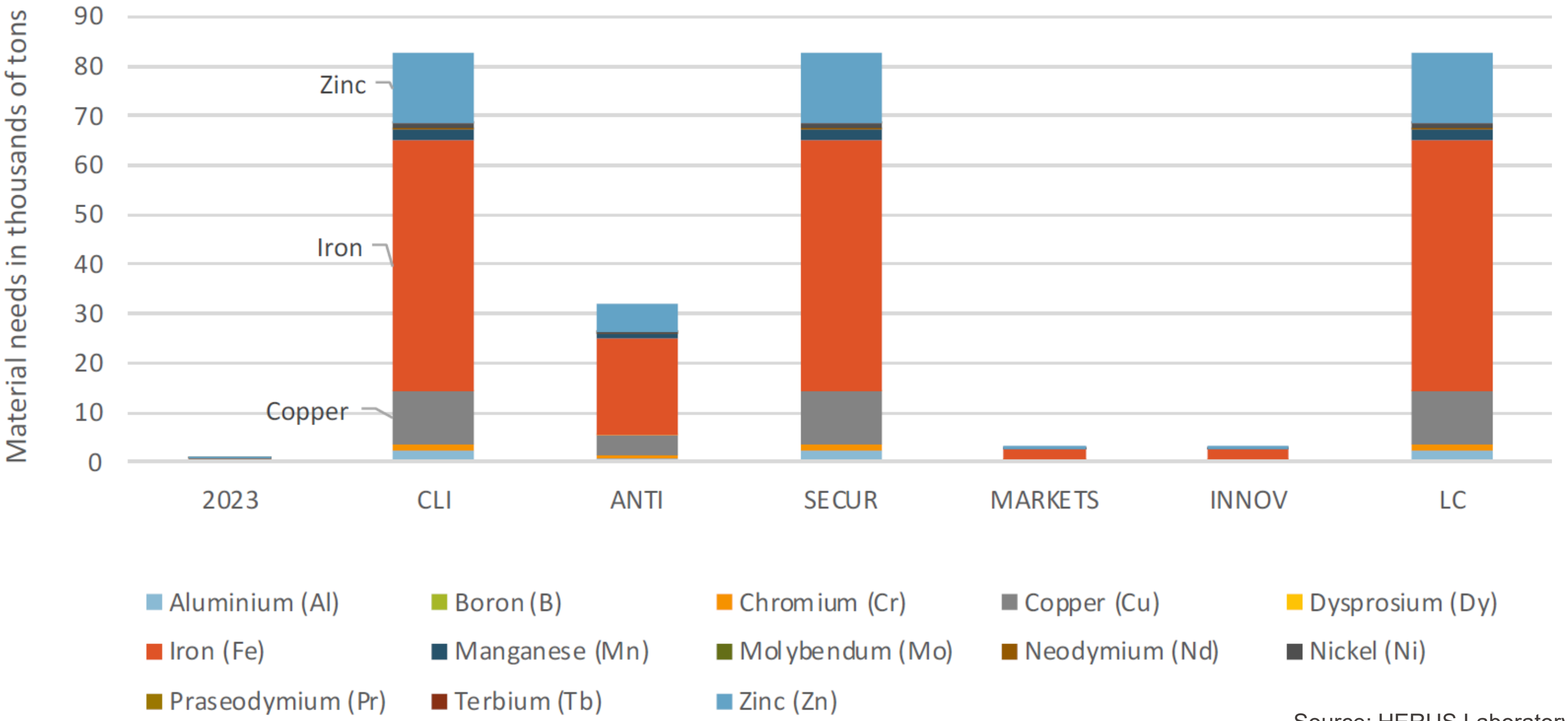
Source: HERUS Laboratory, 2024

# Technology: Wind

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




Source: HERUS Laboratory, 2024

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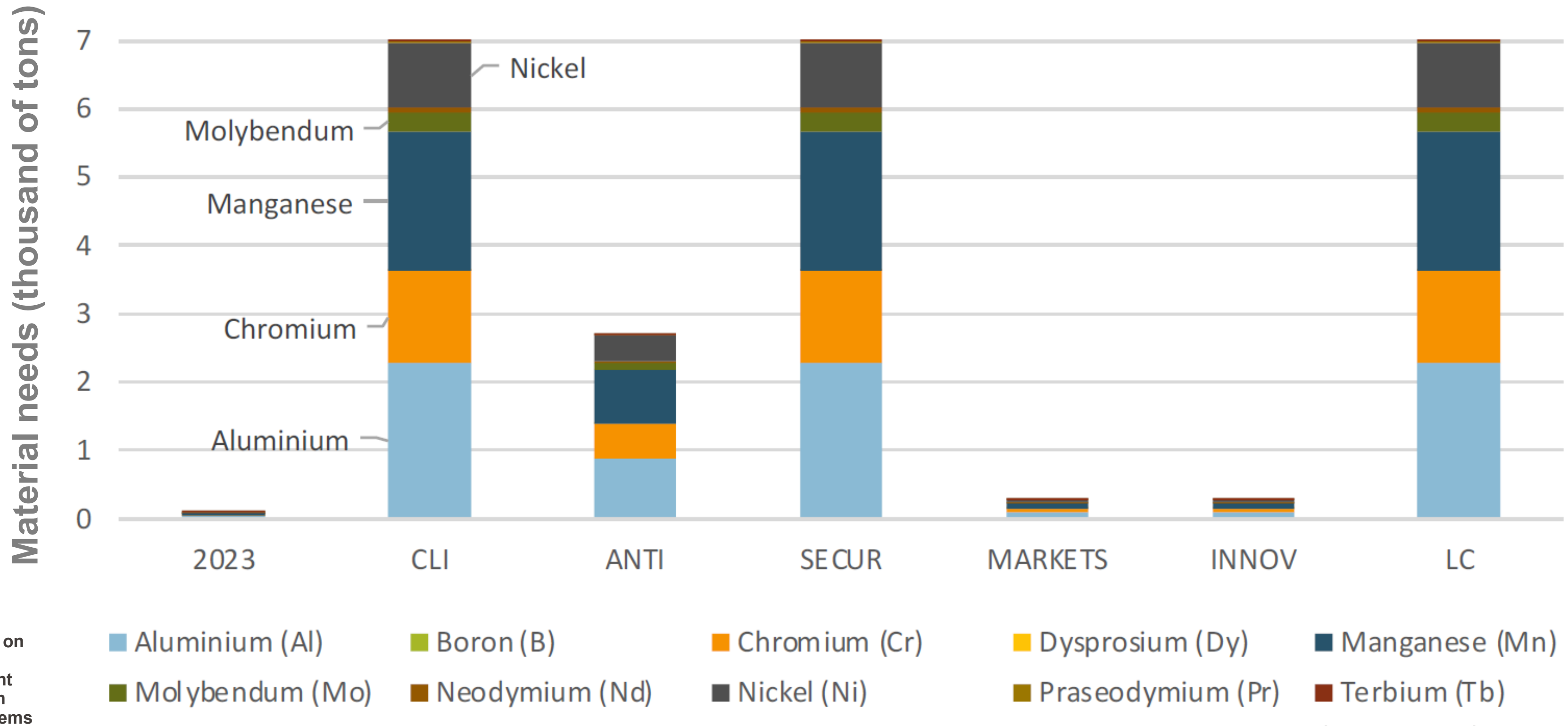
# Technology: Wind

Binder, Félix Martín del Campo, Hecher, Campfens

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

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Source: HERUS Laboratory, 2024

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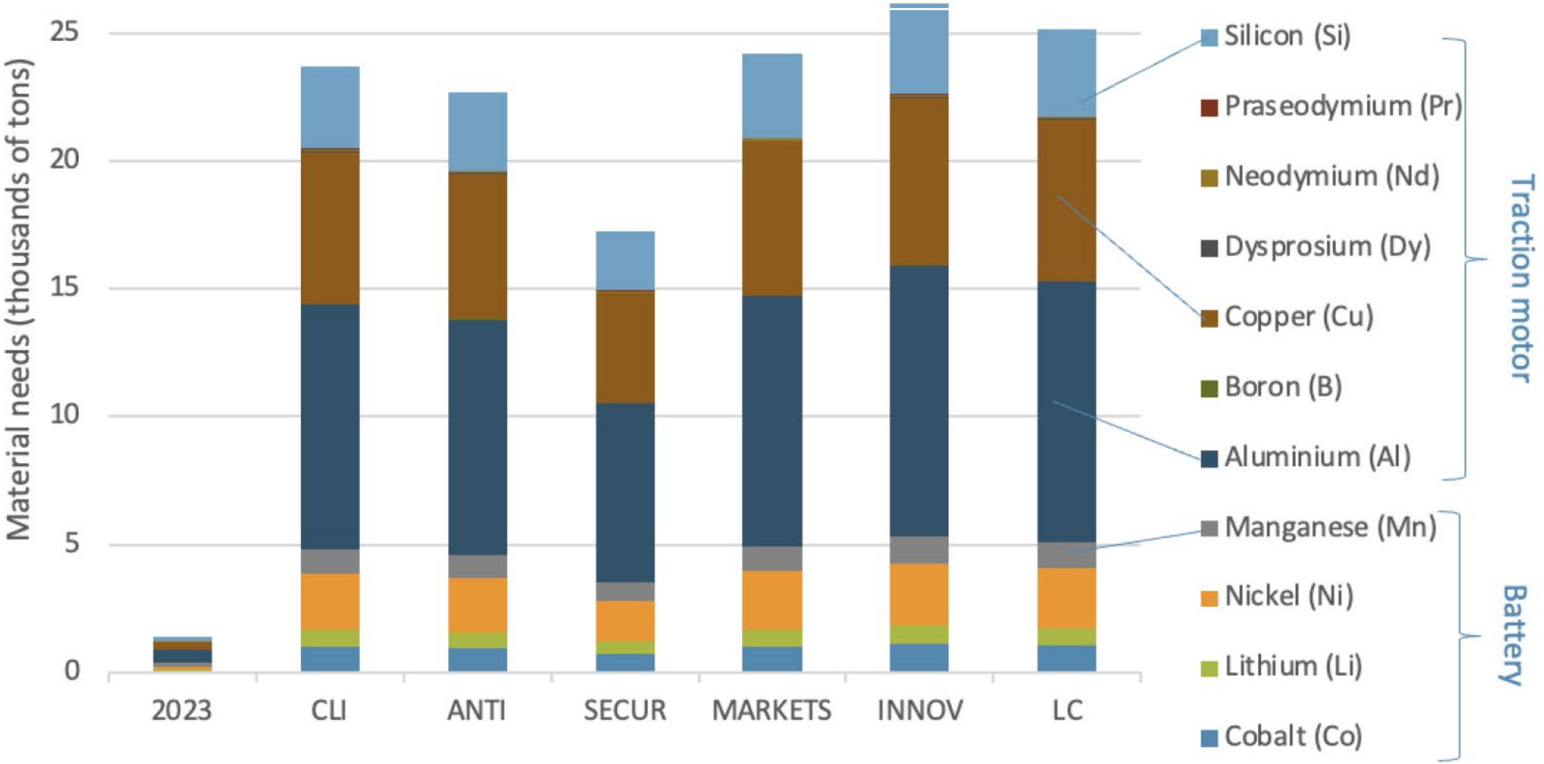
# Technology: E-mobility

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

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Source: HERUS Laboratory, 2024

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# Technology: E-mobility



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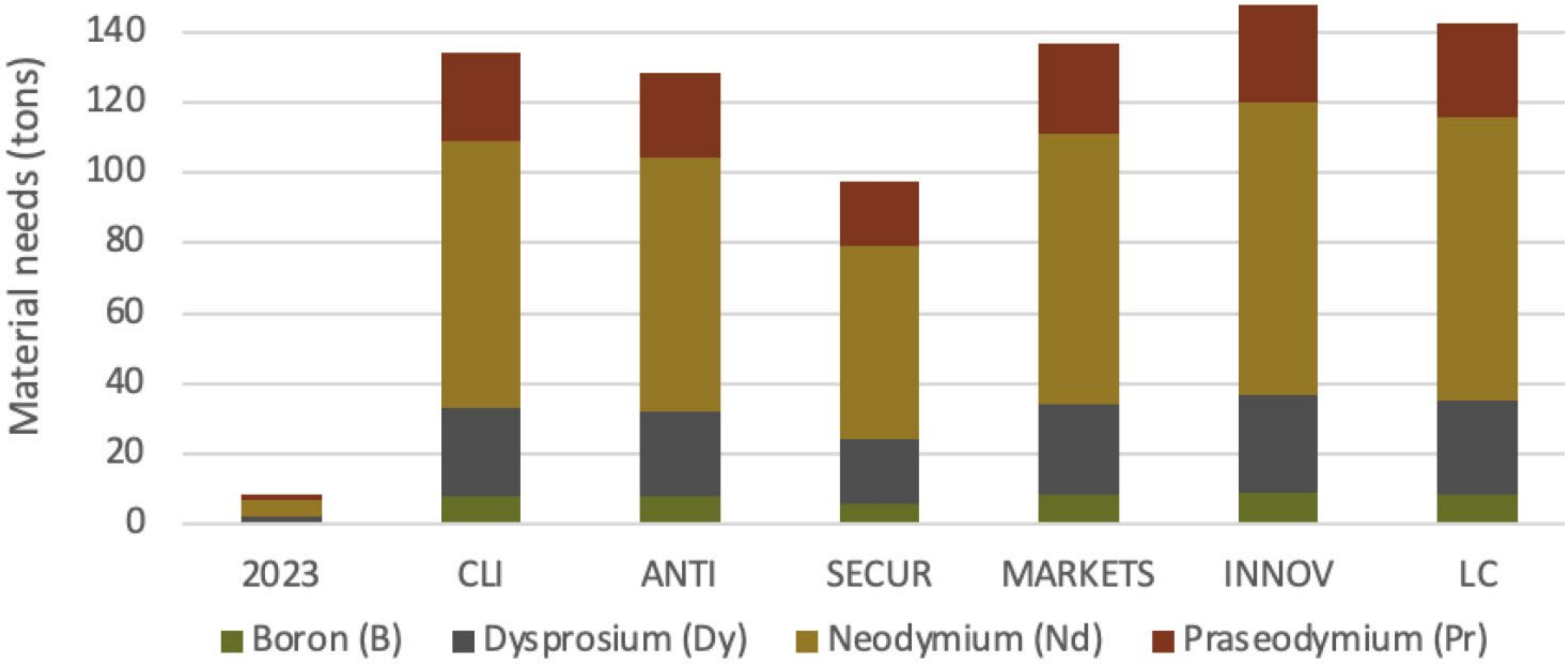
**Current (2030) and 2050 raw material requirements for Electric Vehicles in different scenarios in Switzerland**






Source: HERUS Laboratory, 2024

# All 3 technologies



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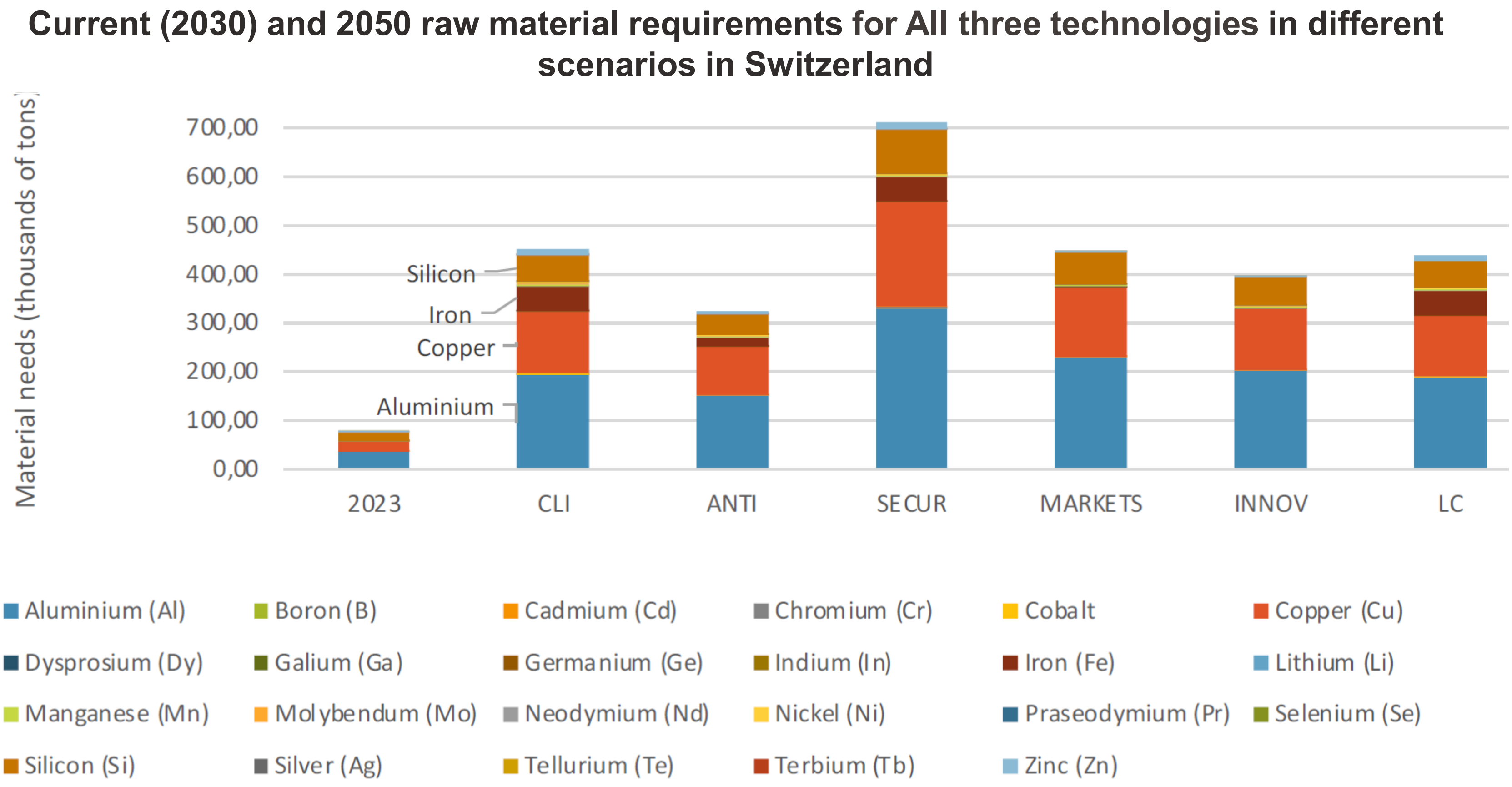


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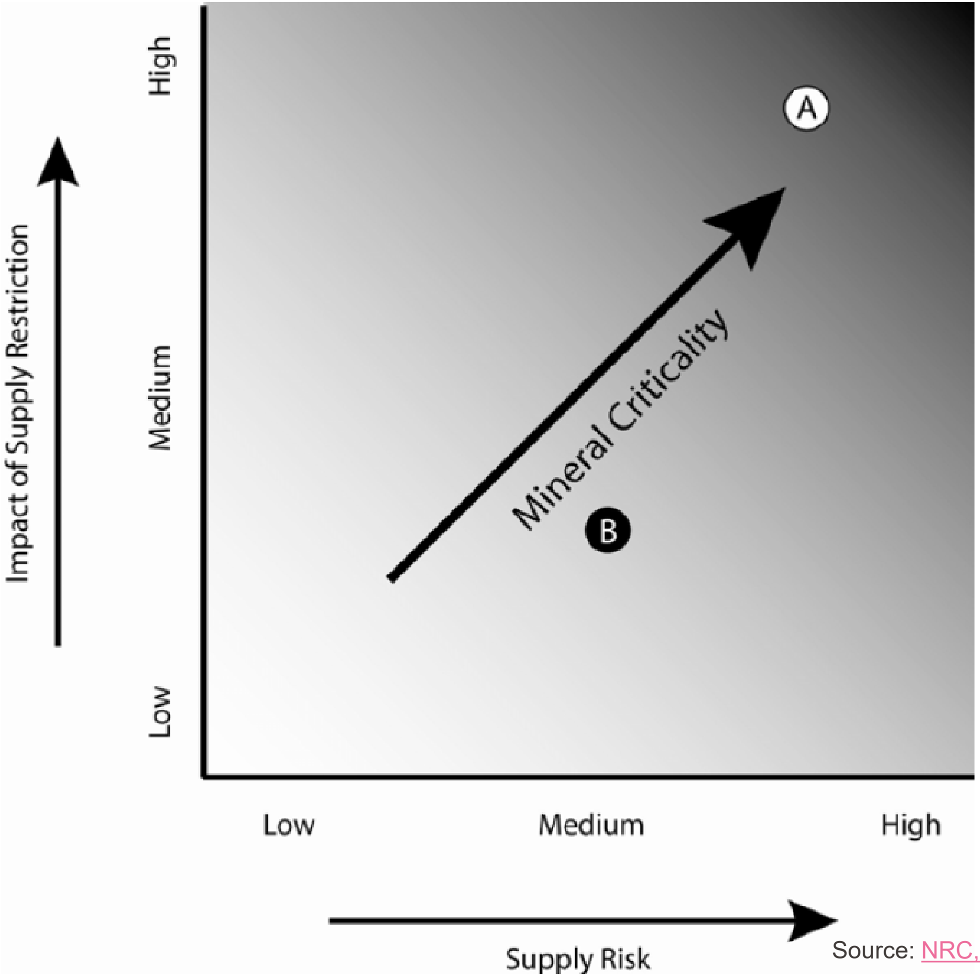
Source: HERUS Laboratory, 2024

# 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

# 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



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**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

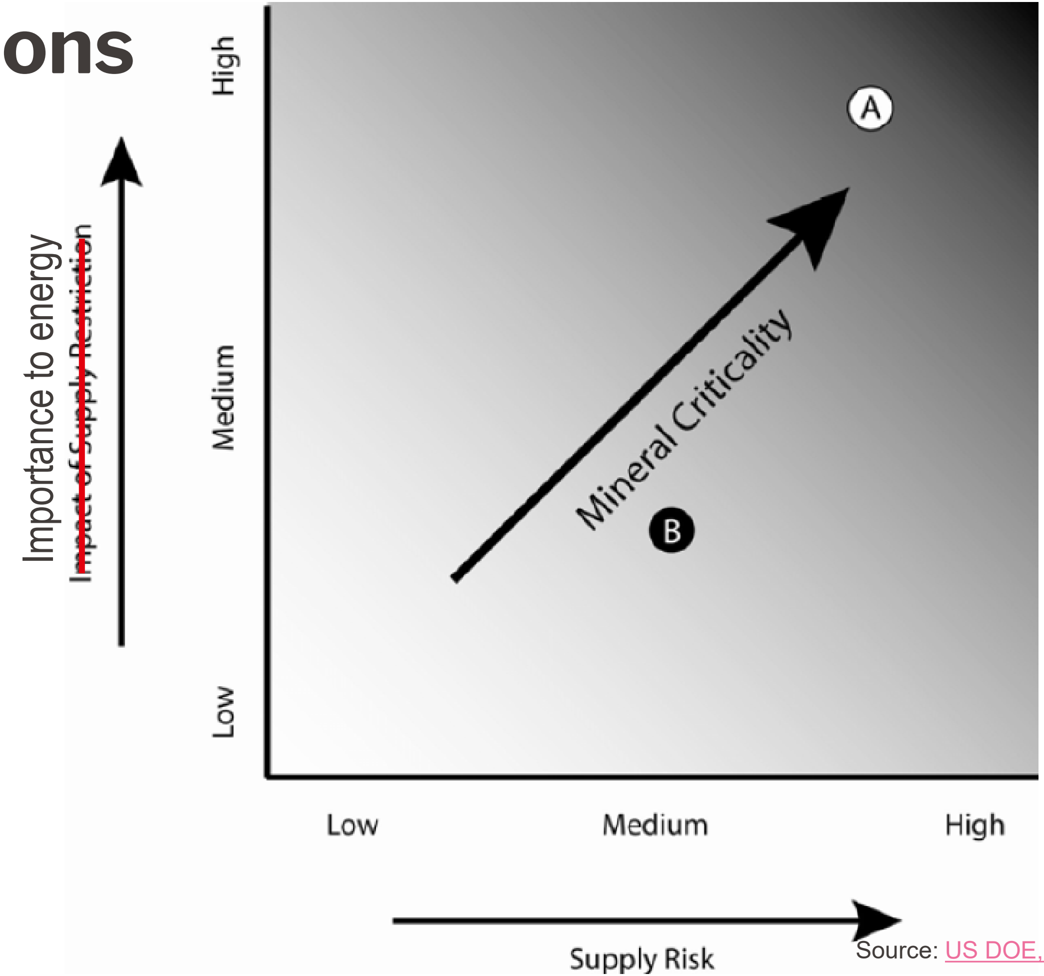
# The criticality matrix: Dimensions

**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

# 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
- **Recycling rates**: recycling rate of materials from solar/wind
- **Political, regulatory, and social factors**: assesses supply risks associated with trends in demand from non-energy sectors through the World Governance Indicators (WGIs)
- **Environmental factors**: Environmental performance index (EPI), measuring the environmental performance of a state's policies
- **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: adapted from US DOE, 2023

# The criticality matrix: Scoring metrics



*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

*Environmental Performance Index (EPI)* - the environmental performance of a state's policies

*World Governance Indicator (WGI)* - assesses supply risks

| Factor | Metrics | | Score | | | |
|---|---|---|---|---|---|---|
| | *Name* | *Weight* | *1* | *2* | *3* | *4* |
| **Importance to Energy** | Energy Demand | *0.7* | Market share of the most dominant specific sub-technology <10% | Market share of the most dominant specific sub-technology ≥10% | Market share of the most dominant sub-technology ≥25% | Market share of the most dominant sub-technology ≥50% |
| | Substitutability Limitations | *0.3* | 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 at either material or system levels with major limitations or concerns. | No substitutes are available at either the material or system levels. |
| **Supply Risk** | Basic Availability | *0.4* | No concerns about existing capacity to meet medium/long term demand. | Minor concerns about existing capacity to meet medium/long term demand. | Major concerns about existing capacity to meet medium/long term demand. | Grave concerns about existing capacity to meet medium/long term demand. |
| | Recycling Rate | *0.1* | The recycling rate of the material from its energy application is from 75 to 100%. | The recycling rate of the material from its energy application is from 50 to 75%. | The recycling rate of the material from its energy application is from 25 to 50%. | The recycling rate of the material from its energy application is from 0 to 25%. |
| | Political, Regulatory, and Social Factors | *0.1* | WGI < 3 | 3 ≤ WGI ≤ 4.5 | 4.5 ≤ WGI ≤ 6 | WGI > 6 |
| | Environmental Factors | *0.1* | EPI > 60 | 45 ≤ EPI ≤ 60 | 30 ≤ EPI ≤ 45 | EPI < 30 |
| | Co-dependence on Other Markets | *0.1* | May or may not be produced as a co-product of other metals. | Most (>50%) production is as co-product or as a by-product of other metals. | Significant (>75%) production is as co-product or as a by-product of other metals. | 100% production is as co-product or as a by-product of other metals. |
| | | | Produced as a main product in most circumstances. | Produced as a main product in some circumstances OR there is excess by-product supply in the market. | May be produced as a main product in some circumstances AND there is no excess by-product supply in the market. | Not produced as a main product anywhere in the world AND there is no excess by-product supply in the market. |
| | Producer Diversity | *0.2* | HHI < 2500 | 2500 ≤ HHI ≤ 3332 | 3333 ≤ HHI ≤ 4999 | HHI ≥ 5000 |

Source: HERUS laboratory, 2024, adapted from US DOE, 2023

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# The criticality matrix: Scoring metrics



| Factor | Metrics | | Score | | | | Final Score |
|---|---|---|---|---|---|---|---|
| | Name | Weight | 1 | 2 | 3 | 4 | |
| Importance to Energy | Energy Demand | 0.7 | Market share of most dominant sub-tech <10% | >=10% | >=25% | >=50% | 3.4 |
| | Substitutability Limitations | 0.3 | Perfect or near perfect substitutes are available at material and system levels with little to no limitations or | 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 | No substitutes are available at either the material or system levels. | |
| Supply Risk | Basic Availability | 0.4 | No concern about existing capacity to meet medium-long-term demands | Minor concern about existing capacity to meet medium-long-term demands | Major concern about existing capacity to meet medium-long-term demands | Grave concern about existing capacity to meet medium-long-term demands | 1.6 |
| | Recycling rates (from technology) | 0.1 | 75-100% | 50-75% | 25-50% | 0-25% | |
| | Political Regulatory, and Social Factors | 0.1 | WGI<3 | 3-4.5 | 4.5-6 | >6 | |
| | Countries environment impact | 0.1 | EPI>60 | 45-60 | 30-45 | <30 | |
| | Co-dependence on other markets | 0.1 | May or may not be produced as a co-product of other<br>Produced as a main product in most circumstances | Most (>50%) prod is as a co/by-product of other<br>Produced as a main product in some circumstances (or there is by product supply in the market) | Significant (>75%) prod is as a co/by-product of other<br>May be produced as a main product in some circumstances and there is no excess by product supply in the market | 100% prod is as a co/by-product of other<br>Not produced as a main product in anywhere and there is no excess by product supply in the market | |
| | Producer diversity | 0.2 | HHI<2500 | 2500-3332 | 3333-4999 | >=5000 | |

Example of Aluminium

Compound Herfindahl-I

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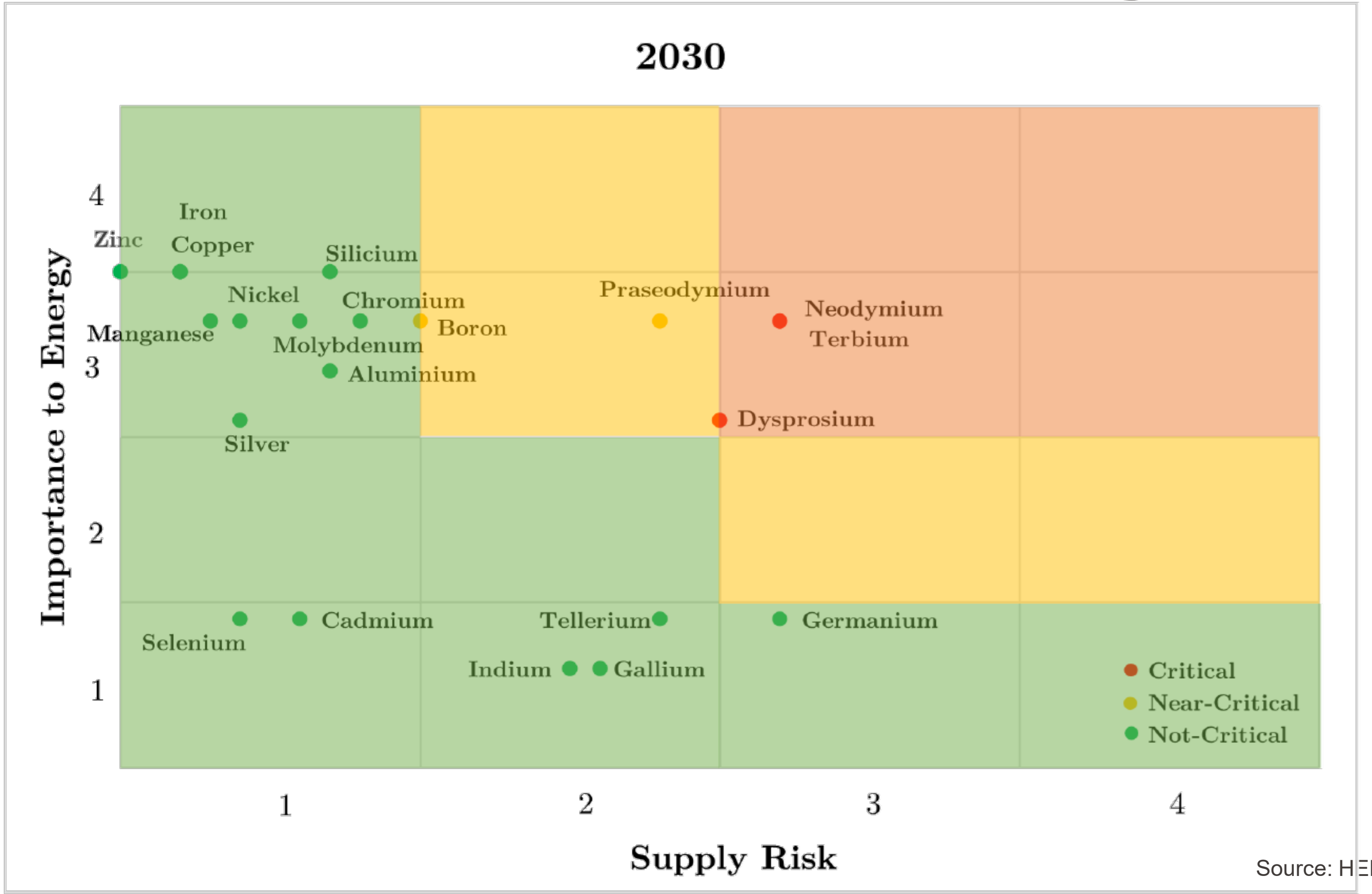
Source: adapted from US DOE, 2023

# The criticality matrix: Scoring metrics



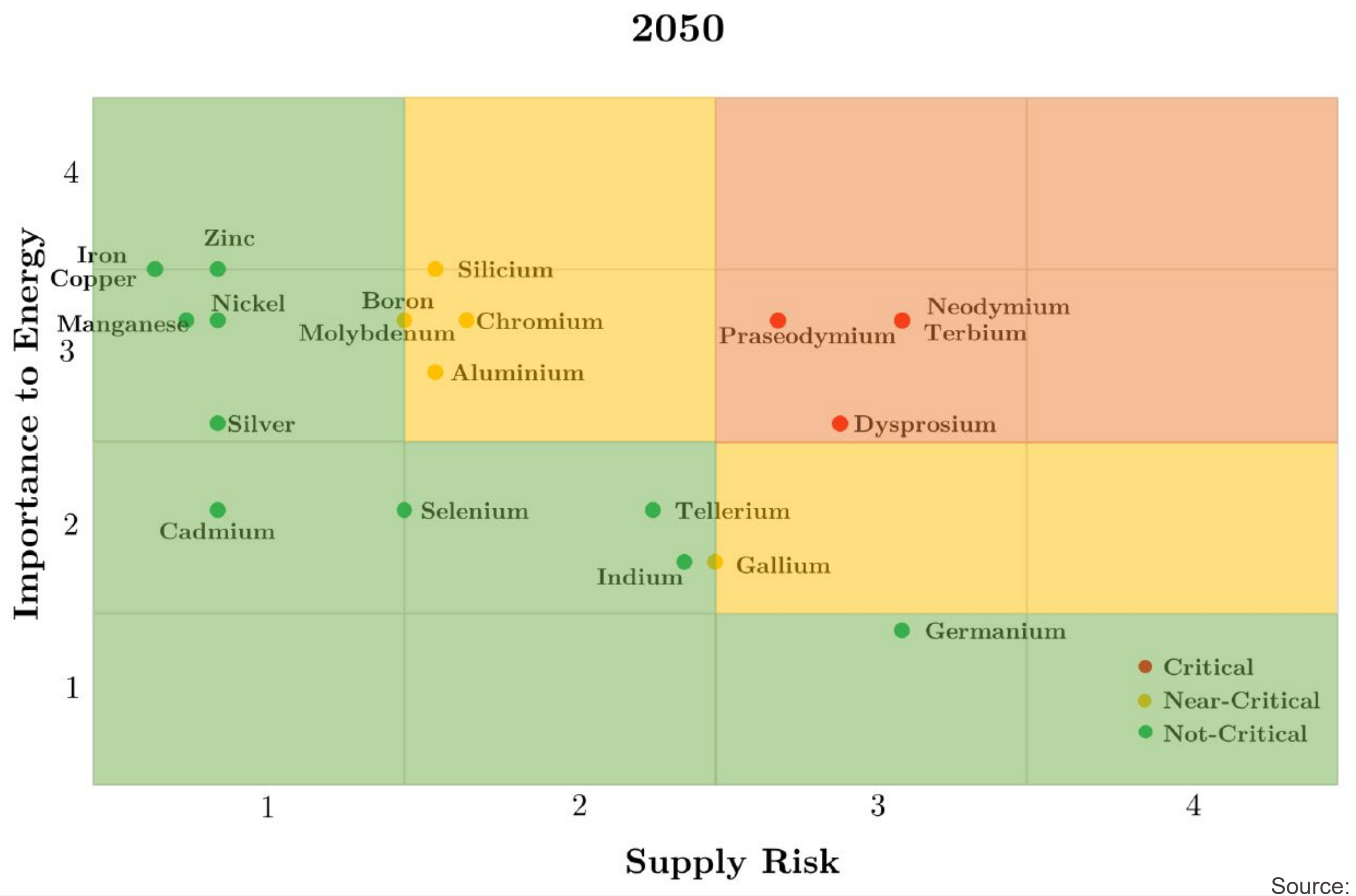



Binder, Félix Martín del Campo, Hecher, Campfens

Source: HERUS Laboratory, 2024

# The criticality matrix: Scoring metrics






Source: HERUS Laboratory, 2024

Binder, Félix Martín del Campo, Hecher, Campfens

# New list of critical raw materials

| 2020 Critical Raw Materials (new as compared to 2017 in bold) | | |
|---|---|---|
| Antimony | Hafnium | Phosphorus |
| Baryte | Heavy Rare Earth Elements | Scandium |
| Beryllium | Light Rare Earth Elements | Silicon metal |
| Bismuth | Indium | Tantalum |
| Borate | Magnesium | Tungsten |
| Cobalt | Natural Graphite | Vanadium |
| Coking Coal | Natural Rubber | **Bauxite** |
| Fluorspar | Niobium | **Lithium** |
| Gallium | Platinum Group Metals | **Titanium** |
| Germanium | Phosphate rock | **Strontium** |

*SWITZERLAND*

| Critical | Near-Critical | Not-Critical |
|---|---|---|
| Aluminium (Al) | Cadmium (Cd) | / |
| Boron (B) | Copper (Cu) | |
| Chromium (Cr) | Germanium (Ge) | |
| Dysprosium (Dy) | Indium (In) | |
| Gallium (Ga) | Iron (Fe) | |
| Molybdenum (Mo) | Manganese (Mn) | |
| Neodymium (Nd) | Nickel (Ni) | |
| Praseodymium (Pr) | Selenium (Se) | |
| Silicium (Si) | Silver (Ag) | |
| Terbium (Tb) | Tellurium (Te) | |
| | Zinc (Zn) | |

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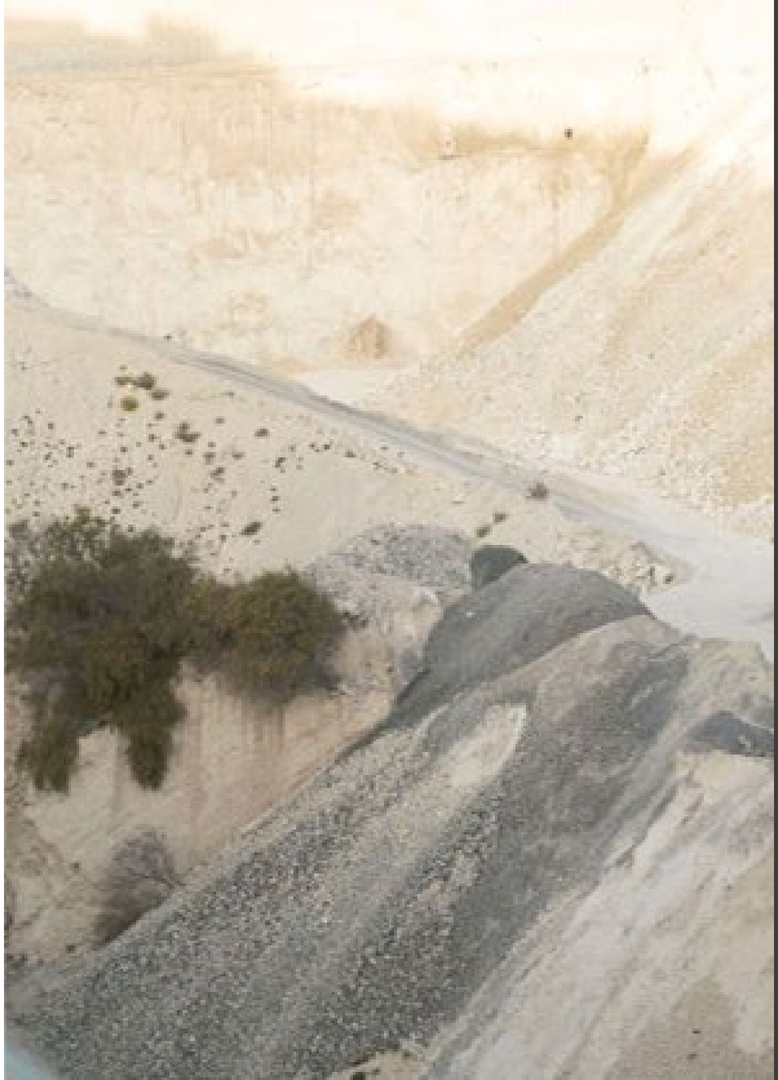
Source: European Commission (2020); HERUS Laboratory, 2024



# Thank you for your attention!

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