

ENV 501 / GR A3 30

# Material Flow Analysis and resource management

Course room  
GR A3 30

Computer lab  
CM 1 111

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- Recap of Material Flow Analysis & Life Cycle Analysis
- Linkages between MFA and LCA
- Example applications
- Key takeaways

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 11	Introduction to the course and general concepts	All	Exercise	Project
W2 - Sep 18	EW – MFA and EW – MFA in the Swiss context	External Guest – Florian Kohler	Exercise	Project
W3 – Sep 25	Examples of EW – MFA. Scaling EW-MFA to Cantons	FMC	Exercise	Project
W4 - Oct 02	Urban Metabolism and Circular Economy	FMC	Exercise	Project

Block II:  
MFA  
regional /  
urban

W5 - Oct 09	MFA method and the Stock-Flows-Service Nexus	CRB	Exercise	Project
W6 - Oct 16	Dynamic MFA	CRB	Exercise	Project
Oct 23	Autumn break			
W7 - Oct 30	Applications of MFA – case study	External Guest – Guillaume Massard	Exercise	Project
W8 - Nov 06	Input-Output Analysis and Material Flow Cost Accounting	External Guest – Vincent Moreau	Exercise	Project
W9 - Nov 13	Spatial MFA	FMC	Exercise	Project
W10 - Nov 20	Combined approaches: MFA + LCA; MFA + sociodemographic	AS & FMC	Exercise	Project

Block III:  
Social  
sciences  
and  
public  
policy

W11 - Nov 27	Combined approaches: Quasi-dynamic MFA; MFA + surveys	GF & FMC	Exercise	Project
W12 - Dec 04	Social metabolism	CRB	Past exam	Project
W13 - Dec 11	Agent-based model	CRB, FMC, MAH, SLC	Project	Project
W14 - Dec 18	Group Project Presentation	All	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

# Case study: The energy transition



# The issue at hand: The Swiss Energy Strategy

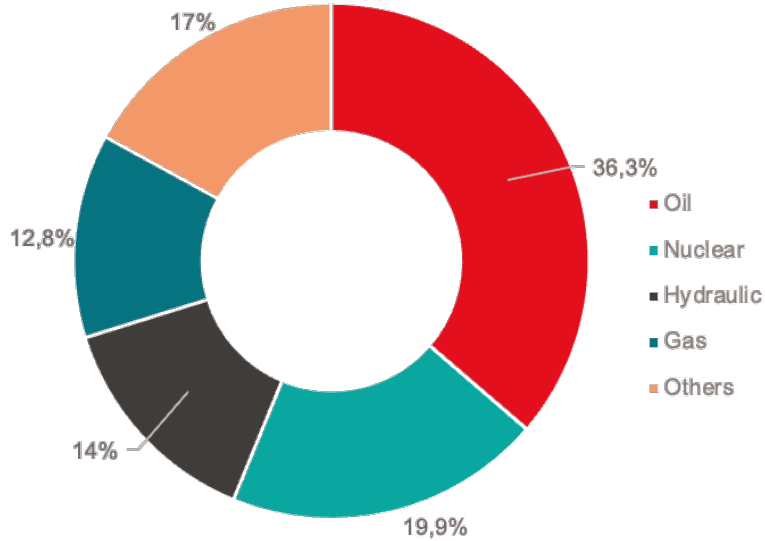
« *The science is clear: to ensure sufficiently high probability of global warming remaining below 1.5°, global CO<sub>2</sub> emissions must be reduced to **net zero by the middle of this century** at the latest* »

**- Federal Council**

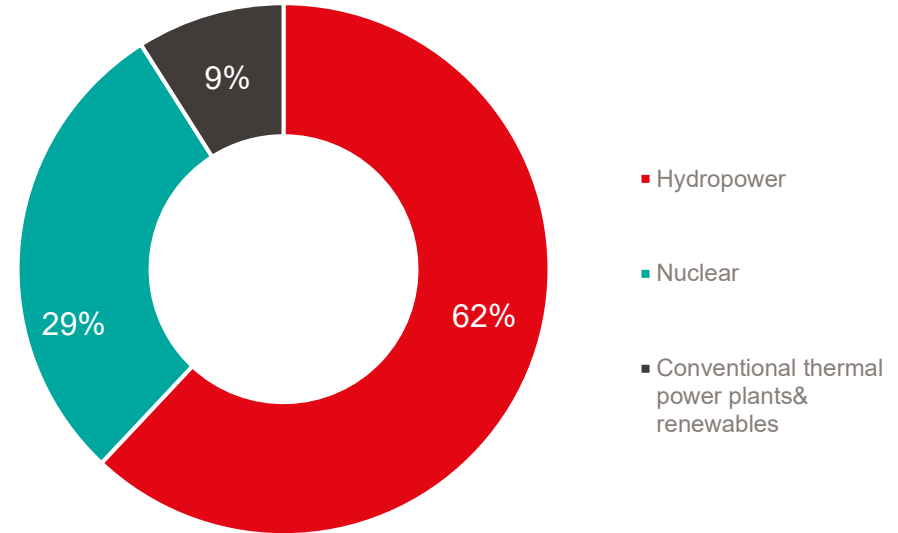
- Increase **energy efficiency** (buildings, mobility, industry, etc.)
- Develop **renewable energies** (promotion, ease the legal framework, etc.)
- Phase out **nuclear energy** (no more construction of nuclear power plants, security concerns, etc.)

# Current Swiss Energy Landscape

## National energy consumption



## National electricity production

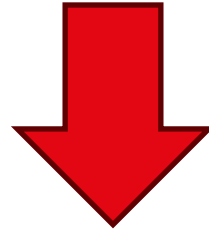


**Energy supply: 70% imported**



# Observations

- **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 current energy consumption by renewables
    - Increase national production (also to reduce foreign dependency)



**What about the materials needed for the transition?**

- 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**)

# 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?**

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:  
Prof. Silvia Fiore  
Dr. Francisco Xavier Félix Martín del Campo

Candidate:  
Matilde Spinello

Spring Semester 2024

Human-  
Environment  
Relations in  
Urban Systems

EPFL

SIE individual project

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

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Prof. Claudia R. Binder

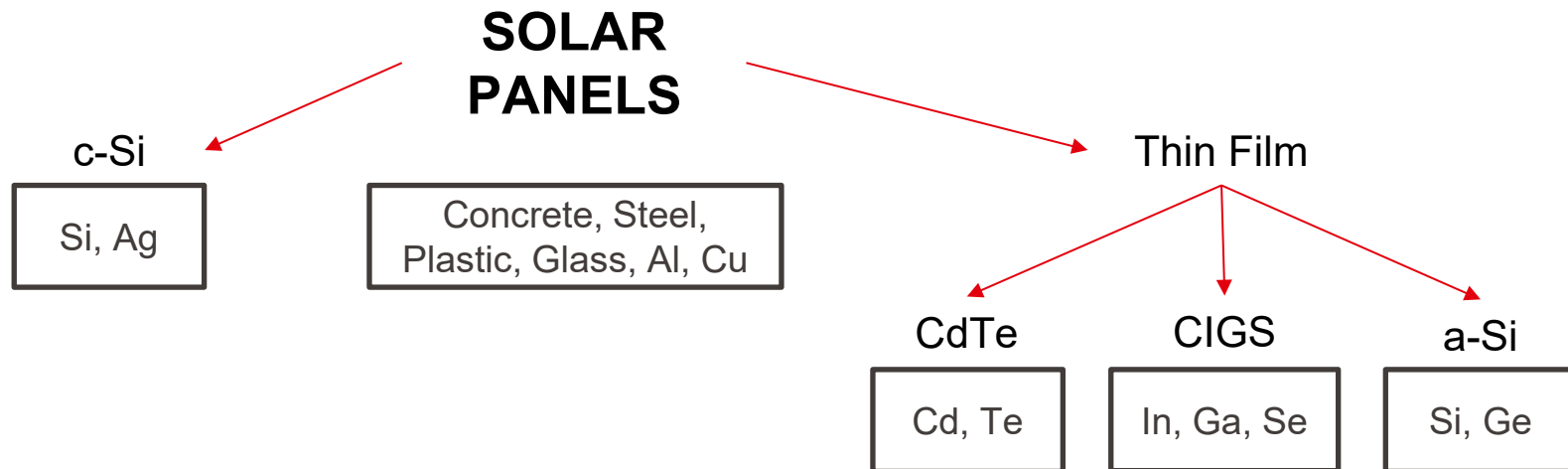
05.02.2024

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

# Renewable energy technologies - Solar

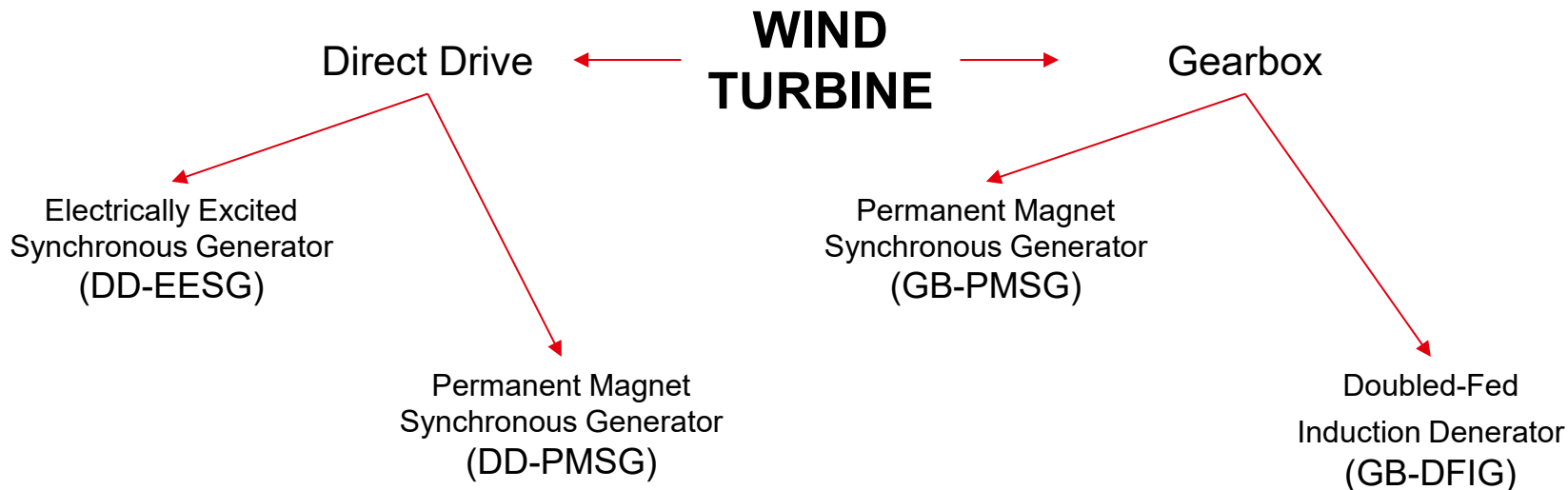
**Step 1:** Determine the type/amount of materials needed to manufacture each technology



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

# Renewable energy technologies - Wind

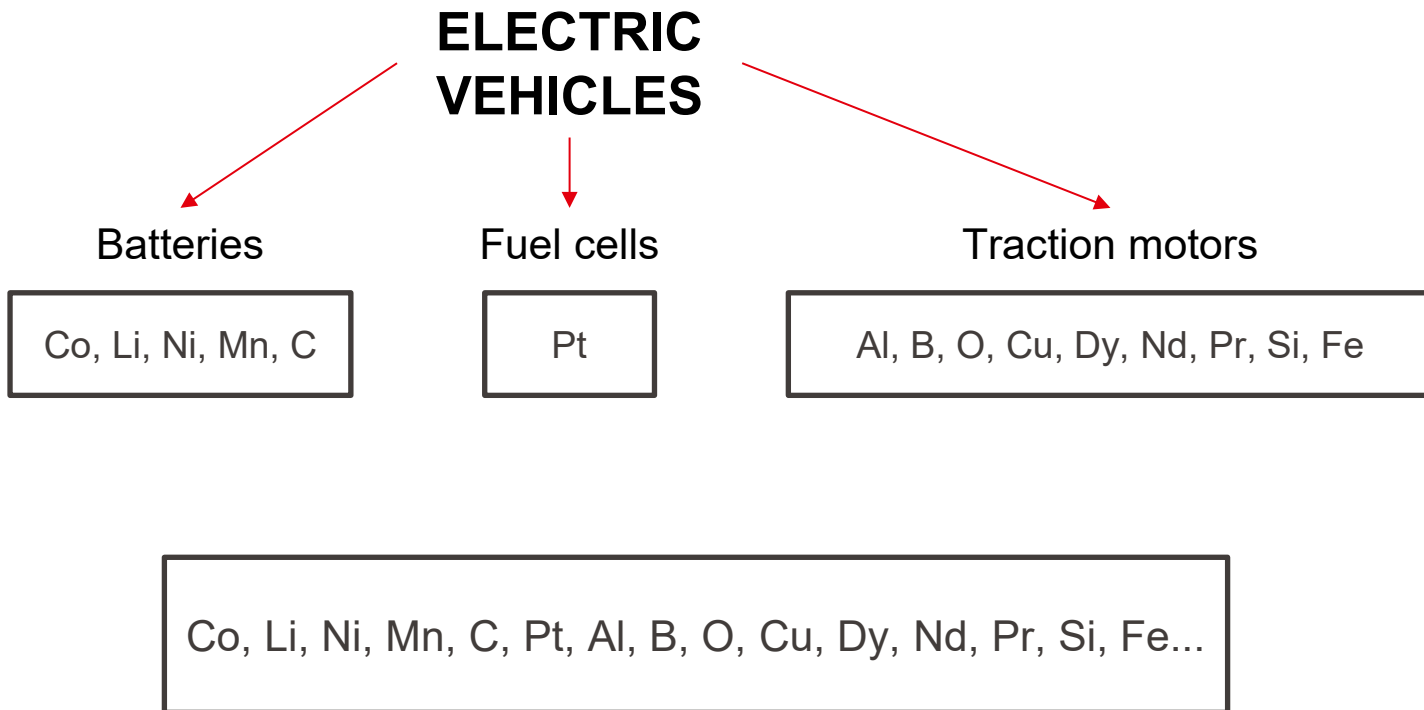
**Step 1:** Determine the type/amount of materials needed to manufacture each technology



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

# Renewable energy technologies – E-mobility

**Step 1:** Determine the type/amount of materials needed to manufacture each technology

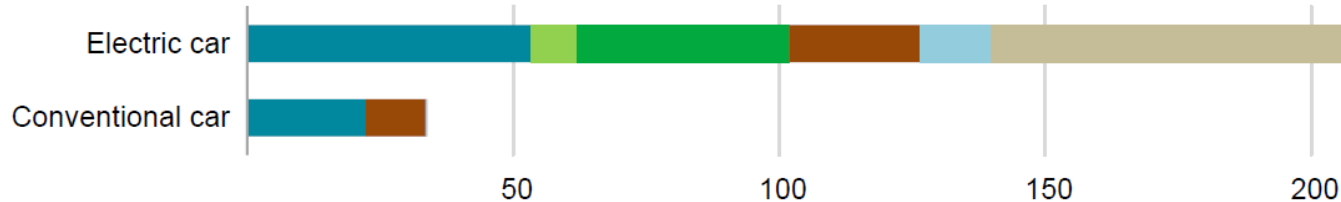


# Critical Raw Materials per tech

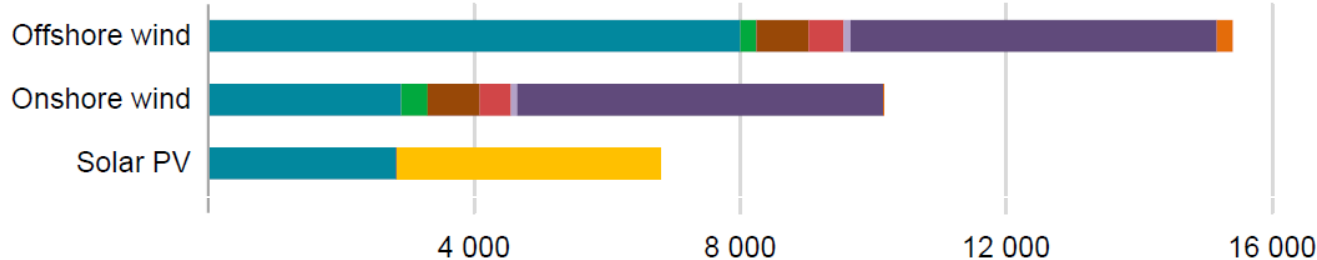
## Critical Raw Materials

Minerals used in selected clean energy technologies

### Transport (kg/vehicle)



### Power generation (kg/MW)



- Copper
- Lithium
- Nickel
- Manganese
- Cobalt
- Graphite
- Chromium
- Molybdenum
- Zinc
- Rare earths
- Silicon
- Others

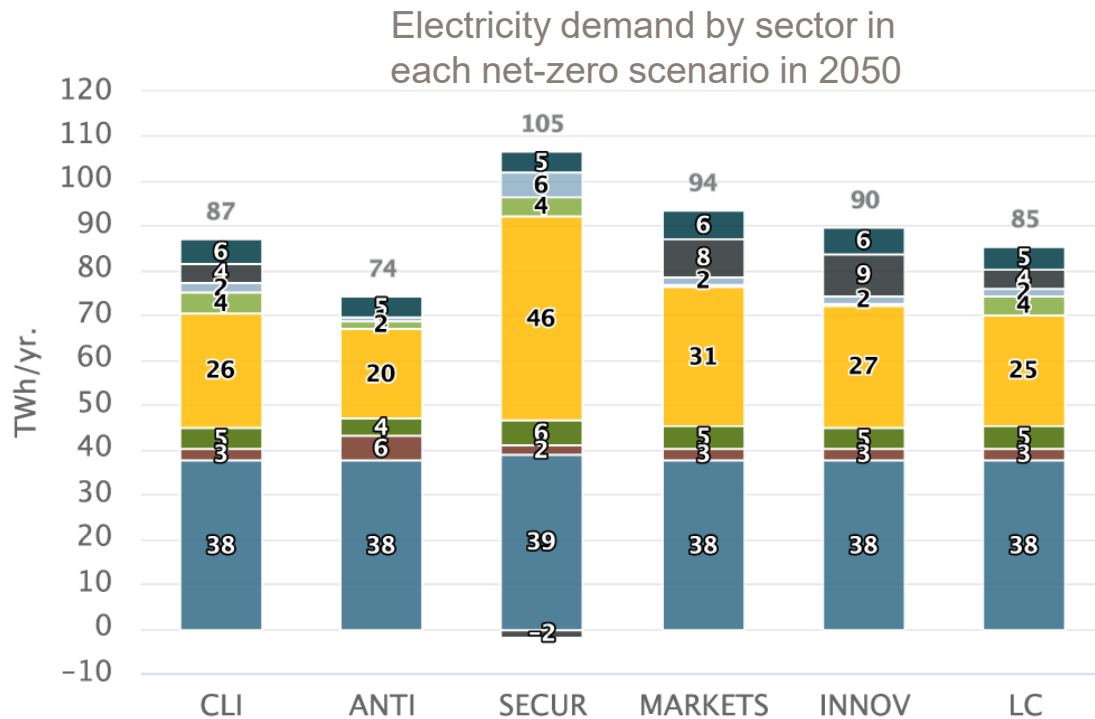
# The Swiss Energy Transition

**Step 2:** Assess the total number of solar panels, wind turbines and EV's necessary for the energy transition

Scenario	Description	Switzerland in 2050
CLI	Full implementation of the energy agreements	<ul style="list-style-type: none"> <li>- Environmental policies and practices put in place.</li> <li>- Energy demand reduced in end-hand sectors.</li> <li>- European level CO<sub>2</sub> grids.</li> </ul>
ANTI	Low international cooperation in mitigating climate change	<ul style="list-style-type: none"> <li>- Limited technological progress leads to high capital costs for low carbon solutions.</li> <li>- Development at local scales (high willingness to pay, local energy networks &amp; self-sufficiency)</li> </ul>
SECUR	International trade is controlled for energy carriers	<ul style="list-style-type: none"> <li>- Restricted access to energy resources leads to an increase in energy import prices.</li> <li>- Domestic renewable energies exploited at their maximum potential.</li> <li>- Annual net energy imports as close to 0 as possible.</li> </ul>
MARKETS	High global cooperation	<ul style="list-style-type: none"> <li>- Increased availability of imported resources leads to more affordable energy</li> <li>- Development of local energy markets in coordination with national ones.</li> </ul>
INNOV	Variant of MARKETS with closer international cooperation	<ul style="list-style-type: none"> <li>- Increased R&amp;D expenditures lead to low-carbon energies costs reduction.</li> </ul>
LC	Least cost variant of the CLI scenarios	<ul style="list-style-type: none"> <li>- Resource potentials are set to the levels of CLI.</li> </ul>

# The Swiss Energy Transition

**Step 3:** Estimate total quantity of materials



# The Swiss Energy Transition

**Step 3:** Estimate total quantity of materials

Forecasted installed capacities to 2050

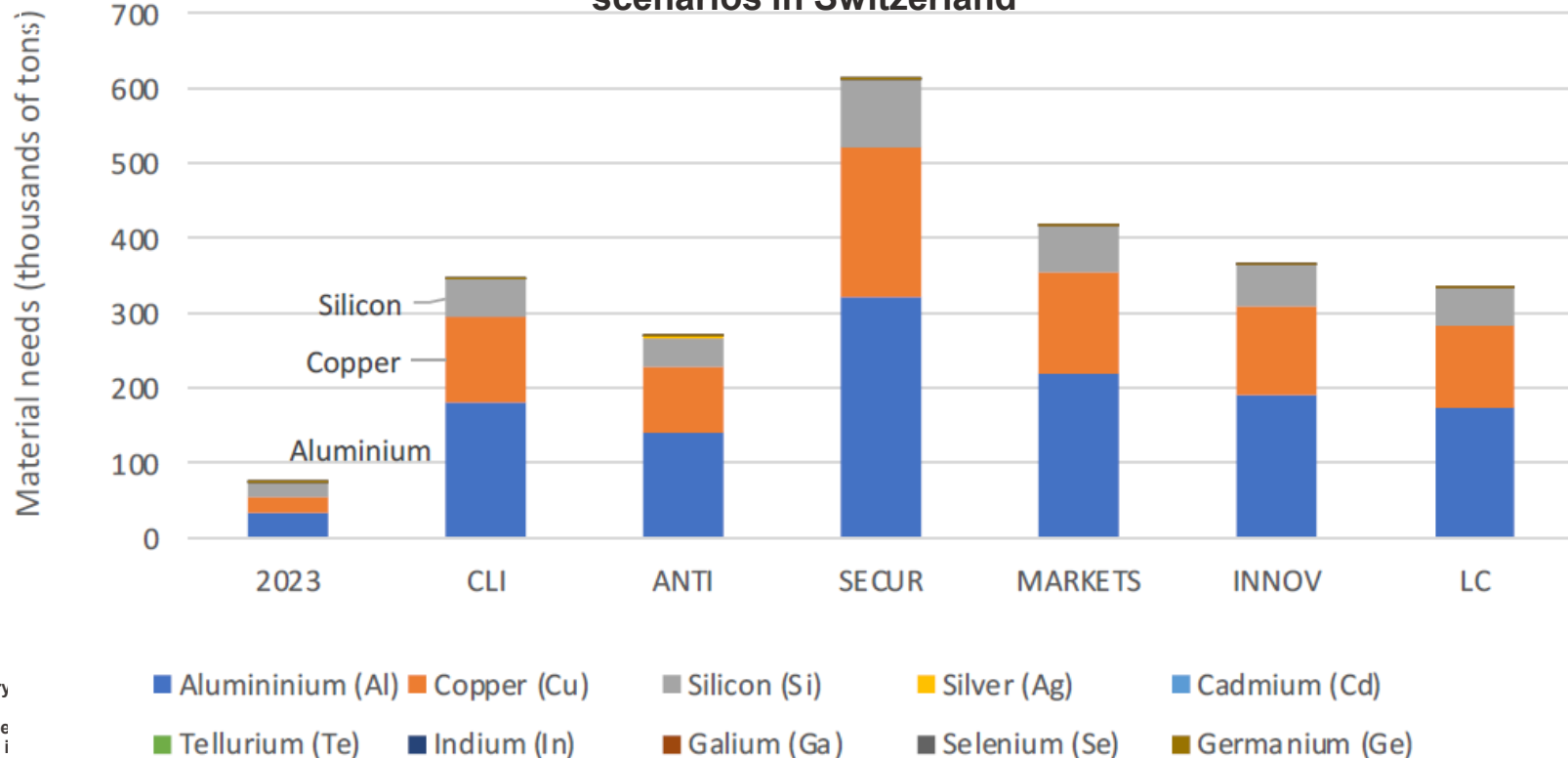
	CLI	ANTI	SECUR	MARKETS	INNOV	LC	TARGET*
Solar panels (GW)	26.8	20.8	47.4	32.4	28.2	28.2	37.5
Wind turbines (GW)	2.6	1.0	2.6	0.1	0.1	0.1	2.2
EV (millions of vehicles)	4.8	4.6	3.5	4.9	5.3	5.3	N.A.

# The Swiss Energy Transition

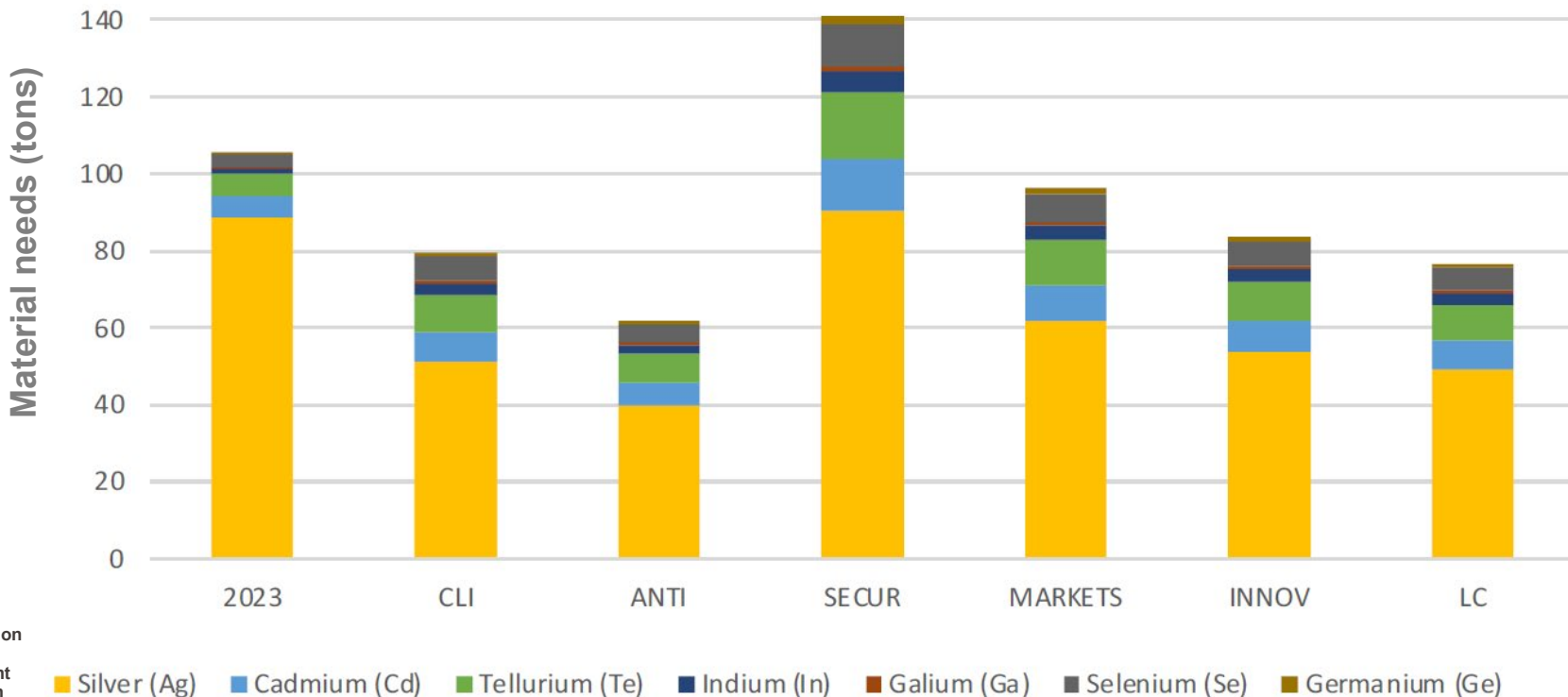
Photovoltaic solar panels																
	All technologies						c-Si		CdTe		CIGS				a-Si	
	Concrete (t/MW)	Steel (t/MW)	Plastic (t/MW)	Glass (t/MW)	Al (t/MW)	Cu (t/MW)	Si (t/MW)	Ag (t/GW)	Cd (t/GW)	Te (t/GW)	Cu (t/GW)	In (t/GW)	Ga (t/GW)	Se (t/GW)	Si (t/GW)	Ge (t/GW)
2010	60.7	67.9	8.6	46.4	7.5	4.6	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

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



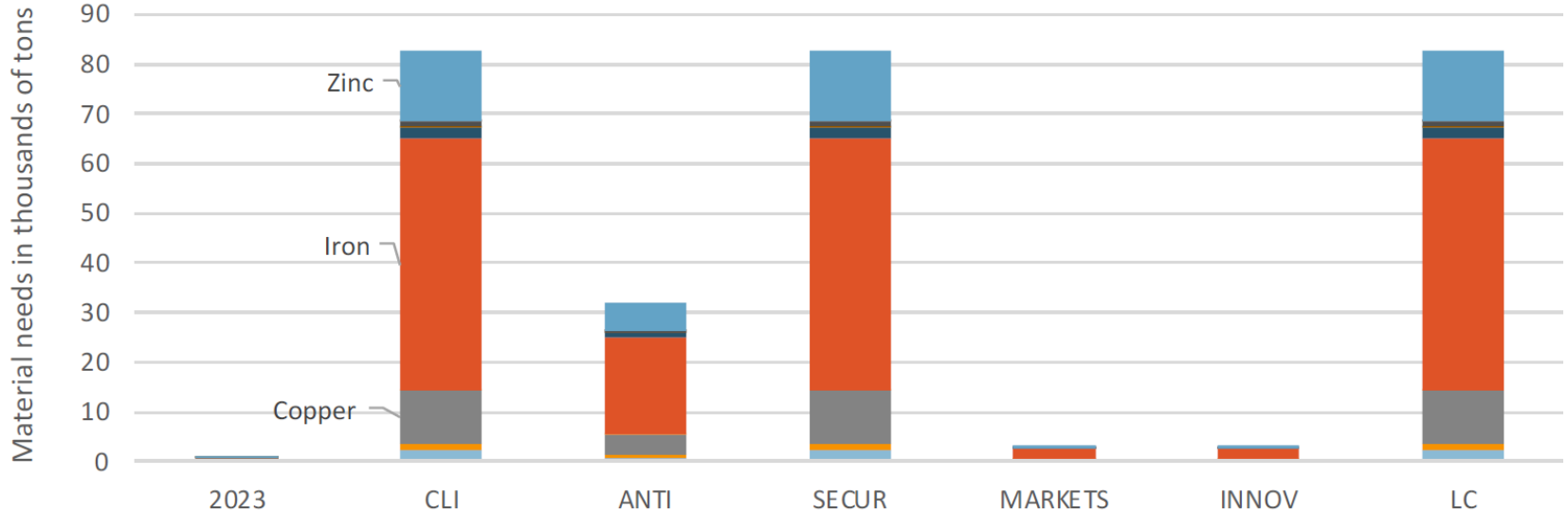
Current (2023) and 2050 raw material requirements for **Solar Panels** in different scenarios in Switzerland



# Technology: Wind

**Step 3:** Estimate total quantity of materials

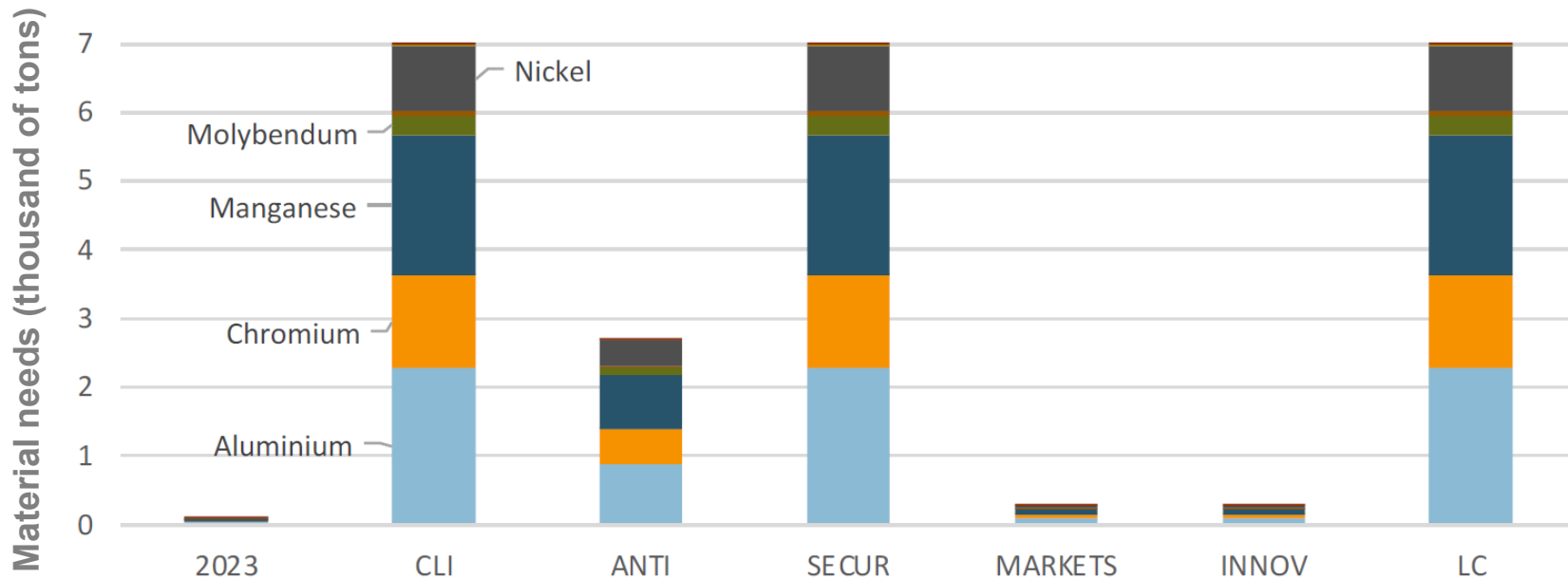
**Current (2023) and 2050 raw material requirements for Wind Turbines in different scenarios in Switzerland**



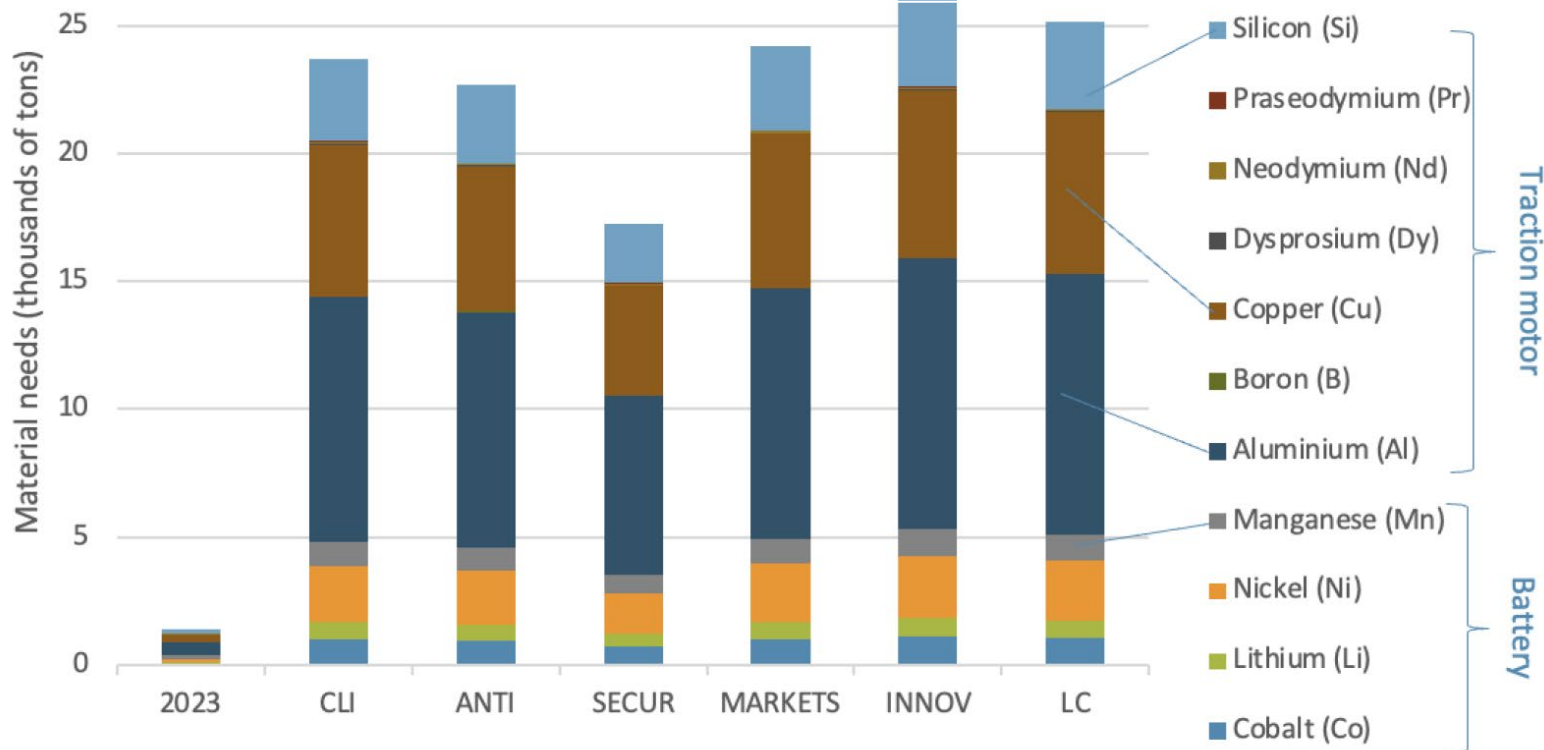
- Aluminium (Al)
- Boron (B)
- Chromium (Cr)
- Copper (Cu)
- Dysprosium (Dy)
- Iron (Fe)
- Manganese (Mn)
- Molybdenum (Mo)
- Neodymium (Nd)
- Nickel (Ni)
- Praseodymium (Pr)
- Terbium (Tb)
- Zinc (Zn)

Source: HERUS Laboratory, 2024

Current (2023) and 2050 raw material requirements for **Wind Turbines** in different scenarios in Switzerland

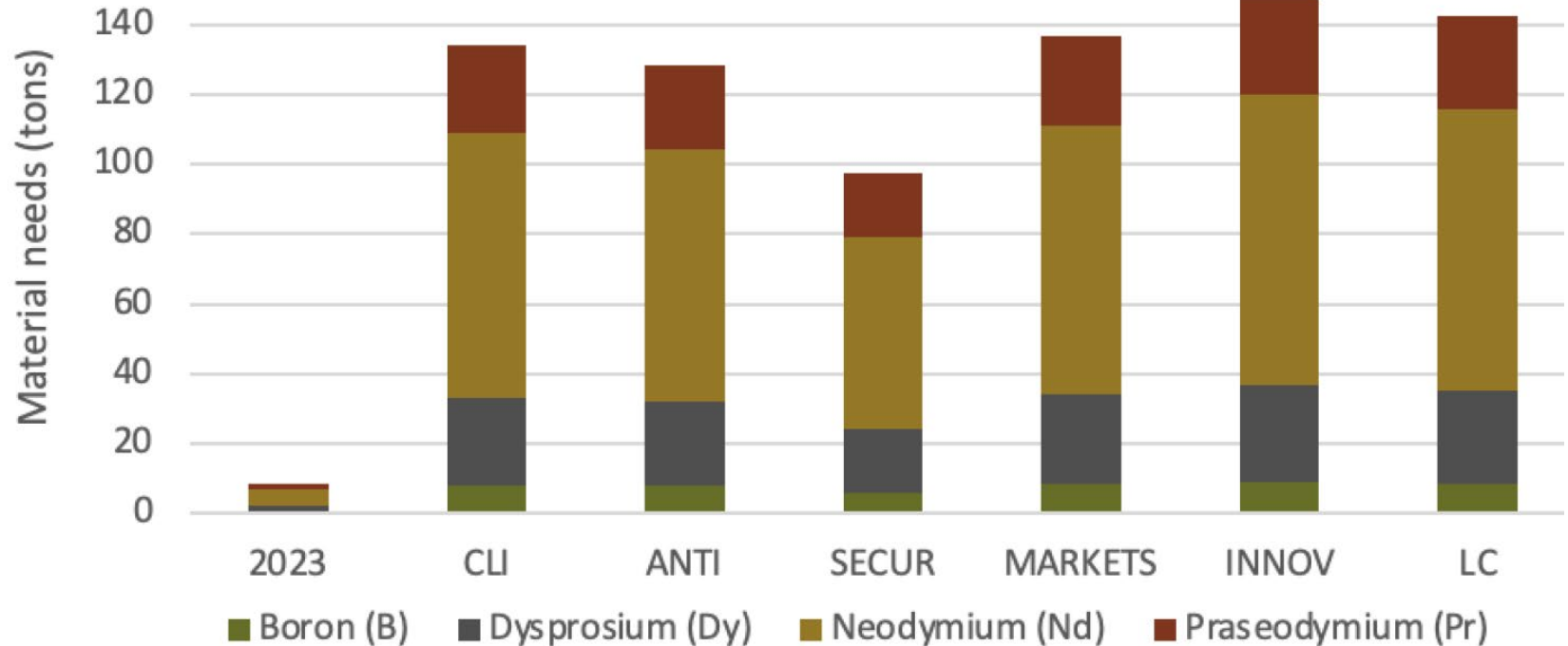


Current (2023) and 2050 raw material requirements for **Electric Vehicles** in different scenarios in Switzerland



Source: HERUS Laboratory, 2024

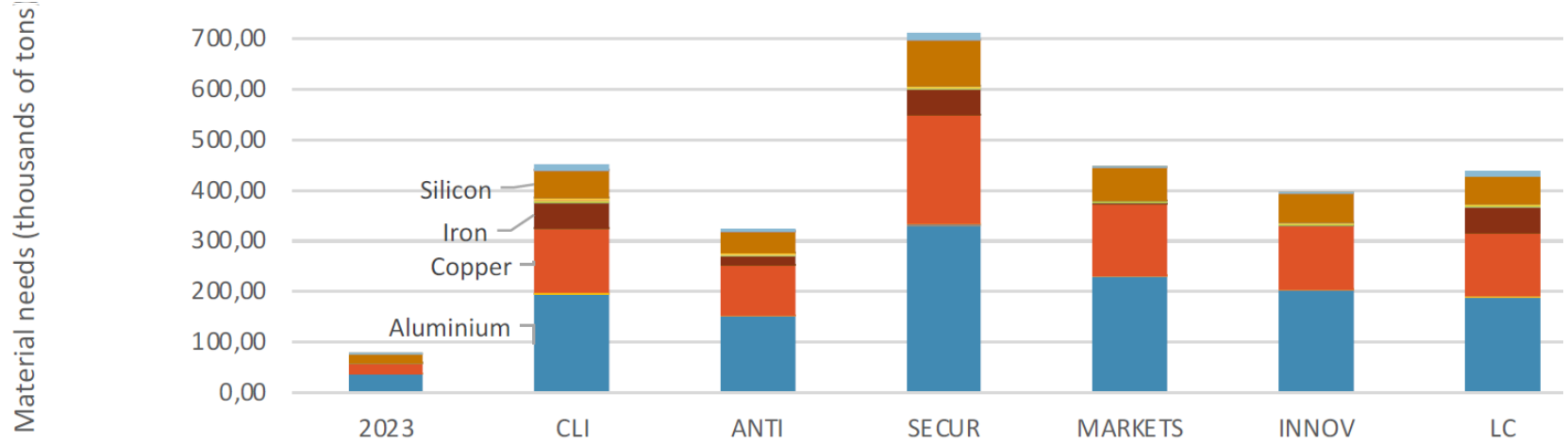
Current (2023) and 2050 raw material requirements for **Electric Vehicles** in different scenarios in Switzerland



# All 3 technologies

**Step 3:** Estimate total quantity of materials

**Current (2023) and 2050 raw material requirements for All three technologies in different scenarios in Switzerland**



- Aluminium (Al)
- Boron (B)
- Cadmium (Cd)
- Chromium (Cr)
- Cobalt
- Copper (Cu)
- Dysprosium (Dy)
- Galium (Ga)
- Germanium (Ge)
- Indium (In)
- Iron (Fe)
- Lithium (Li)
- Manganese (Mn)
- Molybendum (Mo)
- Neodymium (Nd)
- Nickel (Ni)
- Praseodymium (Pr)
- Selenium (Se)
- Silicon (Si)
- Silver (Ag)
- Tellurium (Te)
- Terbium (Tb)
- Zinc (Zn)

# Insights: Going beyond the MFA



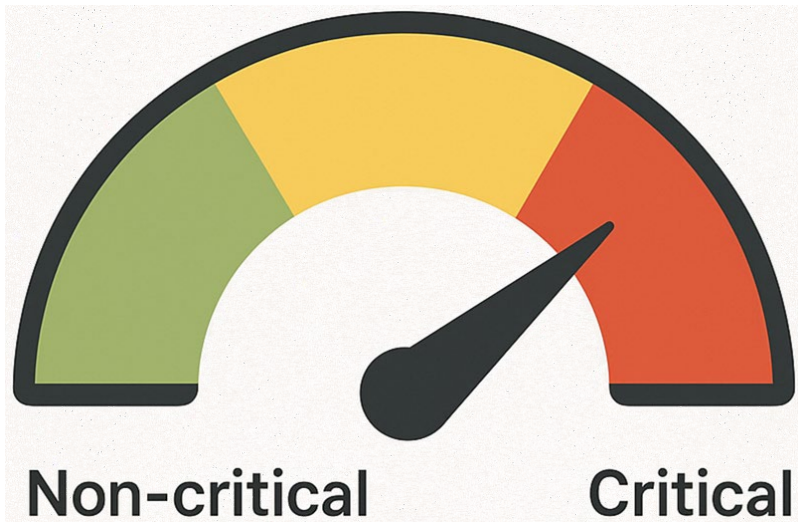
# Critical raw materials (CRMs)

- 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	<b>Bauxite</b>
Fluorspar	Niobium	<b>Lithium</b>
Gallium	Platinum Group Metals	<b>Titanium</b>
Germanium	Phosphate rock	<b>Strontium</b>

Source: [European Commission \(2020\)](#)

# How critical is a material?



## An integrated approach for advancing material criticality assessment in the renewable energy transition: insights from Switzerland and Italy

Francisco Martin del Campo<sup>a</sup>, Matilde Spinello<sup>b</sup>, Silvia Fiore<sup>b</sup>, Claudia R. Binder<sup>a</sup>

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### Highlights

- Combination of global, regional and national dynamics to assess material criticality in renewable energy systems
- Application to Switzerland and Italy reveals divergent material criticality profiles
- Rare earth elements identified as key critical materials in both countries
- Country-specific assessments reveal additional material candidates for mid and long-term EU CRM lists
- Country-specific assessments complement regional criticality frameworks for resilient supply chains

### Scientific publication

### Abstract

Photovoltaic panels and wind turbines are key renewable energy technologies for carbon neutrality, with Critical Raw Materials (CRMs) as essential constituents. Existing criticality assessments often focus on “external” dimensions, encompassing global and regional factors like production volumes, supply concentration, and geopolitical dependencies, and they tend to overlook country-specific or “internal” dimensions, including national deployment trajectories, material demand growth, and recycling capacity. This study addresses that gap by proposing a novel integrated, multi-scalar methodology for assessing the criticality of raw materials required for renewable energy technologies, incorporating both external and internal contexts. The methodology was tested on Italy and Switzerland. Material Flow Analysis (MFA) is combined with an adapted criticality matrix incorporating three adjustment factors: baseline-to-target deployment gaps, projected material-specific demand growth, and recycling maturity, with a focus on materials related to photovoltaic panels and wind turbines. Materials are assigned a criticality score from 0 (lowest) to 6 (highest). Results show that technology deployment drive sharp increases in demand for several materials (e.g. silicon, silver, zinc), with Switzerland exhibiting higher criticality scores than Italy due to steeper projected growth and narrower recovery windows. Comparison with the EU CRMs list reveals that several materials (e.g., rare earth elements) are also highly critical at national level, while new ones (e.g. indium, selenium) emerge despite being overlooked or undifferentiated in regional assessments. These findings underscore the value of national material criticality assessments for manufacturing economies and for technology importers. The proposed framework provides policymakers and stakeholders with a tool to anticipate material supply bottlenecks and supports strategic planning for supply diversification, recycling, and circularity.

*Keywords: Critical raw materials; Energy transition; Circularity; Material flow analysis; Criticality assessment*

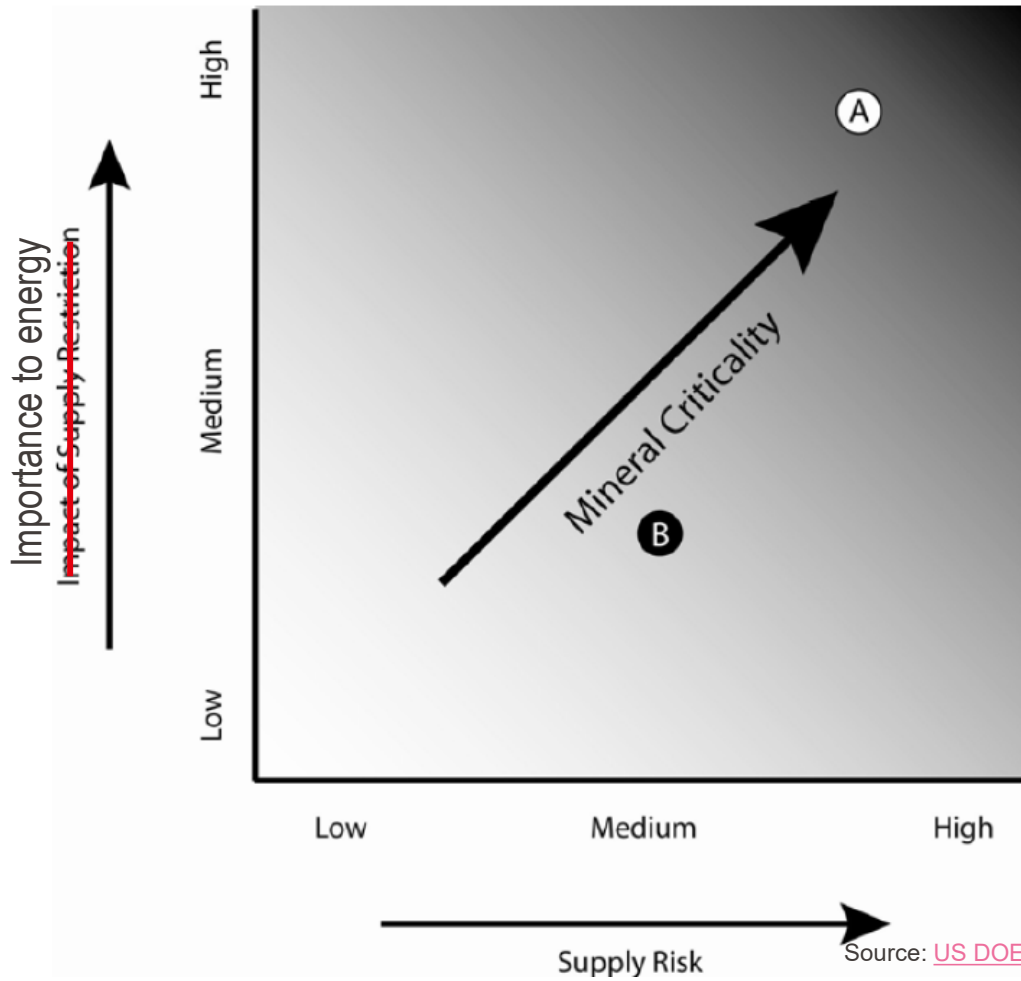
# The criticality matrix

## US Department of Energy 2023:

- Addresses particular concerns for **energy technologies**

## “Importance to energy” and “supply risk”

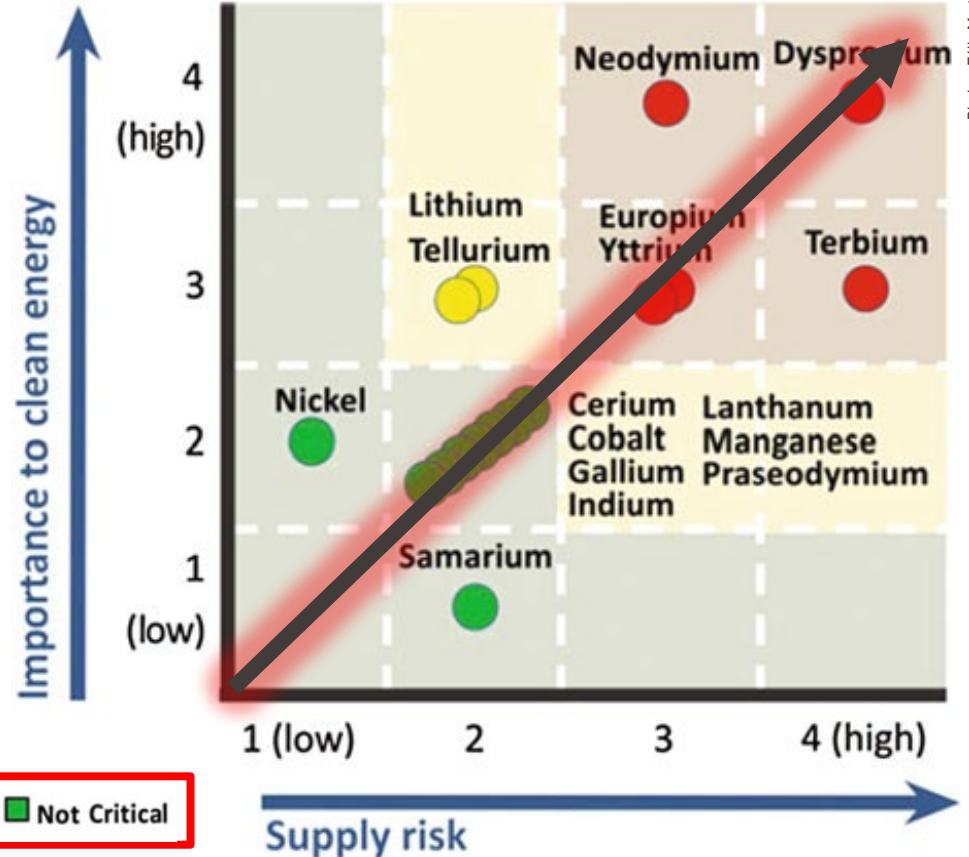
- Weighted averages of several factors
- Score from 1 to 4



# The criticality matrix

## HOW IT WORKS

- A specific material is placed on the matrix based on its importance to energy (**vertical axis**) and the likelihood of a supply restriction (**horizontal axis**)
- The degree of **criticality increases** as one moves from the lower-left to the **upper-right** corner of the matrix



# 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

# 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

# The criticality matrix: Scoring metrics

Factor	Metrics		Score			
	Name	Weight	1	2	3	4
<b>Importance to Energy</b> <i>Compound Annual Growth Rate (CAGR)</i> - mean annual growth rate of an investment over a specified period of time longer than one year	<u>Energy Demand</u>	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%
	<u>Substitutability Limitations</u>	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.
<b>Supply Risk</b> <i>Herfindahl-Hirschman Index (HHI)</i> - measure of the size of firms in relation to the industry. Used as indicator of the amount of competition among them	<u>Basic Availability</u>	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.
	<u>Recycling Rate</u>	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%.
<b>Environmental Performance Index (EPI)</b> - the environmental performance of a state's policies	<u>Political, Regulatory, and Social Factors</u>	0.1	WGI < 3	3 ≤ WGI ≤ 4.5	4.5 ≤ WGI ≤ 6	WGI > 6
	<u>Environmental Factors</u>	0.1	EPI > 60	45 ≤ EPI ≤ 60	30 ≤ EPI ≤ 45	EPI < 30
<b>World Governance Indicator (WGI)</b> - assesses supply risks	<u>Co-dependence on Other Markets</u>	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.
<b>World Governance Indicator (WGI)</b> - assesses supply risks	<u>Producer Diversity</u>	0.2	HHI < 2500	2500 ≤ HHI ≤ 3332	3333 ≤ HHI ≤ 4999	HHI ≥ 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

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

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

• Laboratory on Human-Environment Relations in Urban Systems

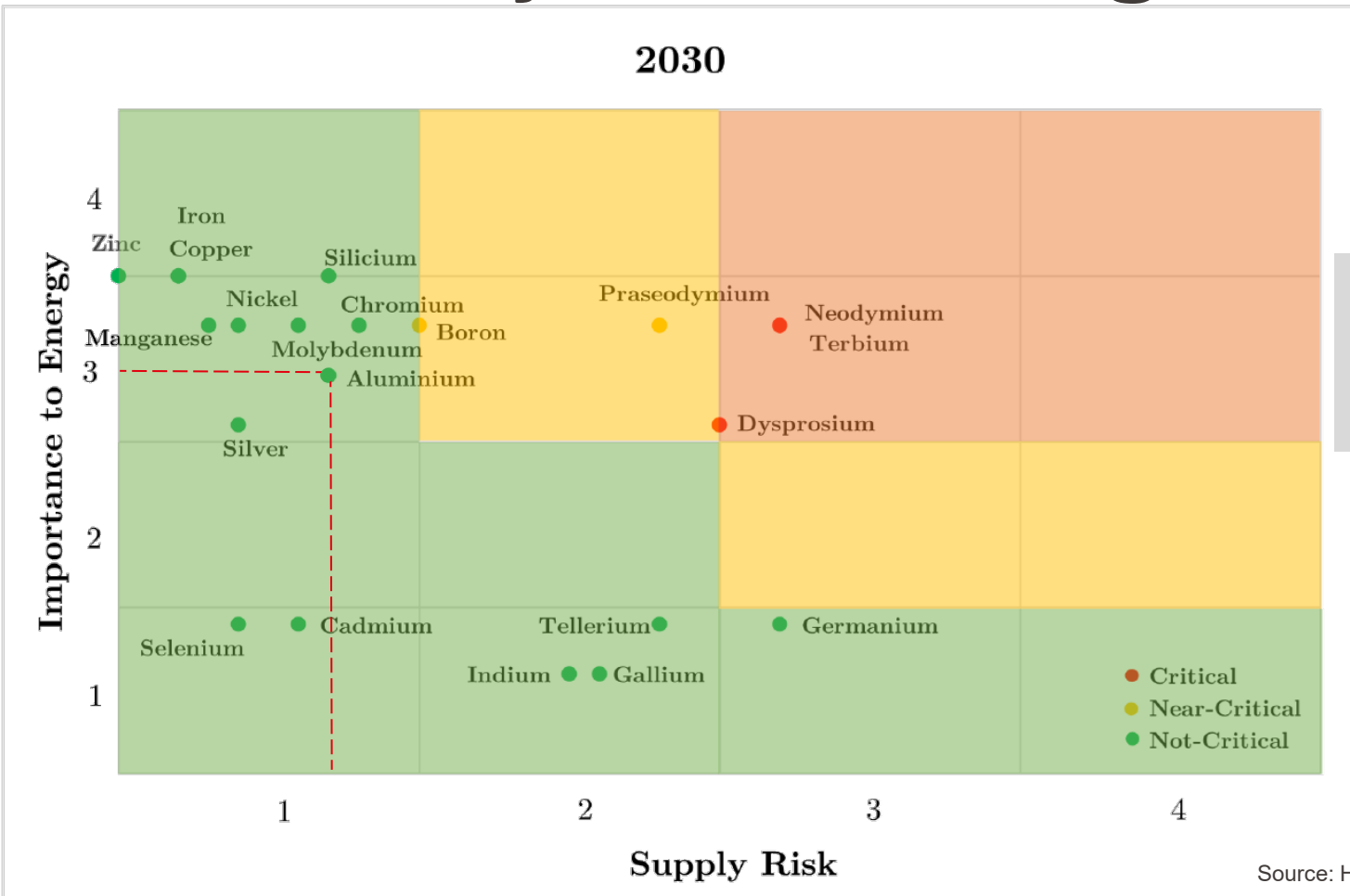
Source: HERUS laboratory, 2024, adapted from US DOE, 2023

# The criticality matrix: Scoring metrics

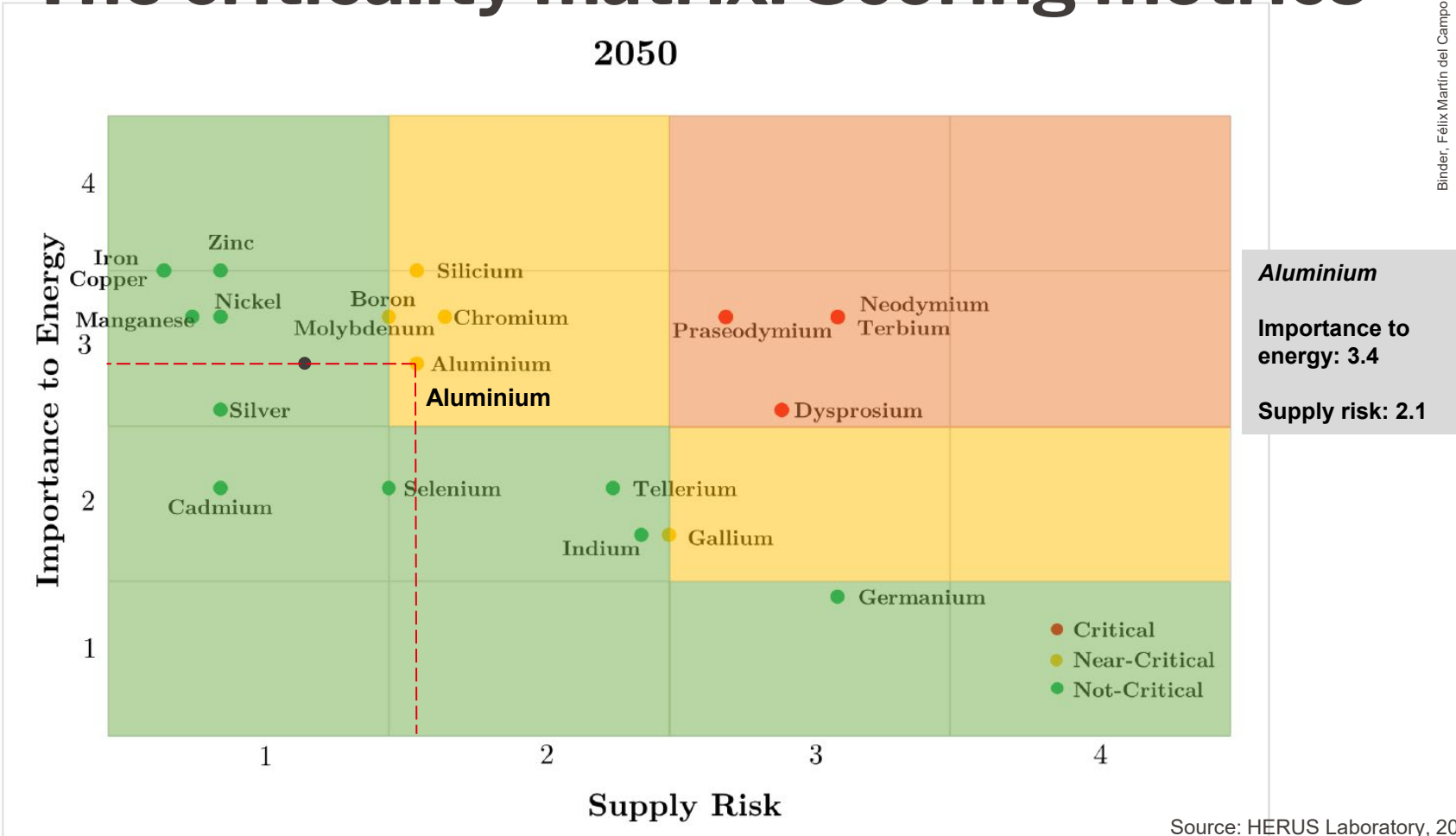
Factor	Metrics		Score				Final Score
	Name	Weight	1	2	3	4	
Importance to Energy	Energy Demand	0.7	Market share of most dominant sub-tech <10%	>=10%	>=25%	>=50%	3.4
	Substitutability Limitations	0.3	Perfect or near perfect substitutes are available at material and system levels with little to no limitations 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 level	
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 Produced as a main product in most circumstances	Most (>50%) prod is as a co/by-product of other 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 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 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

# The criticality matrix: Scoring metrics

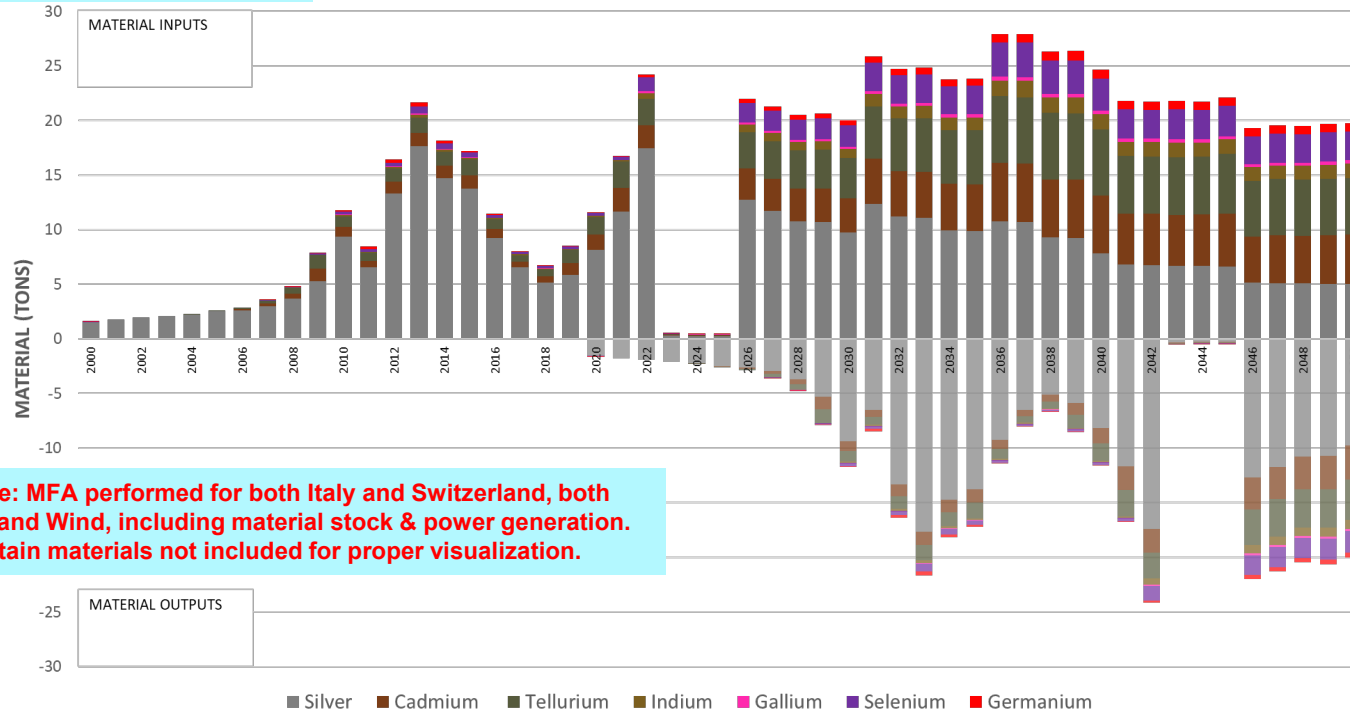


# The criticality matrix: Scoring metrics



## SAMPLE OF MFA

### SWITZERLAND - TIMSERIES PV INPUTS AND OUTPUTS



Note: MFA performed for both Italy and Switzerland, both PV and Wind, including material stock & power generation. Certain materials not included for proper visualization.

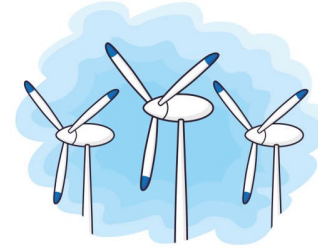
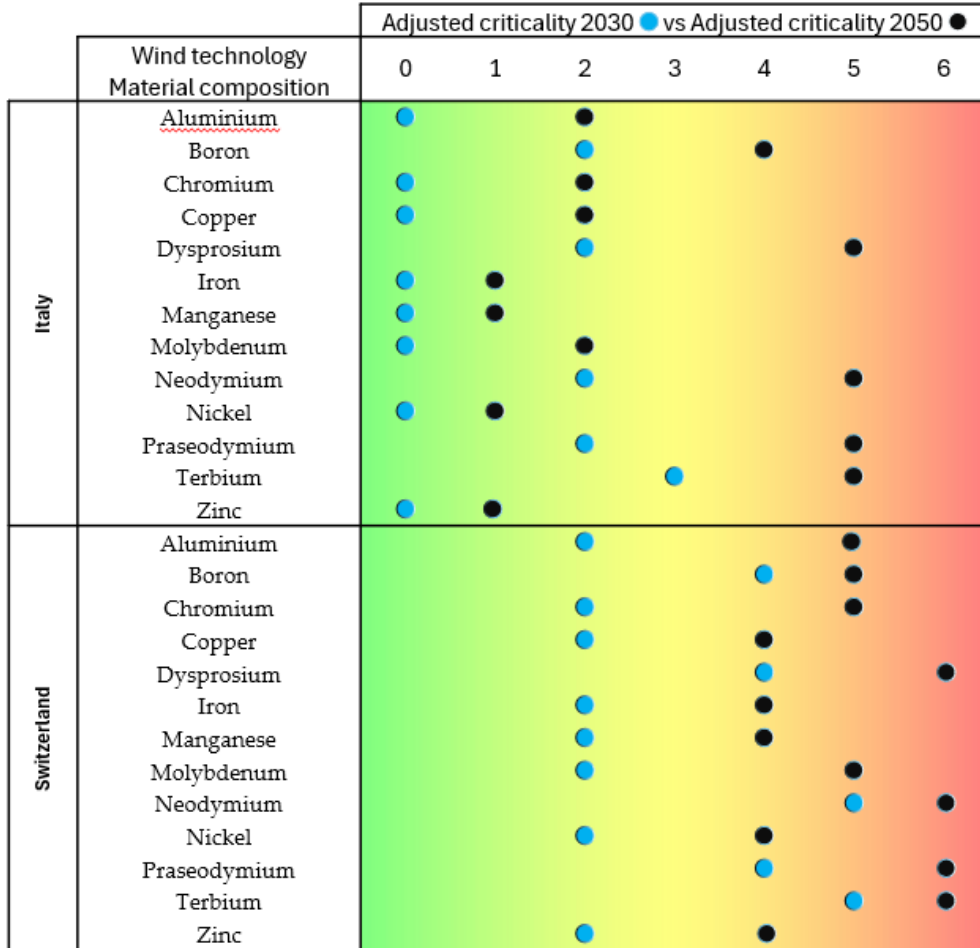
- Different energy technology deployment rates
- Inflows/outflows peaking at specific years
- Changes in material composition

# The integrated criticality



		Adjusted criticality 2030 ● vs Adjusted criticality 2050 ●						
		0	1	2	3	4	5	6
Italy	PV technology							
	Material composition							
	Aluminium			●		●		
	Cadmium		●		●			
	Copper			●	●			
	Gallium			●			●	
	Germanium		●		●			
	Indium			●		●		
	Selenium			●		●		
	Silicon		●				●	
Silver		●	●					
Tellurium		●			●			
Switzerland	Aluminium			●			●	
	Cadmium		●			●		
	Copper			●	●			
	Gallium			●			●	
	Germanium			●		●		
	Indium			●		●		
	Selenium			●	●			
	Silicon		●				●	
	Silver		●	●				
	Tellurium		●			●		

# The integrated criticality



# Criticality over time

CRMs/Lists	2011	2014	2017	2020	2023	Strategic raw materials 2023
Aluminum/Bauxite				x	x	Bismuth
Antimony	x	x	x	x	x	Boron
Arsenic					x	Cobalt (Cobaltum)
Baryte			x	x	x	Copper
Beryllium	x	x		x	x	Gallium
Bismuth			x	x	x	Germanium
Borate/Boron		x	x	x	x	Graphite (natural)
Chromium		x				Lithium
Cobalt (Cobaltum)	x	x	x	x	x	Magnesium
Coking coal		x	x	x	x	Manganese
Feldspar					x	Nickel
Fluorspar (Fluorite)	x	x	x	x	x	Platinum group metals
Gallium	x	x	x	x	x	Ruthenium
Germanium	x	x	x	x	x	Rhodium
Graphite (natural)	x	x		x	x	Palladium
Hafnium			x	x	x	Osmium
Helium			x		x	Iridium
Indium	x	x	x	x		Platinum
Lithium				x	x	Rare earths for magnets
Magnesite		x				Cerium
Magnesium	x	x	x	x	x	Dysprosium
Manganese					x	Gadolinium
Natural rubber			x	x		Neodymium
Nickel					x	Praseodymium
Niobium	x	x	x	x	x	Samarium
Phosphate rock		x	x	x	x	Terbium
Phosphorus			x	x	x	Silicon metal (Silicium)
Platinum	x	x	x	x	x	Titanium
Platinum group metals					x	Tungsten
Heavy Rare Earths	x	x	x	x	x	
Light Rare Earth	x	x		x	x	
Scandium			x	x	x	
Silicon metal		x	x	x	x	
Strontium				x	x	
Tantalum	x		x	x	x	
Titanium				x	x	
Tungsten	x	x	x	x	x	
Vanadium			x	x	x	

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Critical by 2030 (score $\geq$ 4)	Critical by 2050 (score $\geq$ 4)	Non critical by 2030 (score $\leq$ 2)	Non critical by 2050 (score $\leq$ 2)
Boron	Aluminium/Bauxite	Aluminium/Bauxite	Silver
Dysprosium	Boron	Chromium	
Neodymium	Cadmium	Cadmium	
Praseodymium	Chromium	Copper	
Terbium	Copper	Gallium	
	Dysprosium	Germanium	
	Gallium	Indium	
	Germanium	Iron	
	Indium	Manganese	
	Iron	Molybdenum	
	Manganese	Nickel	
	Molybdenum	Selenium	
	Neodymium	Silicon	
	Praseodymium	Silver	
	Selenium	Tellurium	
	Silicon	Zinc	
	Tellurium		
	Terbium		
	Zinc		

- **Solutions to problems are sensitive to methodological choices.** A **combined approach** (e.g., quasi-dynamic MFA + criticality matrix) represents **one possibility** rather than a universal standard
- **For the example shown: Using MFA as the basis**, the combined approach captures how **local energy strategies, deployment trajectories, and recycling rates** shape material stress patterns, offering policy-relevant insights.

**Thank you for your  
attention!**

