SH2E

SH2E Spring School (20-24 May 2024)

Environmental life cycle assessment of hydrogen systems II – Criticality assessment of hydrogen systems

Christina Wulf, Andrea Schreiber
(Forschungszentrum Jülich)

Co-funded by the European Union

Clean Hydrogen Partnership

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101007163. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation program, Hydrogen Europe and Hydrogen Europe Research.

CHRISTINA WULF

- Head of the team Life Cycle Sustainability Assessment Methods at the Institute of Energy and Climate Research – Jülich Systems Analysis
- Fields of Research
  - Life Cycle (Sustainability) Assessment
  - Multi-Criteria Decision-Analysis
  - Specialization on hydrogen energy systems
- Background
  - Since 2015 at FZJ
  - PhD from the Hamburg University of Technology, Institute of Environmental Technology and Energy Economics
  - Engineer

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CRITICALITY ASSESSMENT OF HYDROGEN SYSTEMS

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Founded in 1956

Revenue:
€ 948 million in 2022

Research priorities:
information, energy, bioeconomy

Research campus with 11 institutes and
18 branch offices in Germany and abroad

Shareholders:
Federal Republic of Germany (90%), federal state of North Rhine-Westphalia (10%)

Member of the Helmholtz Association

Co-funded by the European Union

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2,801 publications in 2022

Nobel Prize in Physics 2007: Peter Grünberg

Shaping change:

We conduct research into options for a digital society, a climate-friendly energy system, and a resource-efficient economy. We combine the natural, life, and engineering sciences with specialist expertise in high-performance computing and we also deploy unique scientific infrastructures.

Programme-oriented funding (PoF):

Energy

Earth & Environment

Matter

Information

19 research infrastructures

78 patent applications in 2022

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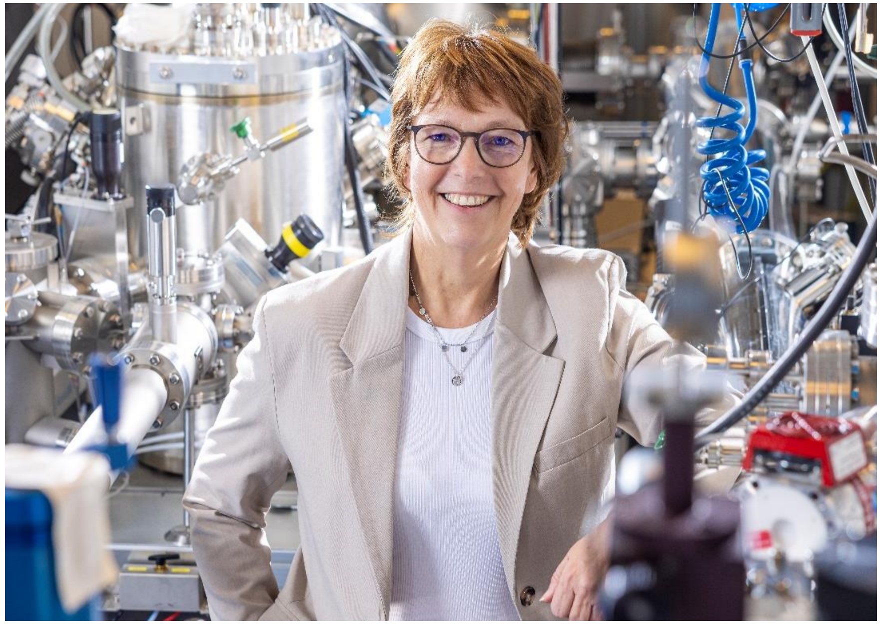
1,595

technical and laboratory employees

2,891

scientists



We seek to be a pioneer in catalysing transformation and progress in society.

Almost 7,250 employees from 111 countries

937

administrative

employees

Involvement in 572 national research projects

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67

joint professorial

appointments within the

Jülich Aachen Research Alliance (JARA)

Our network:

164 joint professorial appointments with 18 universities in Germany and Europe

Involvement in

176 EU projects; coordination of 31 of these

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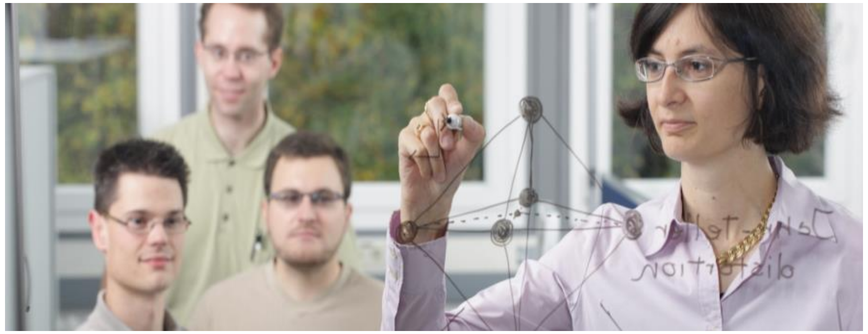

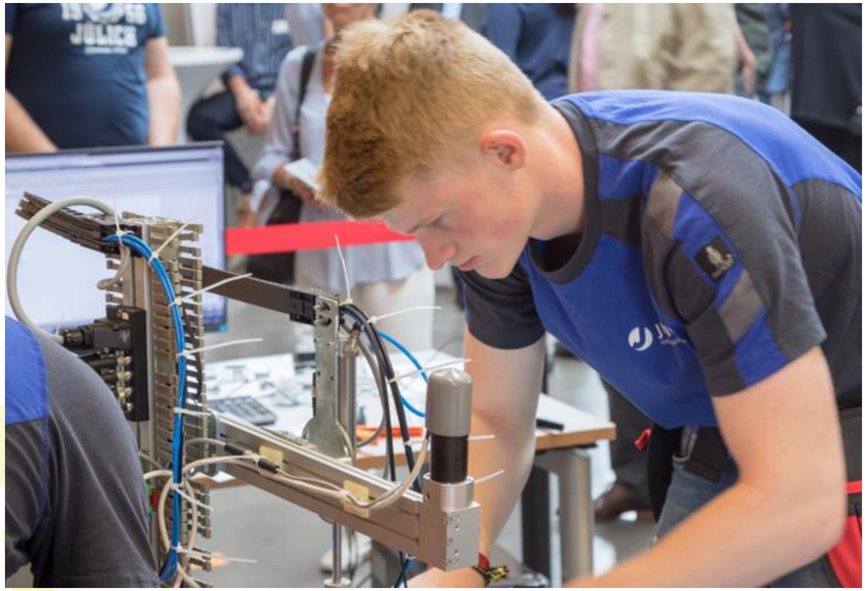

284 trainees and students on placement in over 20 occupations

International:

1,217 visiting scientists from 79 countries

1,364 doctoral researchers, 43 % from abroad

309 postdocs 50 % from abroad

Diversity is a requirement for success in our work.

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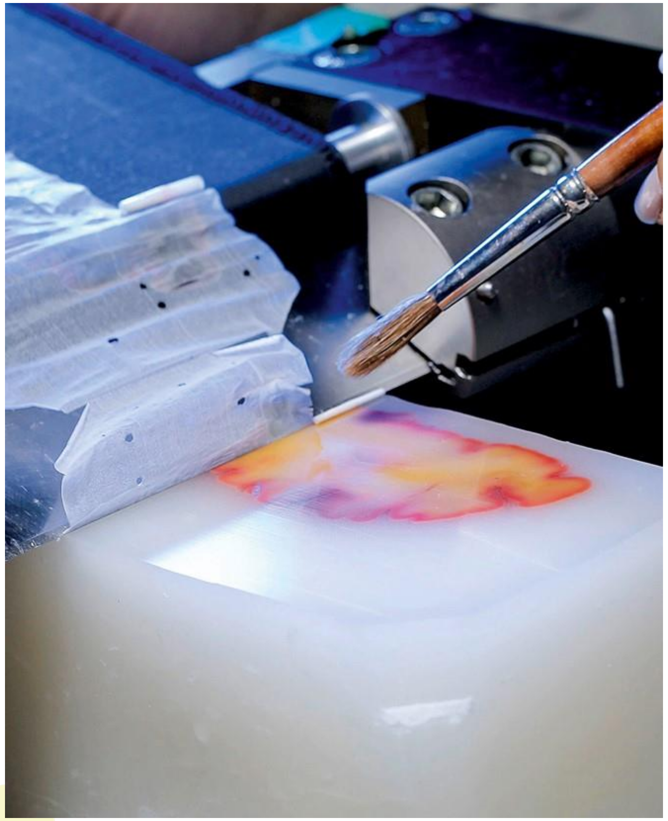

Information

Bioeconomy

Energy

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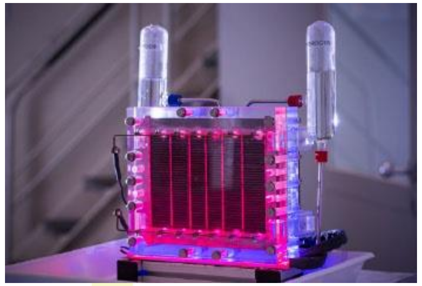
We conduct research for a climate-friendly energy system:

… by developing new materials,

… by integrating new components into innovative process chains,



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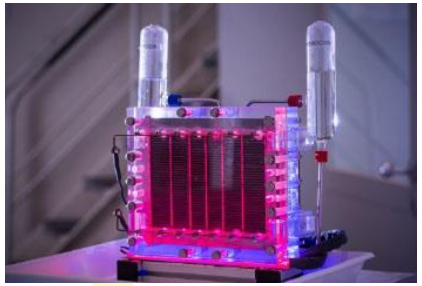
… while taking a holistic approach to the system

… and always taking into account air quality and the climate.



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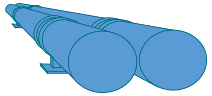
Societal feasibility

Renewable Energy Resources

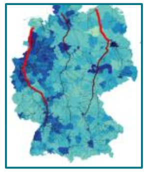
Electricity transmission & distribution grids

Gas transmission grid



Technology Database

H_2 and PtX Infrastructure



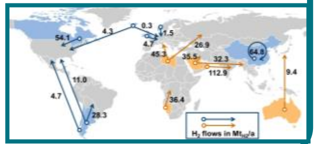
Macro-economics

Sustainability Assessment

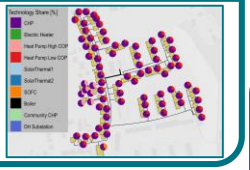
JÜLICH SYSTEMS ANALYSIS

Buildings

H_2 global

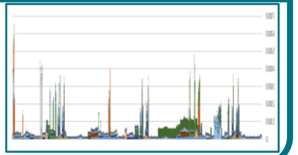


Districts

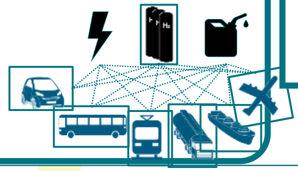


Activity-based transport demand

From demand to load profile



Transport sector
– Passenger
– Freight



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DEPARTMENT SUSTAINABLE LIFE CYCLES

Methodology development for Sustainability Assessment:

- Life cycle approach
- Widening environmental assessment by economic and social dimension
- Prospectivity in LCSA
- Multi criteria decision analysis, MCDA

Technology expertise:

- Power-to-X (electrolyzer, fuel cells, PtFuels, PtSyngas, PtChemicals)
- CO2-reduction (CCUS, DAC, batteries, PV, wind)
- Resource supply technologies (Al, Cu, RE)
- Bio-based value chains (energy, surfactants, aerogels, batteries)

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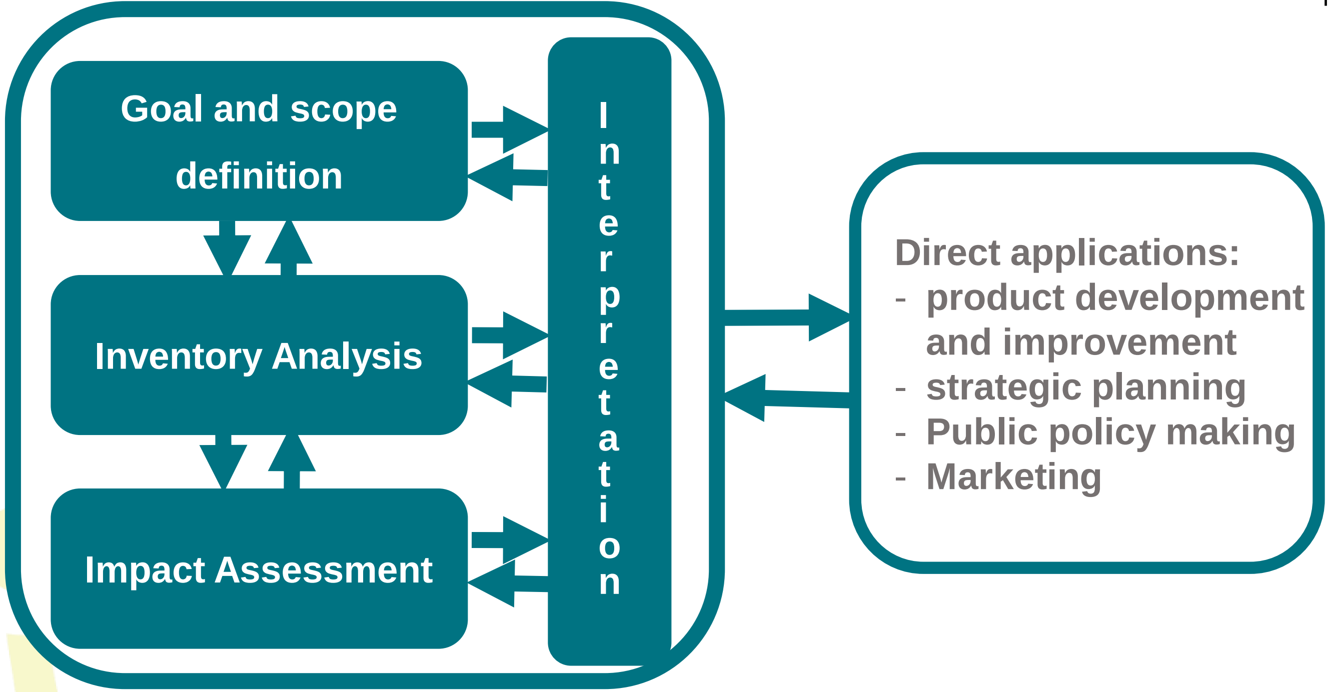
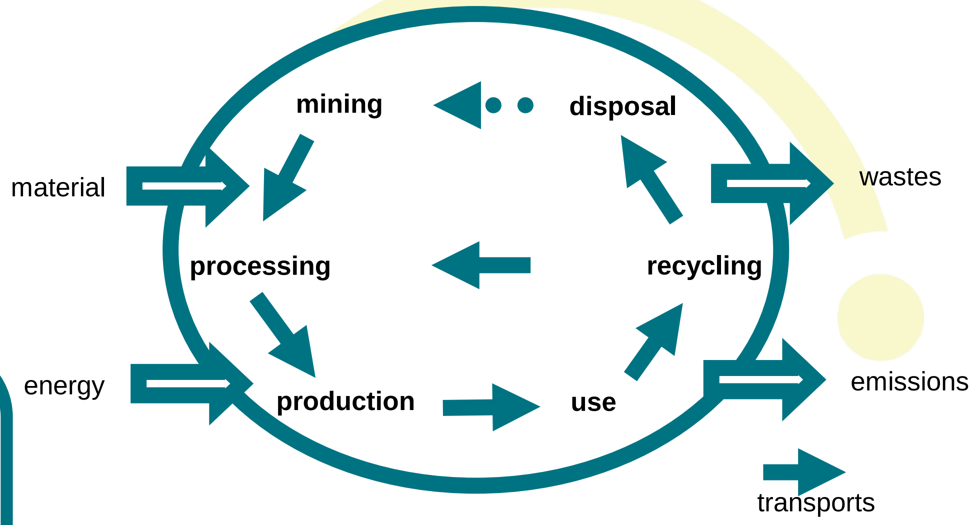
INTRODUCTION – WHAT IS LCA?

“LCA is a tool for the analysis of the **environmental burden** of products at all stages in their **life cycle**” (Van der Heede and De Belie 2012)



“LIFE CYCLE THINKING” – FROM CRADLE-TO-GRAVE



International Organization for Standardization

Source: ISO 14040, 14044

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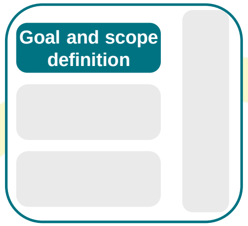
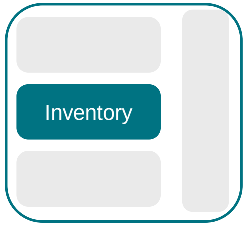
INTRODUCTION – WHAT IS LCA?

The goal and scope of the study shall be clearly defined and consistent with the intended application

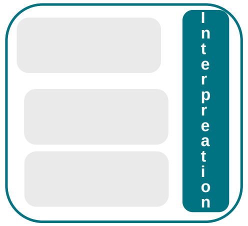


Inventory analysis (LCI) involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system



Impact assessment (LCIA) aims at evaluating the significance of potential impacts using the results of the inventory

Interpretation deliver results that are consistent with the goal and scope, and which reach conclusions, explain limitations and provide recommendations



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INTRODUCTION – WHAT IS LCA?

DIFFERENT TECHNOLOGIES CAUSE DIFFERENT ENVIRONMENTAL IMPACTS:

Climate change

Water scarcity

Eutrophication

Acidification

Resource depletion

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INTRODUCTION – WHAT IS LCA?

POTENTIAL IMPACTS

• Climate Change	GWP	kg CO_2 eq.
• Eutrophication potential	EP	kg P eq./kg N eq.
• Acidification	AP	kg SO_2 eq.
• Human toxicity	HTP	kg 1,4-DCB eq.
• Ecotoxicity	FAETP / MAETP / TETP	kg 1,4-DCB eq.
• Resource depletion	ADP	kg Sb eq.
• Water use		m^3 world eq.
• Land use		m^2a
• ….		

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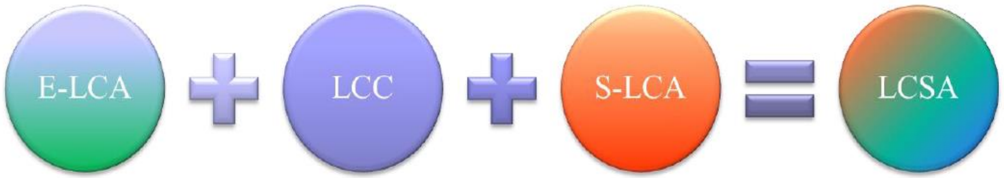
INTRODUCTION – WHAT IS LIFE CYCLE SUSTAINABILITY ASSESSMENT (LCSA)?

KEEPING THE LIFE CYCLE APPROACH BY COMBINING ENVIRONMENTAL ASSESSMENT (E-LCA), LIFE CYCLE COSTING (LCC) AND SOCIAL ASSESSMENT (S-LCA)



Environmental Evaluation

Economic Evaluation

Social Evaluation

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INTRODUCTION – WHAT IS LIFE CYCLE SUSTAINABILITY ASSESSMENT (LCSA)?

E-LCA is "…a tool for the analysis of the **environmental** burden of products at all stages in their life cycle…."

LCC is "…an assessment of all **costs** associated with the life cycle of a product that are directly covered by anyone or more of the actors in the product life cycle…."

S-LCA is "…an impact assessment technique that aims to assess the social and socio-economic aspects of products and their potential positive and negative impacts along their life cycle…."

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INTRODUCTION – WHAT IS LIFE CYCLE SUSTAINABILITY ASSESSMENT (LCSA)?

TYPICAL LCC INDICATORS:

- Investment costs
- Variable operation and maintenance costs
- Fixed operation and maintenance costs (wages, taxes, heating, lighting)
- Levelized costs of electricity (Σ Invest, fix & variable O&M)
- Internalized external effects (CO_2 taxes)

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INTRODUCTION – WHAT IS LIFE CYCLE SUSTAINABILITY ASSESSMENT (LCSA)?

STAKEHOLDER GROUPS AND TYPICAL S-LCA INDICATORS:

- **Workers**
  - Child labor
  - Fatal accidents
  - Fair salary
- **Local communities**
  - Unemployment rate
  - Drinking water coverage
  - Indigenous rights
- **Society**
  - Illiteracy
  - Contribution to economic development
- **Consumers**
  - Deceptive or unfair business practices
  - End of life responsibility
- **Value chain actors**
  - Fair competition
  - Corruption

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CRITICALITY ASSESSMENT OF HYDROGEN SYSTEMS

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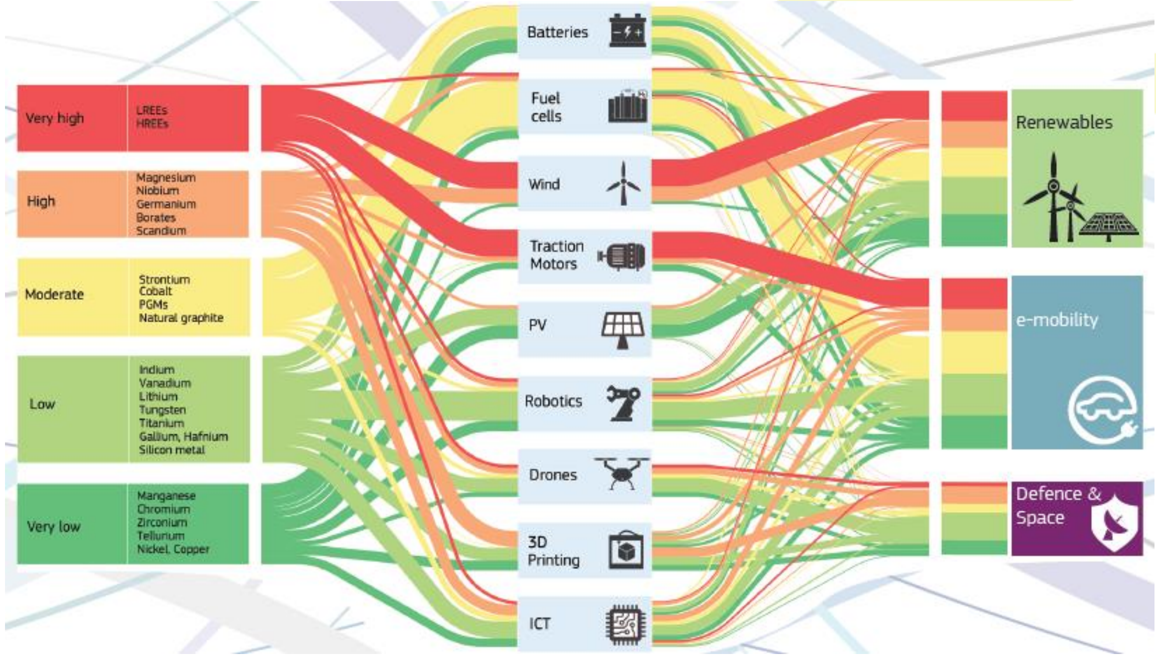
MOTIVATION FOR RESOURCE CRITICALITY ASSESSMENT

- Transformation of the energy system requires a high intensity of mineral raw materials
- Continuous and secure supply of raw materials is highly relevant
- Raw material criticality: assessment of vulnerability to supply disruptions



Source: EC, Joint Research Centre, 2020, Critical Raw Materials for Strategic Technologies and Sectors in the EU - A Foresight Study

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MOTIVATION FOR RESOURCE CRITICALITY ASSESSMENT

ENERGY-RELATED TECHNOLOGY APPLICATIONS

Global demand for certain raw materials will increase dramatically

		Main	Other
27 Co	Cobalt	• EV batteries	• Battery storage • Bioenergy • Electrolysers
29 Cu	Copper	• Electricity grid • EV batteries • Solar PV	• Battery storage • Bioenergy • CSP • Electrolyser • Geothermal • Hydro
66 Dy	Dysprosium	• EV motors • Wind	
6 C	Graphite	• EV batteries	• Battery storage
77 Ir	Iridium	• PEM Electrolysers	
3 Li	Lithium	• EV batteries	• Battery storage
25 Mn	Manganese	• EV batteries	• Battery storage • CSP • Electrolysers • Geothermal • Hydro • Wind
60 Nd	Neodymium	• EV motors • Wind	
28 Ni	Nickel	• Electrolyser • EV batteries	• Battery storage • Bioenergy • CSP • Geothermal • Hydro • Solar PV
78 Pt	Platinum	• PEM Electrolysers	

Source: IRENA (2023), Geopolitics of the energy transition: Critical materials, Int. Renewable Energy Agency, Abu Dhabi

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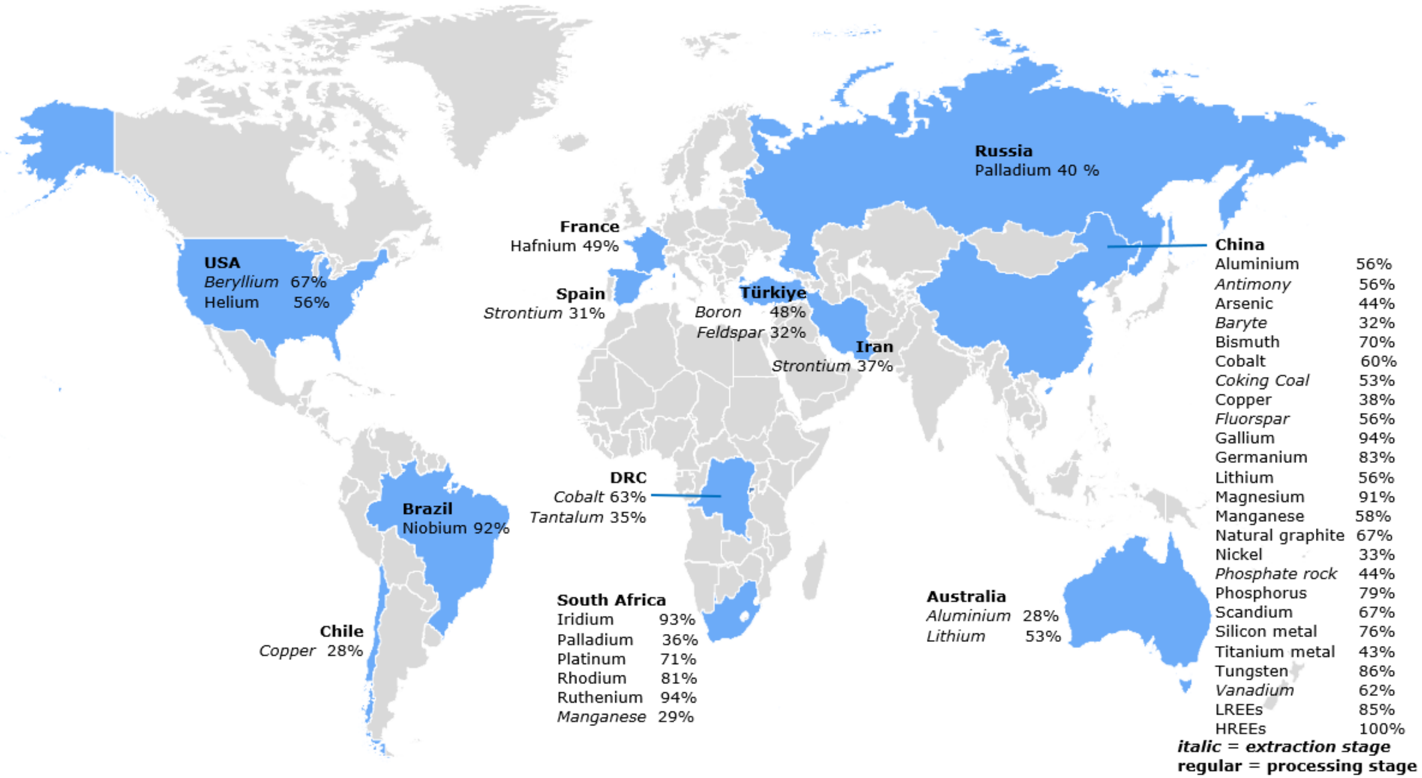
MOTIVATION FOR RESOURCE CRITICALITY ASSESSMENT

- EU is highly dependent on Critical Raw Material (CRM) imports
- CRMs subject to supply disruption
  → obstacle for a climate neutral economy by 2050
- European Critical Raw Materials Act (EC-CRM): Framework for ensuring a secure and sustainable supply of CRMs (March 2023)



Source: EC 2023

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MOTIVATION FOR RESOURCE CRITICALITY ASSESSMENT

KEY MINING COUNTRIES FOR SOME MINERALS

Iridium (77 Ir)	
South Africa	88.9%
Zimbabwe	8.1%
Russian Federation	2.9%
Others	0.1%

Dysprosium (Dy)	
China	48.7%
Myanmar	23.1%
Australia	7.6%
United States	2.9%
Canada	2.7%
Others	15.0%

Neodymium (60 Nd)	
China	45.8%
Australia	23.1%
Greenland*	8.2%
Myanmar	7.4%
Brazil	4.4%
India	2.1%
Others	9.0%

Platinum (Pt)	
South Africa	73.6%
Russian Federation	10.5%
Zimbabwe	7.8%
Canada	3.1%
United States	1.7%
Others	3.3%

Cobalt (Co)	
Democratic Republic of the Congo	70.0%
Indonesia	5.4%
Russian Federation	4.8%
Australia	3.2%
Canada	2.1%
Cuba	2.0%
Philippines	2.0%
Others	10.5%

Nickel (Ni)	
Indonesia	48.8%
Philippines	10.1%
Russian Federation	6.7%
France (New Caledonia)	5.8%
Australia	4.9%
Canada	4.0%
China	3.3%
Brazil	2.5%
Others	13.9%

Copper (29 Cu)	
Chile	23.6%
Peru	10.0%
Democratic Republic of the Congo	10.0%
China	8.6%
United States	5.9%
Russian Federation	4.5%
Indonesia	4.1%
Australia	3.7%
Zambia	3.5%
Mexico	3.3%
Kazakhstan	2.6%
Canada	2.4%
Poland	1.7%
Others	16.1%

Source: IRENA (2023), Geopolitics of the energy transition: Critical materials, Int. Renewable Energy Agency, Abu Dhabi

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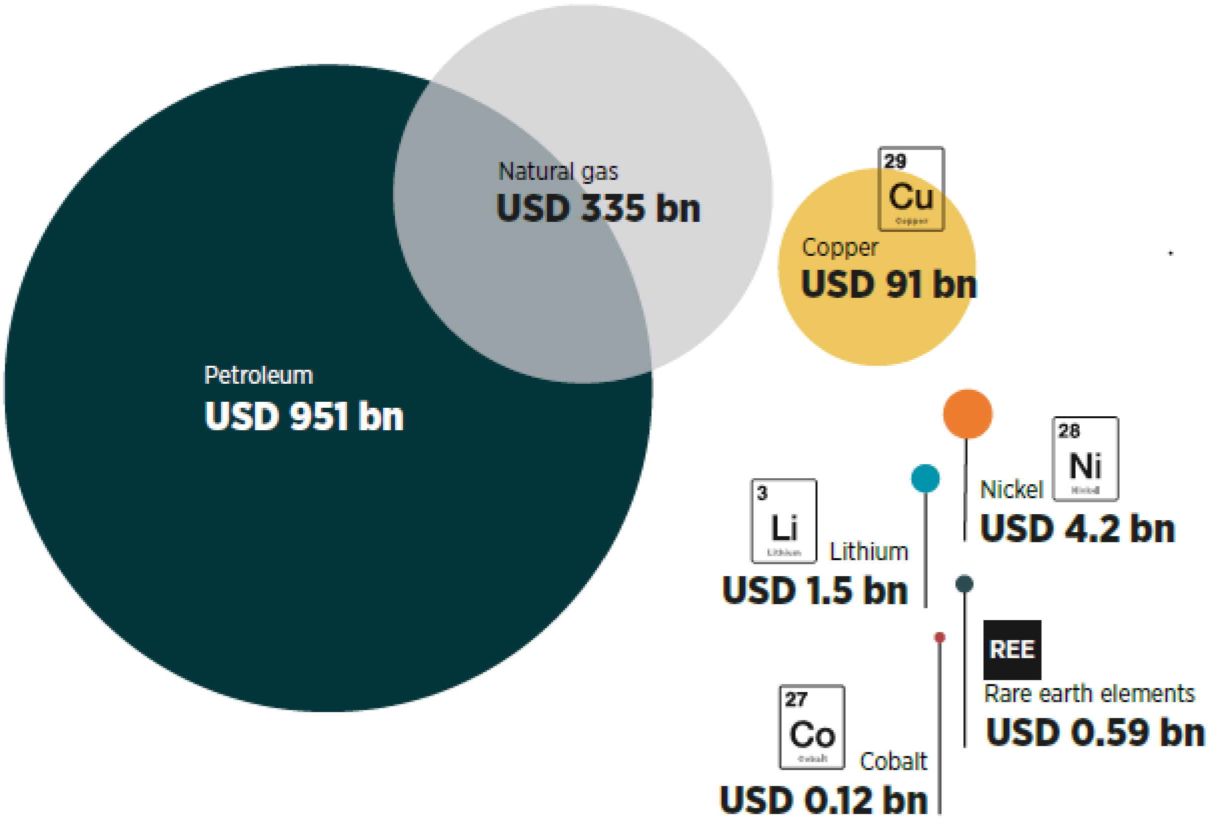
MOTIVATION FOR RESOURCE CRITICALITY ASSESSMENT

VALUE OF EXPORTS FOR SELECTED COMMODITIES (2021): COMPARISON OF FOSSIL AND MINERAL RESOURCES



Source: IRENA (2023), Geopolitics of the energy transition: Critical materials, Int. Renewable Energy Agency, Abu Dhabi

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MOTIVATION FOR RESOURCE CRITICALITY ASSESSMENT

KEY GEOPOLITICAL RISKS TO THE SUPPLY OF MATERIALS

1	**External shocks**	Natural disasters, pandemics, wars, mine accidents, etc.
2	**Resource nationalism**	Tax disputes, expropriation, foreign investment screening, etc.
3	**Export restrictions**	Export quotas, export taxes, obligatory minimum export prices, licensing, etc.
4	**Mineral cartels**	Co-ordination of production, pricing, market allocation, etc.
5	**Political instability and social unrest**	Labour strikes, violence, corruption, etc.
6	**Market manipulation**	Short squeezing, market cornering, spoofing, insider trading, etc.

Source: IRENA (2023), Geopolitics of the energy transition: Critical materials, Int. Renewable Energy Agency, Abu Dhabi

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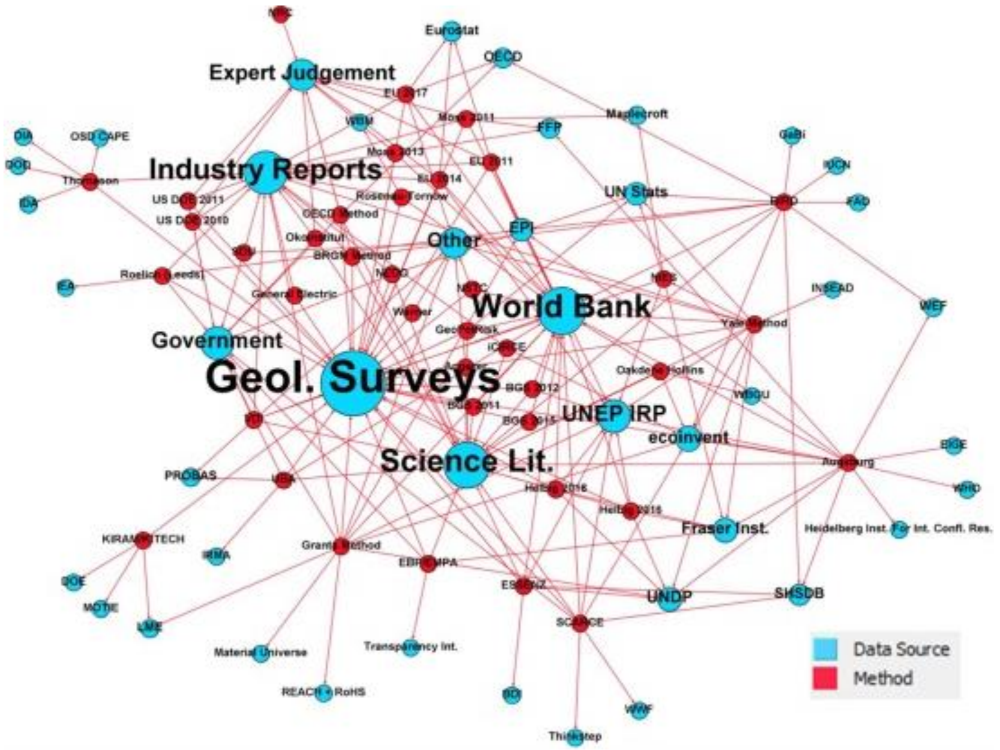
CRITICALITY IN LCA



Source: Schrijvers D, Hool A, Blengini GA, et al. (2020) A review of methods and data to determine raw material criticality. Resources, Conservation and Recycling 155:104617.

- Resource assessment ongoing discussion within LC(S)A community
- Confusion due to the ambiguity of terms such as scarcity, rarity, criticality, depletion
- Various methods for assessing criticality of raw materials within LCSA with different foci, scope of application, and criteria
  - EC's Critical Raw Material List
  - GeoPolRisk
  - ESSENZ
  - SCARCE
  - VDI approach
  - YALE approach
  - British Geology Survey (BGS)
  - Erdmann & Graedel 2011
  - …..

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CRITICALITY IN LCA

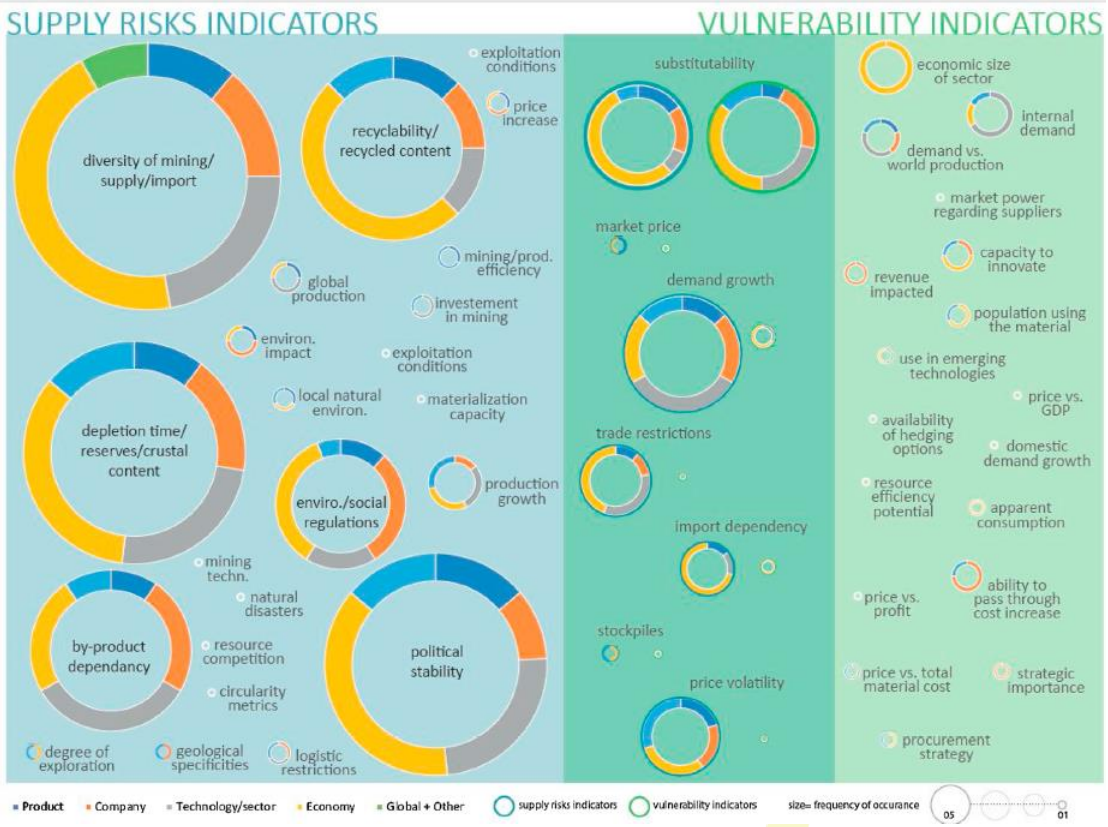
VARIETY OF INDICATORS FOR ASSESSING CRITICALITY OF RAW MATERIALS

Supply risk

- Reserves
- Depletion time
- Crustal content
- Global production
- By-product dependency
- Circularity
- Recyclability

Vulnerability

- Price
- Trade restrictions
- Substitutability
- Import dependency



Source: Schrijvers et al. 2020

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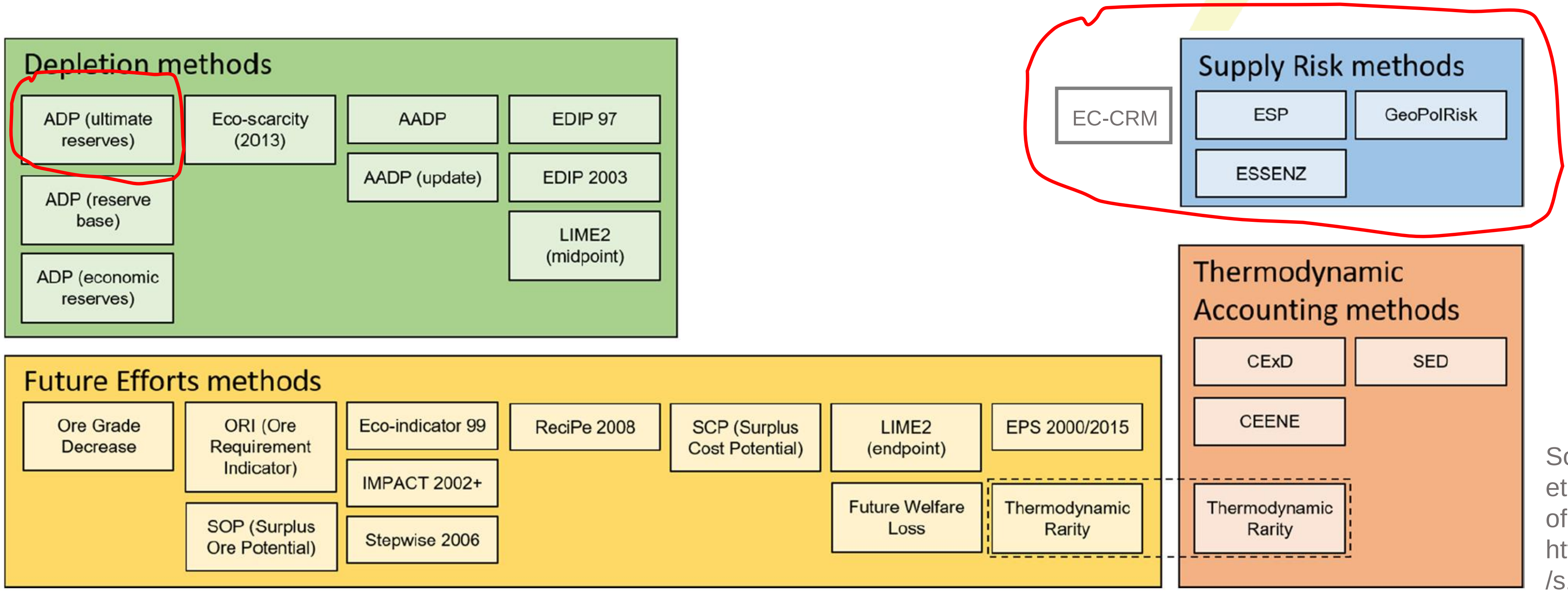
CRITICALITY IN LCA

LIFE CYCLE INITIATIVE: EXPERT TASK FORCE ON MINERAL RESOURCES

- SCREENING OF VARIOUS METHODS FOR ASSESSING THE IMPACTS OF MINERAL RESOURCE USE IN FOUR METHODOLOGY SECTIONS



Source: Sonderegger et al. 2020 The Int. J. of LCA, https://doi.org/10.1007/s11367-020-01736-6

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CRITICALITY AND THE EU

EC'S CRITICAL RAW MATERIAL LIST (EC-CRM)

Ongoing report by the EC with resulting list of CRM's is updated every three years (2011, 2014, 2017, 2020, 2023)

Critical Raw Materials Act (**CRMA**): Final approval for a strategy to secure a sustainable supply of critical raw materials (March 2024). Targets for covering the EU's own annual raw material requirements:

- min. 10% of ores and concentrates
- min. 40% refined products
- min. 25% from recycling from the EU
- max. 65% of the import volume of a raw material from a third country

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CRITICALITY ASSESSMENT OF HYDROGEN SYSTEMS

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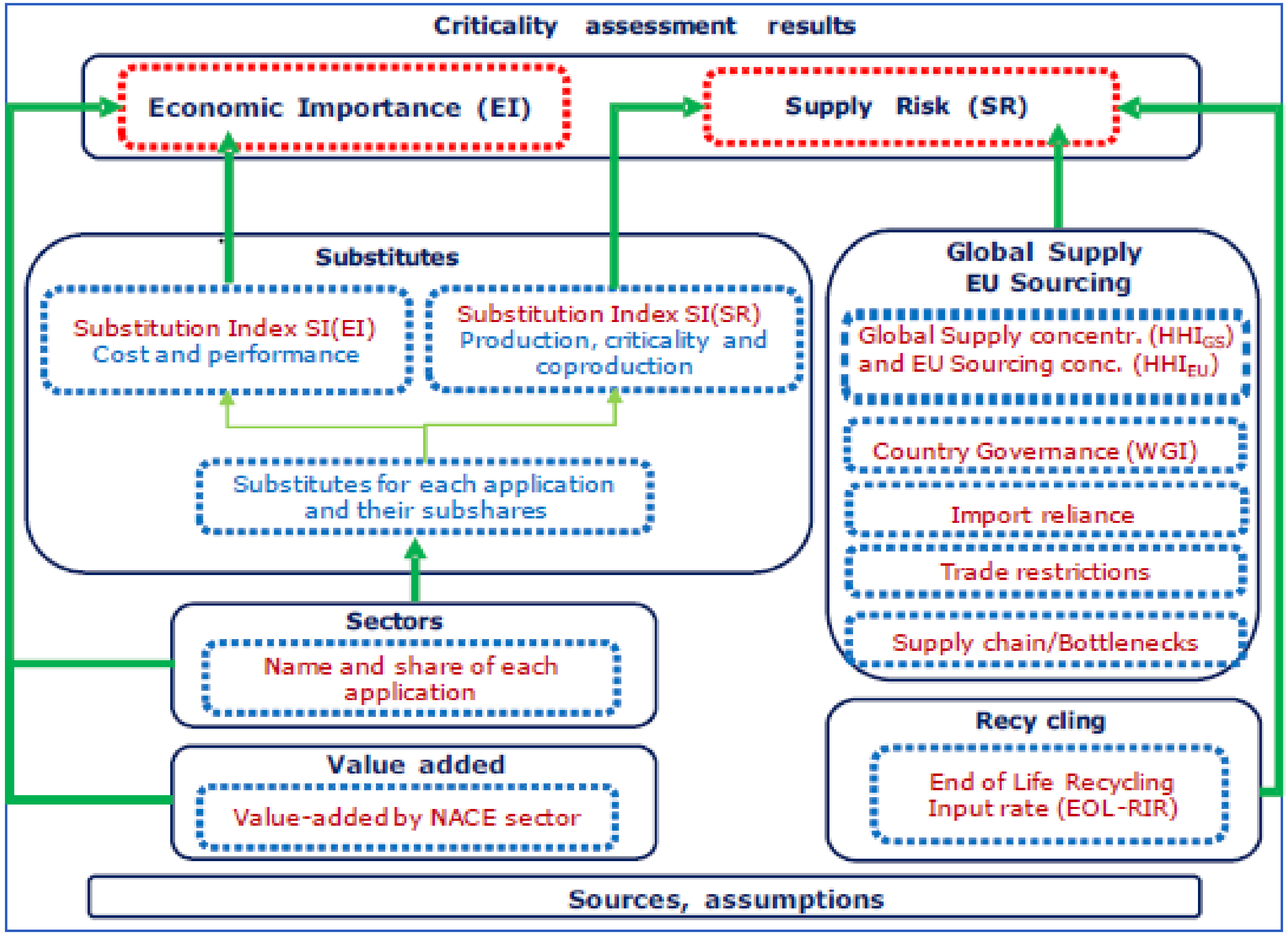
FROM THE EU APPROACH TO AN LCA II

EC'S CRITICAL RAW MATERIAL LIST (EC-CRM)

Both indicators (EI, SR) must exceed a criticality threshold (SR > 1, EI > 2.8) for a material to be classified as critical



Source: EC 2023

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FROM THE EU APPROACH TO AN LCA IMPACT ASSESSMENT

EC'S CRITICAL RAW MATERIAL LIST (EC-CRM)

Calculation of Supply Risk (SR) and Economic Importance (EI)

$$SR = \left[HHI_{gs} \cdot \frac{IR}{2} + HHI_{EUsourcing} \cdot \left(1 - \frac{IR}{2}\right)\right] \cdot (1 - EoL_{RIR}) \cdot SI_{SR}$$

HHI Herfindahl-Hirschman Index
WGI Worldwide Governance Indicator
IR Import reliance
EoL_{RIR} End-of-life recycling input rate
SI Substitution index
GS Global supply

$$EI = \sum_{a} (A_S \cdot Q_S) \cdot SI_{EI}$$

As Share of material end use in a NACE sector
Qs NACE sector's value added
SI Substitution index

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FROM THE EU APPROACH TO AN LCA IMPACT ASSESSMENT

EC'S CRITICAL RAW MATERIAL LIST (EC-CRM)

Results of the 2023 EC-CRM list: 34 raw materials are considered as critical:

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 SRMs.

Source: EC 2023

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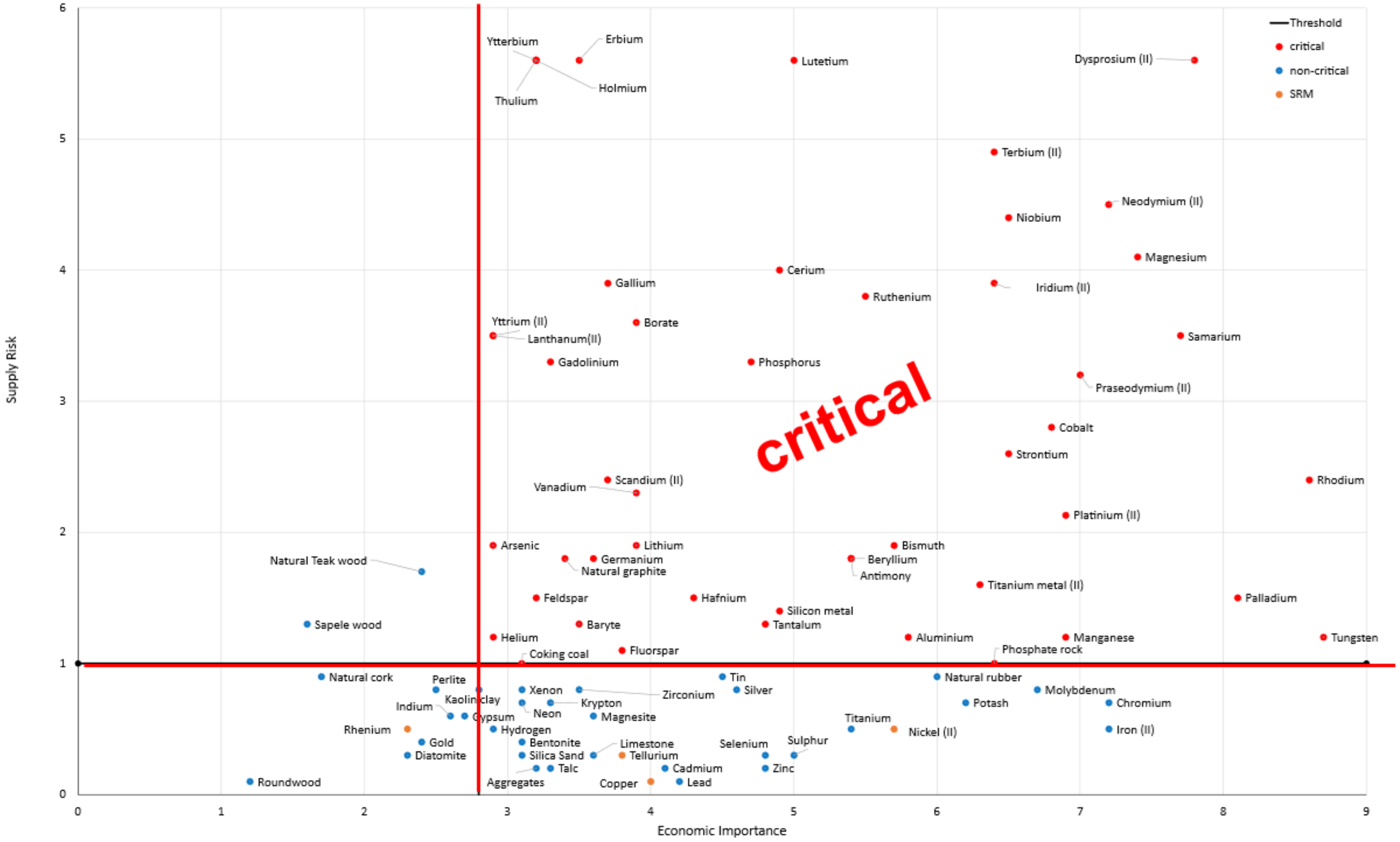
FROM THE EU APPROACH TO /

EC’S CRITICAL RAW MATERIAL LIST (EC-CRM) 2023 - RESULTS

SR/EI Matrix with the criticality threshold (red lines)



Source: EC 2023

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FROM THE EU APPROACH TO AN LCA IMPACT ASSESSMENT

CALCULATION OF MATERIAL CRITICALITY

According to Life Cycle Impact Assessment logic, a **characterization factor (CF)** is multiplied by the quantities (mass (m)) of a considered resource (i) from the Life Cycle Inventory results:

$$\mathbf{Criticality} = \sum_{i=1}^{n} CF_i \cdot m_i$$

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FROM THE EU APPROACH TO AN LCA IMPACT ASSESSMENT

CALCULATION OF OF THE CHARACTERIZATION FACTORS (CF)

New approach developed within SH_2E project

- Starting point: EC-CRM list
- combines supply risk (SR) and economic importance (EI)
- consumption is included, since a high consumption poses a high risk if the EU relies heavily on imports, and it is not recycled within the EU

$$CF = SR / (C * (1 – IR * (1 – EoL_{RIR})))$$

SR	Supply Risk (EC-CRM list 2023)
EI	Economic Importance (EC-CRM list 2023)
C	European Consumption of a material (EC Factsheet 2023 https://scrreen.eu/crms-2023/)
IR	Import Reliance (EC-CRM list 2023)
EoL_{RIR}	End-of-life recycling input rate (EC-CRM list 2023)

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FROM THE EU APPROACH TO AN LCA IMPACT ASSESSMENT

CALCULATION OF OF THE CHARACTERIZATION FACTORS (CF)

PHYSICAL AVAILABILITY

Abiotic depletion potential ADP

$$CF = \frac{\text{Extraction rate of resource i (kg/year)/Reserve}^2 \text{ of resource i (kg)}}{\text{Extraction rate of Antimony (kg/year)/Reserve}^2 \text{ of Antimony (kg)}}$$

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FROM THE EU APPROACH TO AN LCA IMPACT ASSESSMENT

CALCULATION OF OF THE CHARACTERIZATION FACTORS (CF)

GEOPOLITICAL APPROACH

GeoPolRisk methodology

- import-based indicator for the geopolitical supply risk of resources in LCSA
- method includes features similar to the EU assessment
- GeoPolRisk is at a country level, employing global shares

$$CF = \left[\left(\sum_{k=1}^{n} s_k^2\right) * \left(\sum_{k=1}^{n} g_k * f_{i,k}\right)\right]$$

SR Supply risk of country i concerning commodity c
s_k share of country k in global production of commodity c
g_k political instability indicator of country k (derived from WGI)
$F_{i,k}$ Import share of country k in the supply chain of country i

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FROM THE EU APPROACH TO AN LCA IMPACT ASSESSMENT

CALCULATION OF OF THE CHARACTERIZATION FACTORS (CF)

BINARY APPROACH USING EC-CRM

- combines supply risk (SR) and economic importance (EI)
- materials defined as ‘critical’ if SR ≥ 1 and EI ≥ 2.8
- output: list of CRMs, updated every 3 years, 34 CRM in 2023

CF = Mass of CRMs

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CRITICALITY ASSESSMENT OF HYDROGEN SYSTEMS

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1. Introduction FZJ
2. Introduction of LCA and LCSA
3. Motivation for resource criticality assessment
4. Criticality in LCA
5. From the EU approach to an LCA impact Assessment
6. **Case study**
7. Summary
8. Start your own criticality assessment

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CASE STUDY

Manufacturing of 1 m^2 of cell area for alkaline water electrolysis (AEL), proton exchange membrane electrolysis (PEM-EL) and solid oxide electrolysis (SOEC)

Required materials for manufacturing of 1 m^2 cell area:

AEL	Mass, g	PEM-EL	Mass, g	SOEC	Mass, g
Nickel	6987	Titanium	9689	LSCF	72
Zirfon	122	Platinum	43	CGO	75
Polyphenylene sulfide	1944	Iridium	13	YSZ	283
Stainless steel	2328	Stainless steel	1185	Stainless steel	15,420
		Nafion	167	Glass ceramic	20
		Carbon paper	198	MCO	
		Rubber	21		
		Ink materials	202		

Source: Zhao G, Kraglund MR, Frandsen HL, Wulff AC, Jensen SH, Chen M, Graves CR (2020) Life cycle assessment of H2O electrolysis technologies. International Journal of Hydrogen Energy 45 (43):23765-23781

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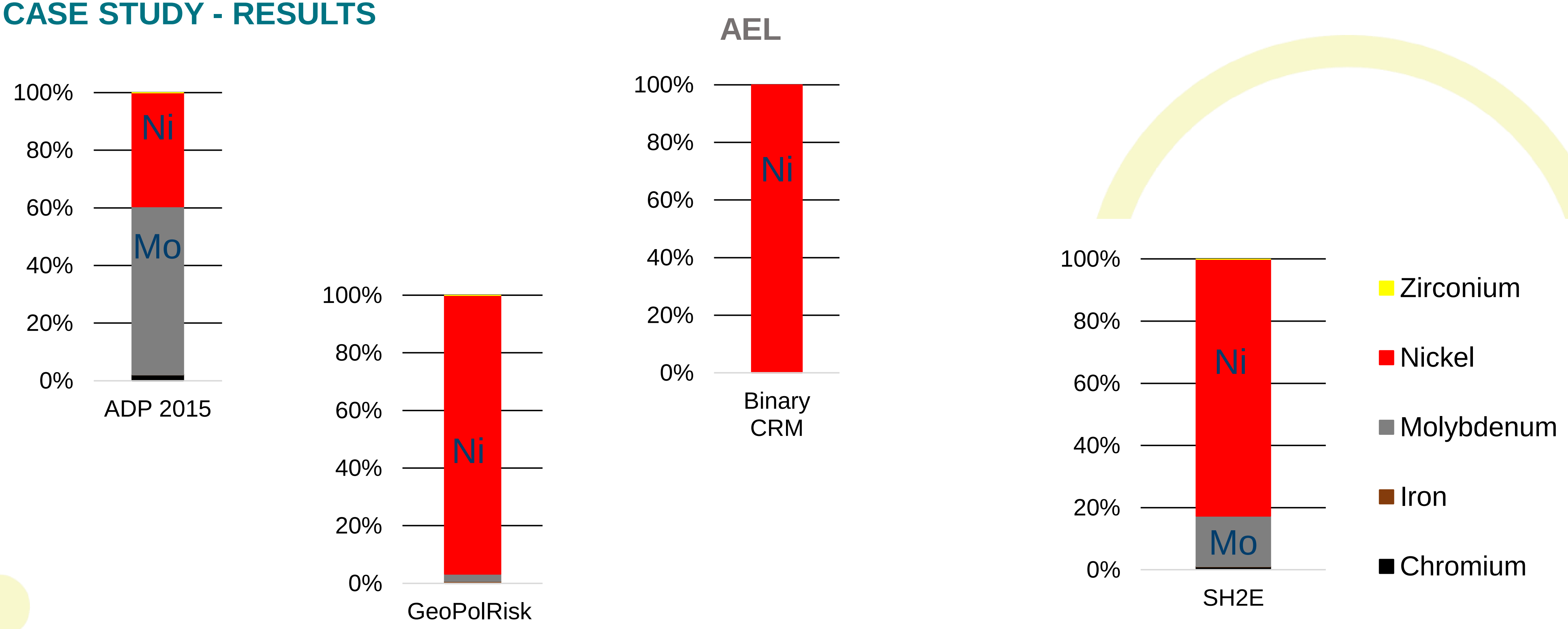
CASE STUDY - RESULTS



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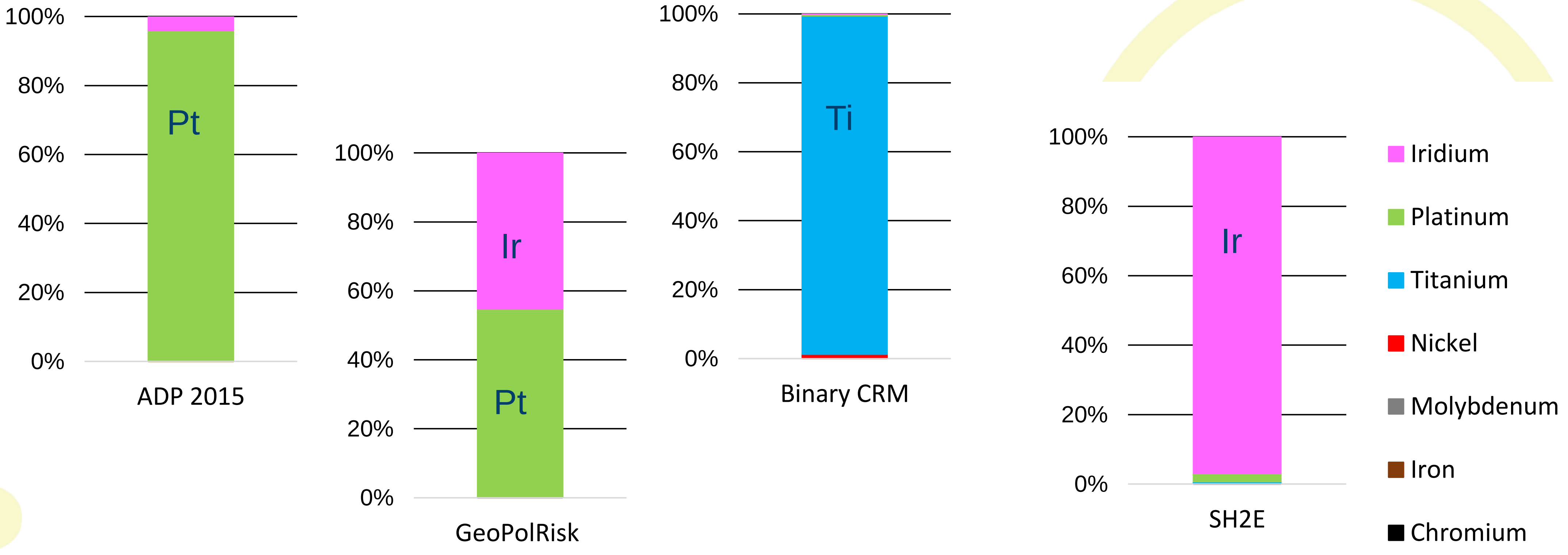
CASE STUDY - RESULTS

PEM-EL



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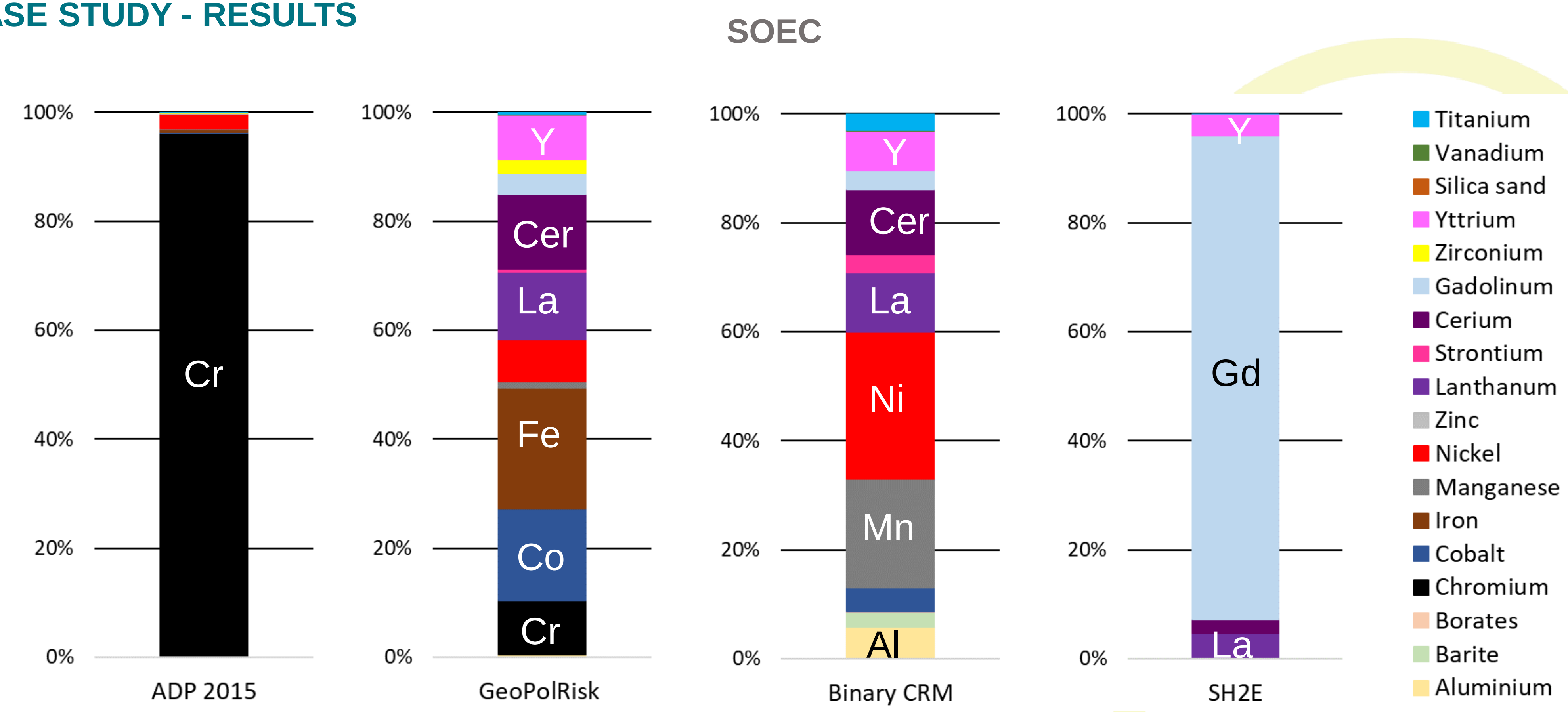

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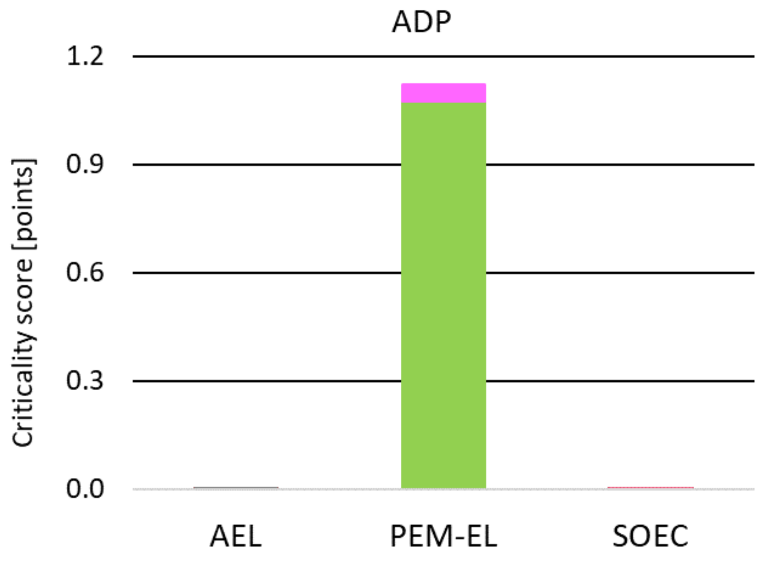
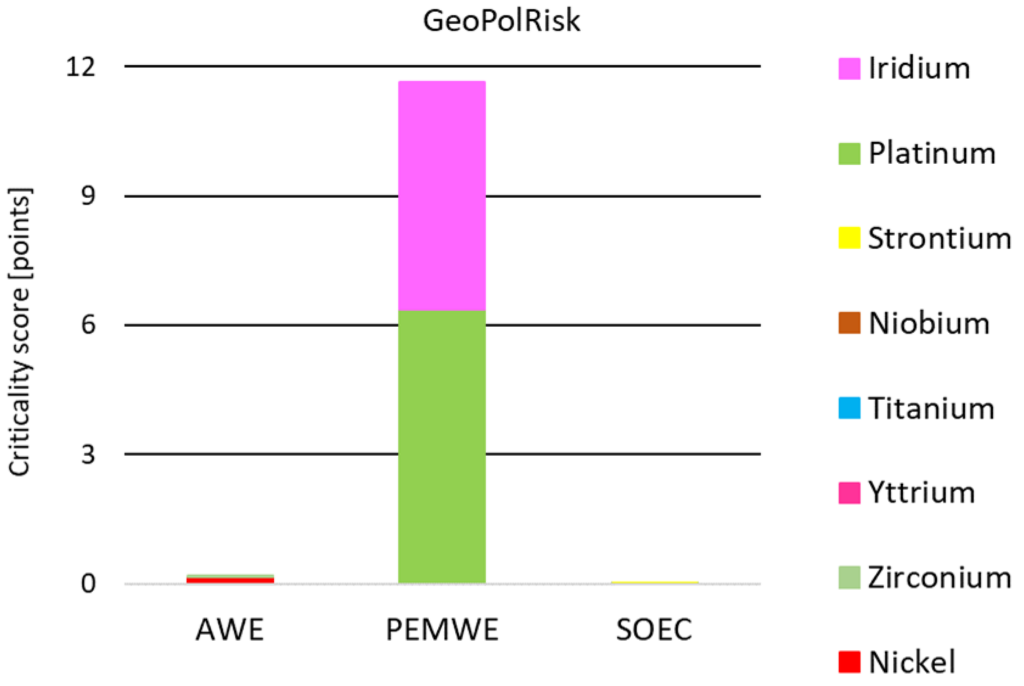
CASE STUDY

Results related to **1 kg of hydrogen** produced

Total hydrogen production over life time: 16 t/m^2 SOEC
40 t/m^2 PEM-EL
19 t/m^2 AEL





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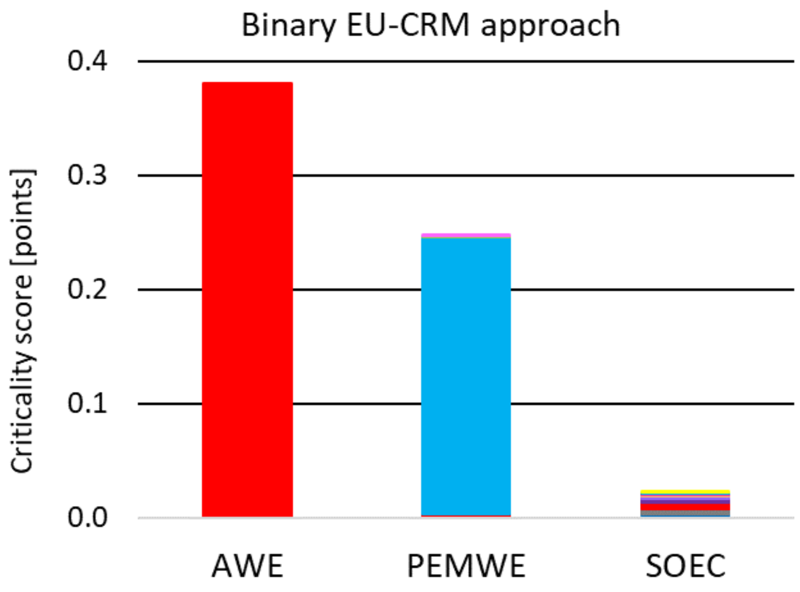

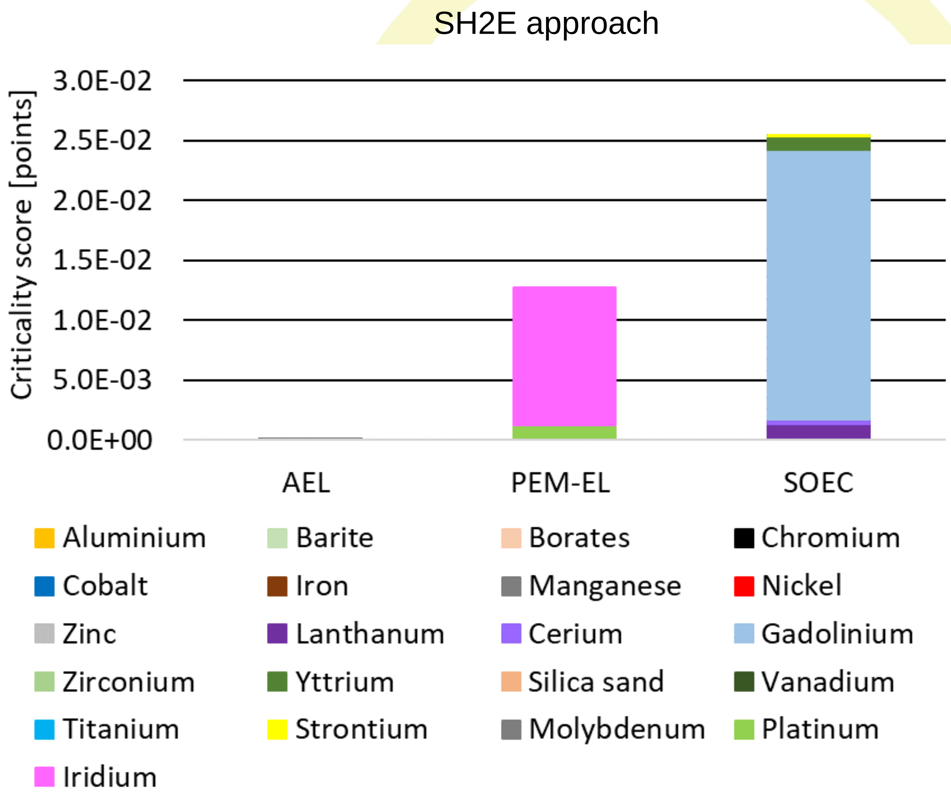

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SUMMARY

- different methods lead to different results ☹
- Resource depletion methods (e.g. ADP) differ most from the criticality methods (e.g. GeoPolRisk, EC-CRM, SH2E) ✓
- be cautious in drawing conclusions !
- used several methods for final evaluation ☺

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START YOUR OWN CRITICALITY ASSESSMENT

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SH2E

SUSTAINABILITY ASSESSMENT OF HARMONISED HYDROGEN ENERGY SYSTEMS

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