“Yale” criticality assessment methodology

Criticality of metals and metalloids

PNAS | **April 7, 2015** | vol. 112 | no. 14 | **4257–4262**

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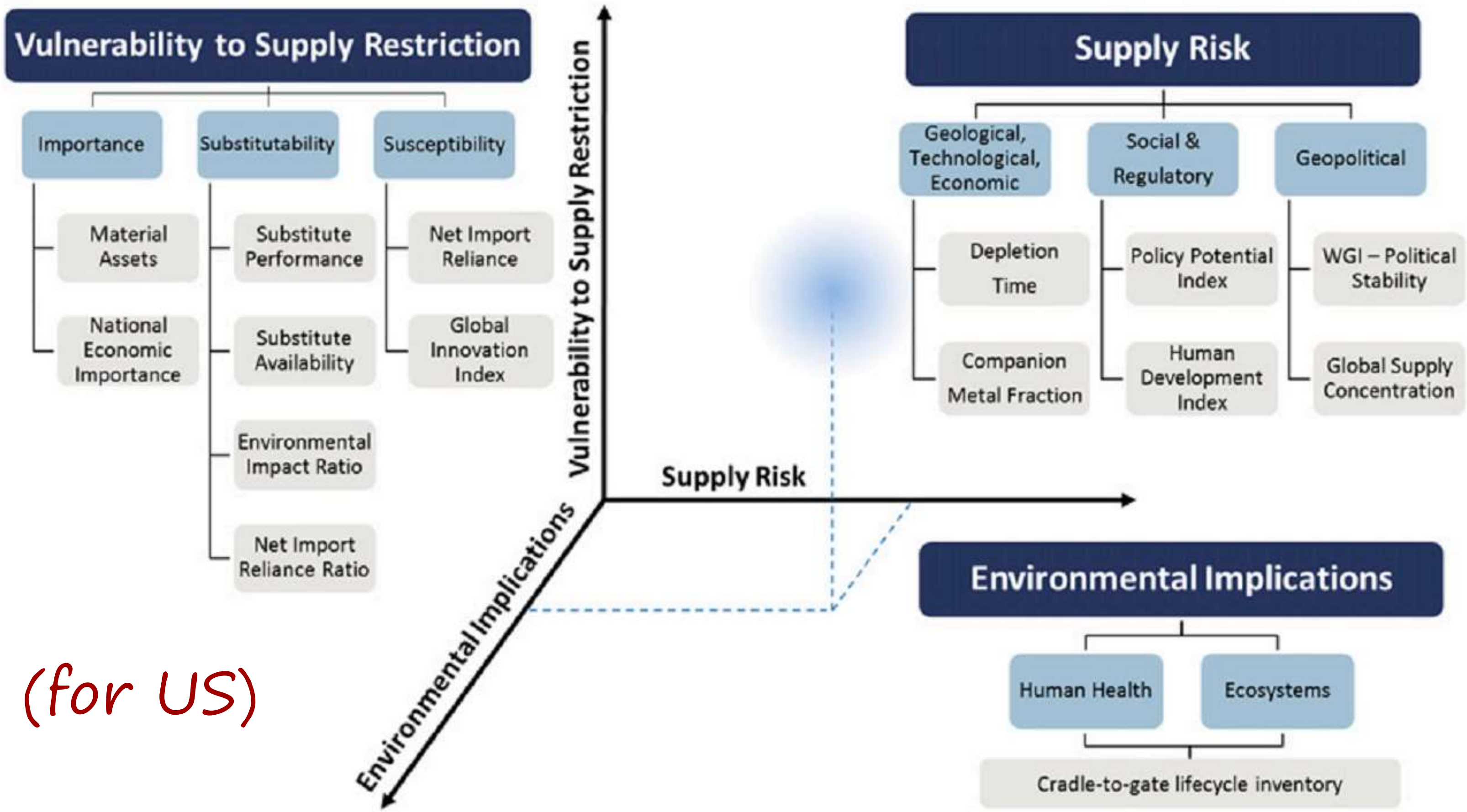
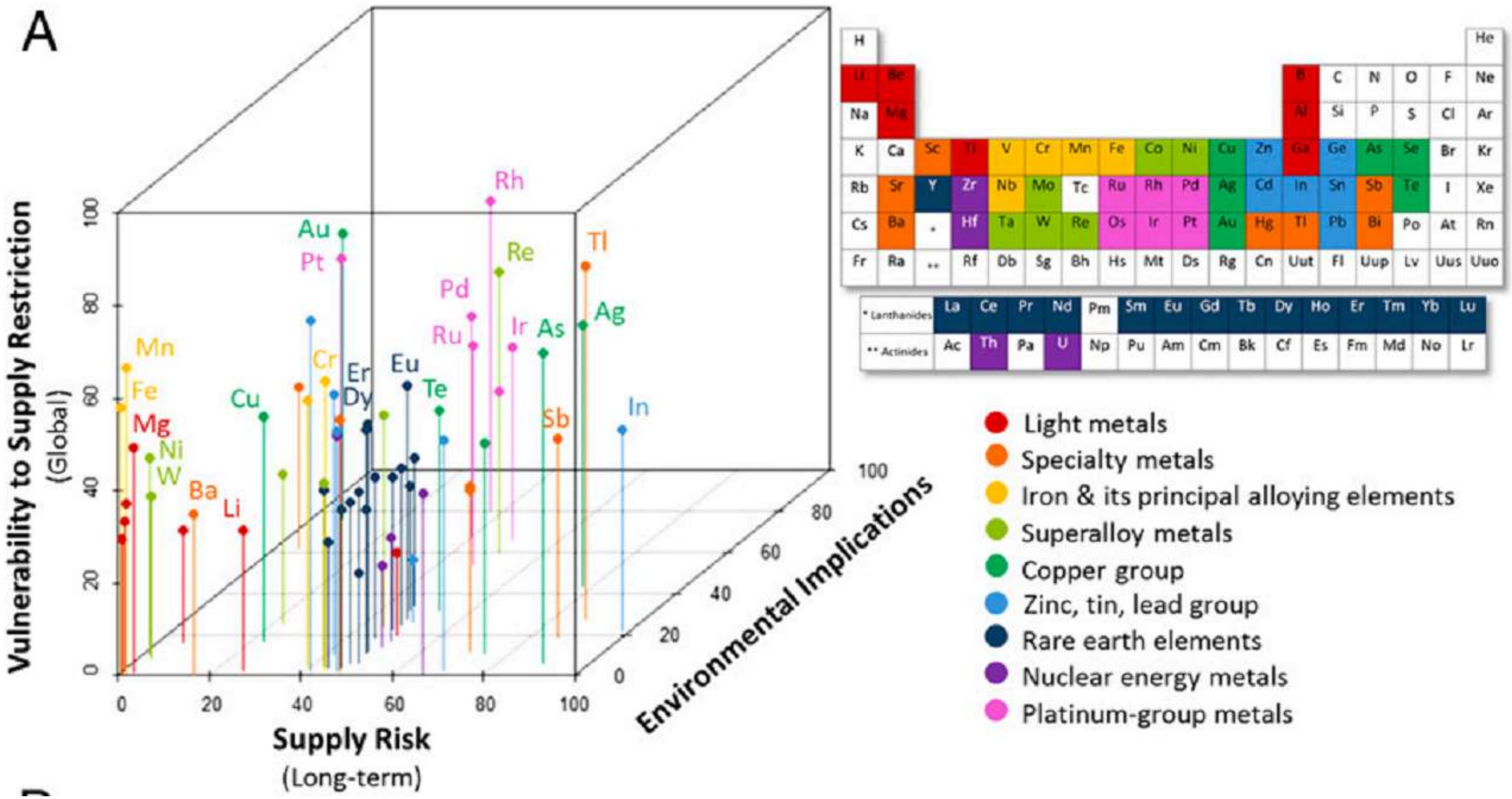


(for US)

“Yale” criticality assessment methodology



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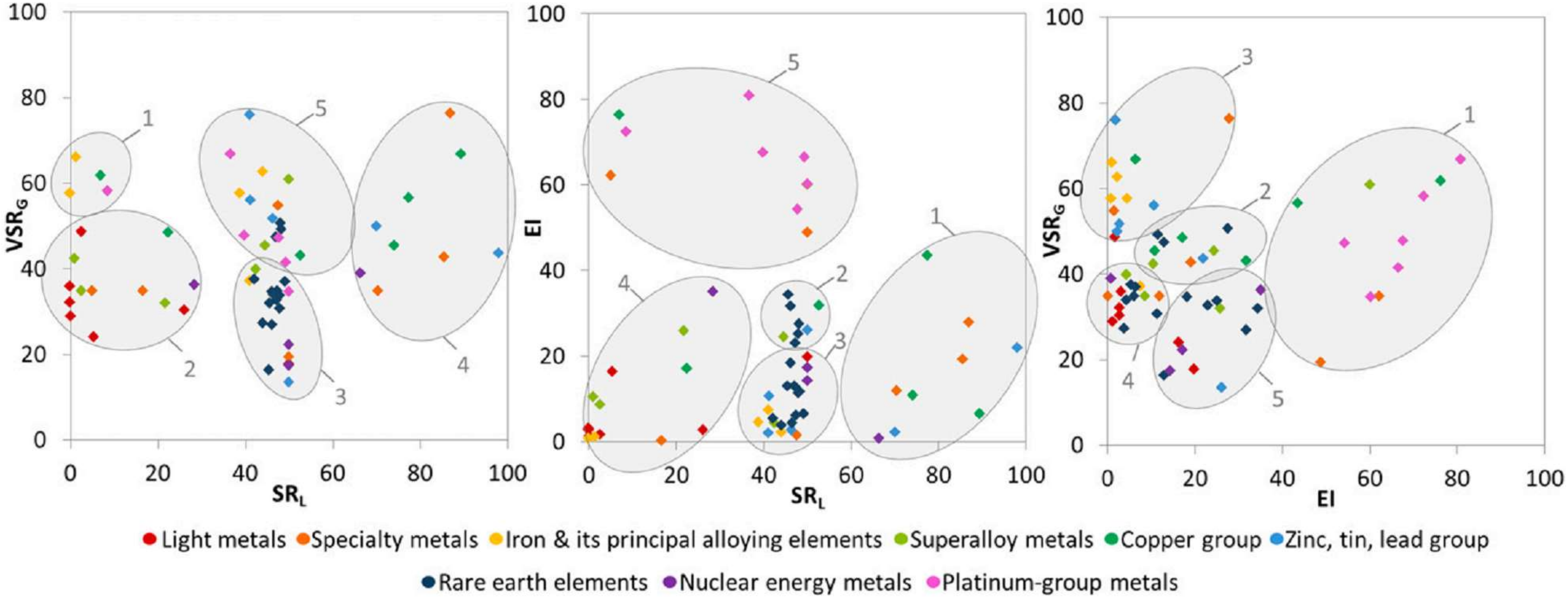
“Yale” criticality assessment methodology



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“Yale” criticality assessment methodology

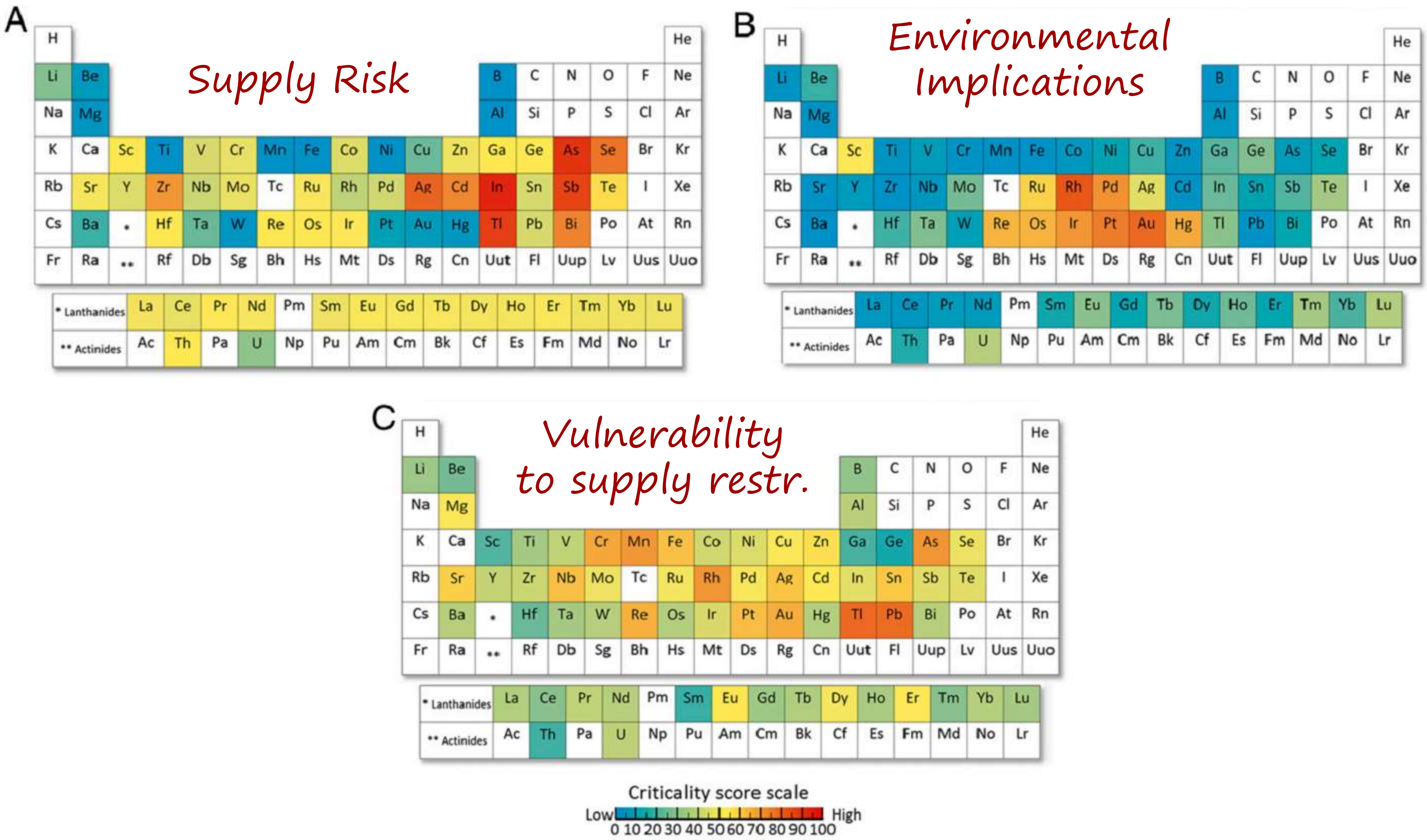
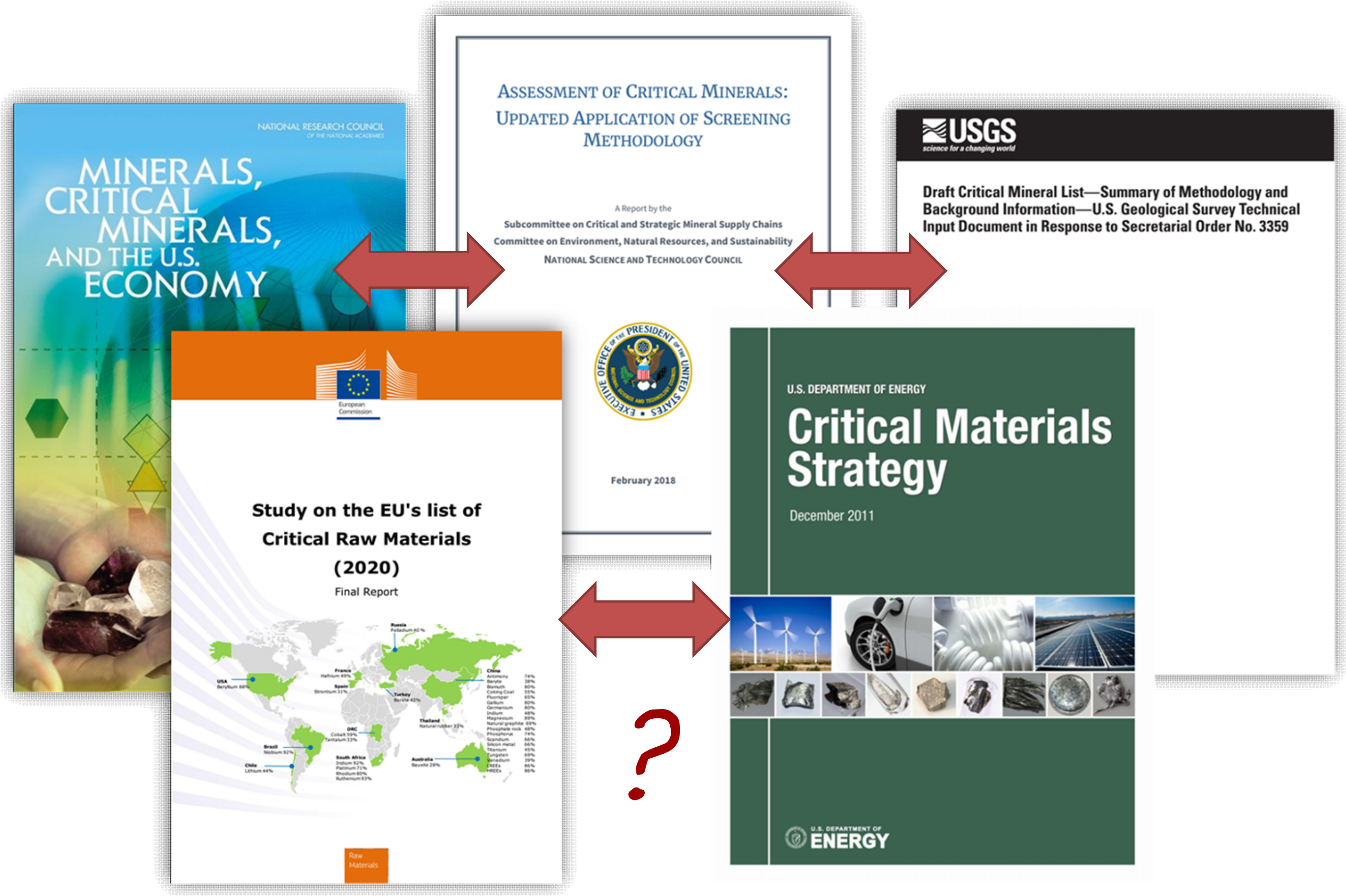


Fig. 6. Periodic tables of criticality for 62 metals, 2008 epoch, global level for (*A*) supply risk, (*B*) environmental implications, and (*C*) vulnerability to supply restriction.

PNAS | **April 7, 2015** | vol. 112 | no. 14 | **4257–4262**

Criticality assessment comparison



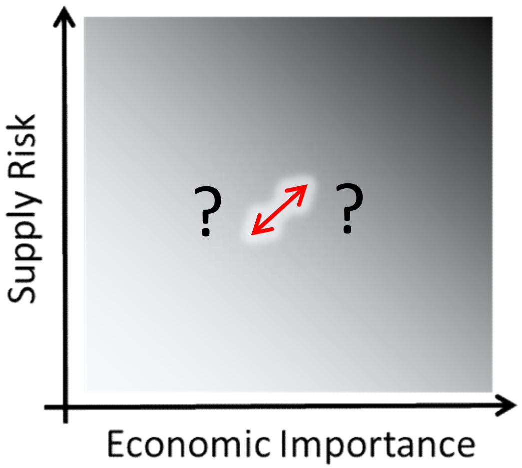
Criticality assessment comparison

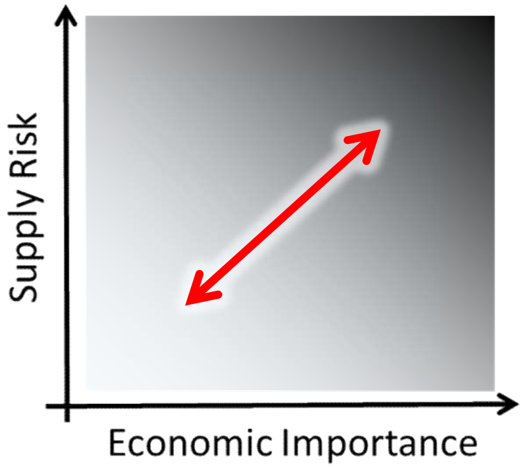
***different results** because of:*

- different perspectives on criticality
  (specific countries, technologies, companies, products)
- methodologies are not standardized
- data sources can vary *(e.g. expert opinion)*
- different time or timescales
  (current or recent years, future)
- different type and number of materials

Criticality assessment comparison

- **no global consensus** on what materials are critical
  (i.e. no universal CRMs list!)
- assessments are **qualitative/approximate** guides
- only **large differences** are significant
  (i.e. no precise measurements!)





Criticality assessment comparison

critical on critical materials…

OPEN ACCESS
IOP Publishing
Journal of Physics D: Applied Physics
J. Phys. D: Appl. Phys. 50 (2017) 123002 (18pp)
doi:10.1088/1361-6463/aa5b64

Topical Review

Raw material 'criticality'—sense or nonsense?

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CrossMark

Abstract

The past decade has seen a resurgence of interest in the supply security of mineral raw materials. A key to the current debate is the concept of 'criticality'. The present article reviews the criticality concept, as well as the methodologies used in its assessment, including a critical evaluation of their validity in view of classical risk theory. Furthermore, it discusses a number of risks present in global raw materials markets that are not captured by most criticality assessments. Proposed measures for the alleviation of these risks are also presented.

We find that current assessments of raw material criticality are fundamentally flawed in several ways. This is mostly due to a lack of adherence to risk theory, and highly limits their applicability. Many of the raw materials generally identified as critical are probably not critical. Still, the flaws of current assessments do not mean that the general issue of supply security can simply be ignored. Rather, it implies that new assessments are required. While the basic theoretical framework for such assessments is outlined in this review, detailed method development will require a major collaborative effort between different disciplines along the raw materials value chain.

In the opinion of the authors, the greatest longer-term challenge in the raw materials sector is to stop, or counteract the effects of, the escalation of unit energy costs of production. This issue is particularly pressing due to its close link with the renewable energy transition, requiring more metal and mineral raw materials per unit energy produced. The solution to this problem will require coordinated policy action, as well as the collaboration of scientists from many different fields—with physics, as well as the materials and earth sciences in the lead.

Keywords: supply security, high-tech metals, critical metals, critical mineral resources, strategic raw materials

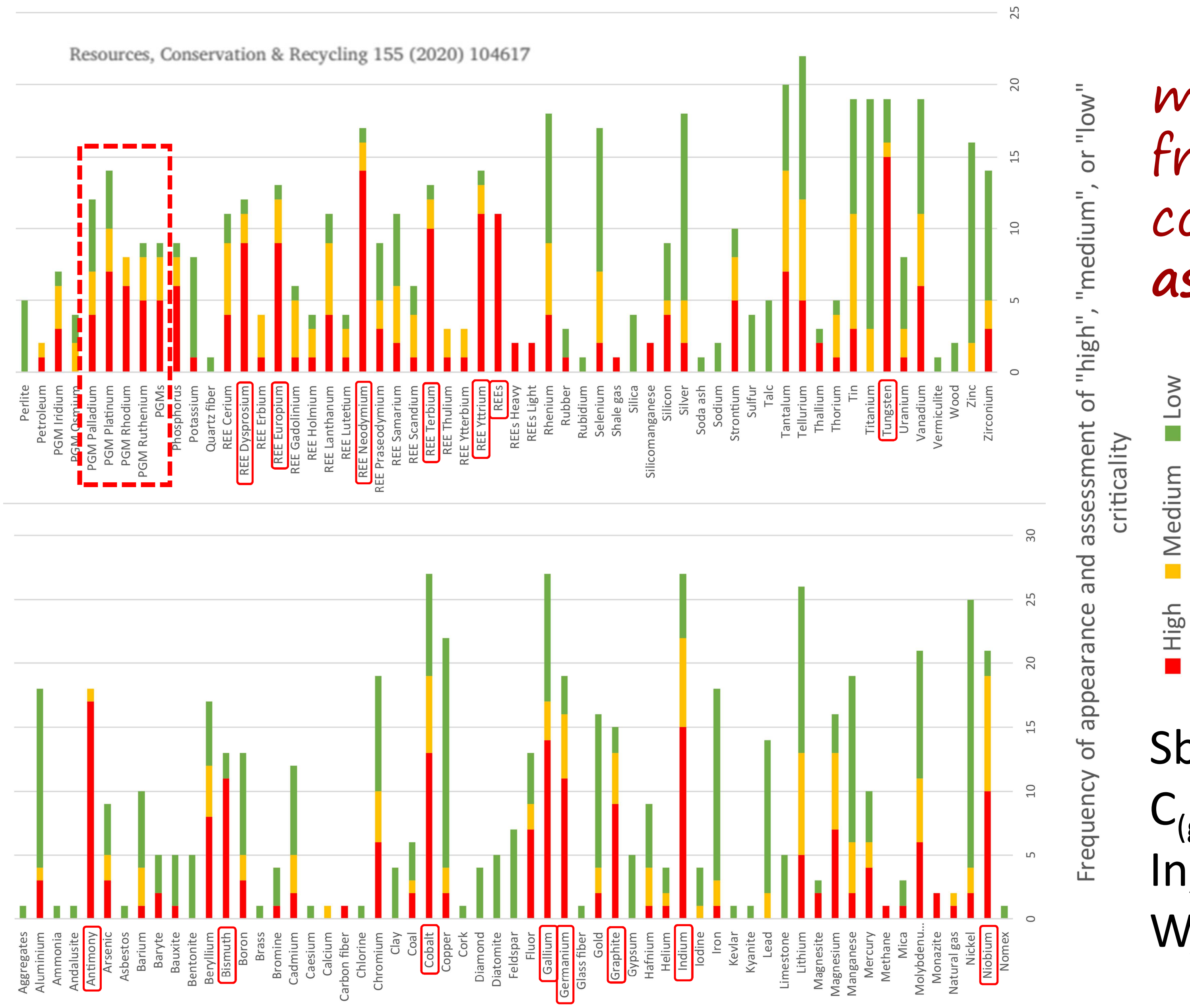
(Some figures may appear in colour only in the online journal)

"Despite the evident shortcomings of available work on raw material criticality, we note that **criticality assessments are nevertheless important**. […] even inaccurate assessments **raise awareness** about the general issue of raw material supply security, a topic that until recently had mostly been ignored in western countries."

Criticality assessment comparison

comparative overview on different materials

Criticality assessment comparison



most frequently considered as critical

Sb, Bi, Co, $C_{(gr)}$, Ga, Ge, In, Nb, REEs, W, (PGMs)

Criticality assessment comparison *over time*

repetition of **some studies** over time

(same or identical methdology)

INFO available:

- **varying criticality levels** of individual materials
- **varying number of materials** considered as critical

Criticality assessment comparison *over time*

n° of CRMs increases

European Commission

2011: 14 CRMs /41 *(ratio 0.34)*

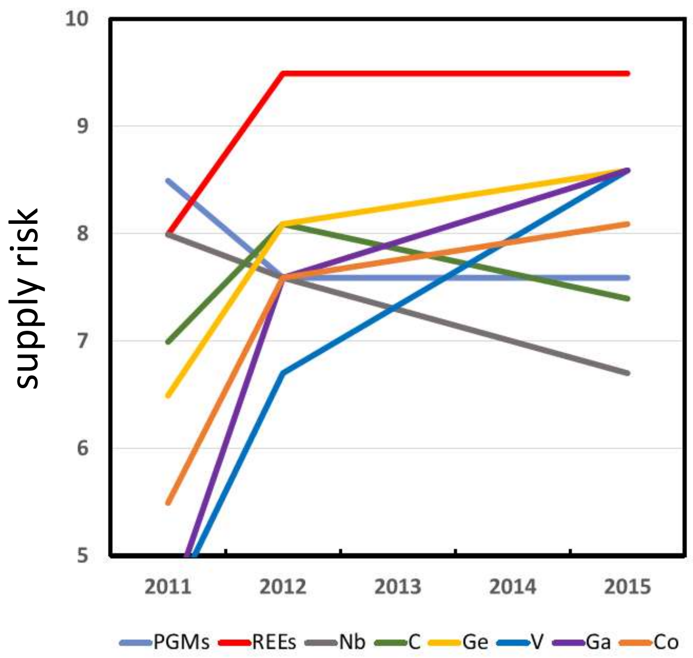
2014: 20 CRMs /54 *(ratio 0.37)*

2017: 26 CRMs /61 *(ratio 0.42)*

2020: 30 CRMs /66 *(ratio 0.45)*

supply risk increases

BGS British Geological Survey



(A.King, Critical Materials, Elsevier 2021)

Criticality assessment comparison *over time*

EC CRMs Report 2020 vs 2017 (same methodology)

Table 6: Key changes to the 2020 list of CRMs compared to the 2017 CRMs list

2020 CRMs vs. 2017 CRMs			Legend:
Antimony	LREEs	Tungsten	Black: CRMs in 2020 and 2017
Baryte	Indium	Vanadium	Red: CRMs in 2020, non-CRMs in 2017
Beryllium	Magnesium		Green: CRMs assessed in 2020, not assessed in 2017
Bismuth	Natural Graphite	Bauxite	~~Strike out:~~ Non-CRMs in 2020, critical in 2017
Borate	Natural Rubber	Lithium	
Cobalt	Niobium	Titanium	
Coking Coal	PGMs		
Fluorspar	Phosphate rock	Strontium	
Gallium	Phosphorus		
Germanium	Scandium	~~*Helium*~~	
Hafnium	Silicon metal		
HREEs	Tantalum		

Criticality assessment comparison *over time*

EC CRMs Report 2020 vs 2017 (same methodology)

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Cobalt	Niobium	Titanium	
Coking Coal	PGMs		
Fluorspar	Phosphate rock	Strontium	
Gallium	Phosphorus		
Germanium	Scandium	~~Helium~~	
Hafnium	Silicon metal		
HREEs	Tantalum		

Lithium	SR: 1.0 to 1.6	In 2020 the stage with the higher SR is the processing stage, which was not evaluated in the 2017 exercise.
	EI: 2.4 to 3.1	Changes in the value-added of NACE Rev. 2 sectors.

Criticality assessment comparison *over time*

EC CRMs Report 2020 vs 2017 (same methodology)

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Coking Coal	PGMs		
Fluorspar	Phosphate rock	Strontium	
Gallium	Phosphorus		
Germanium	Scandium	~~Helium~~	
Hafnium	Silicon metal		
HREEs	Tantalum		

Helium	SR: 1.6 to 1.2	Both global supply and EU sourcing became less concentrated.
	EI: 2.8 to 2.6	Sectors distribution changed to better represent EU applications.

Criticality assessment comparison *over time*

EC CRMs Report 2020 vs 2017 (same methodology)

Table 6: Key changes to the 2020 list of CRMs compared to the 2017 CRMs list

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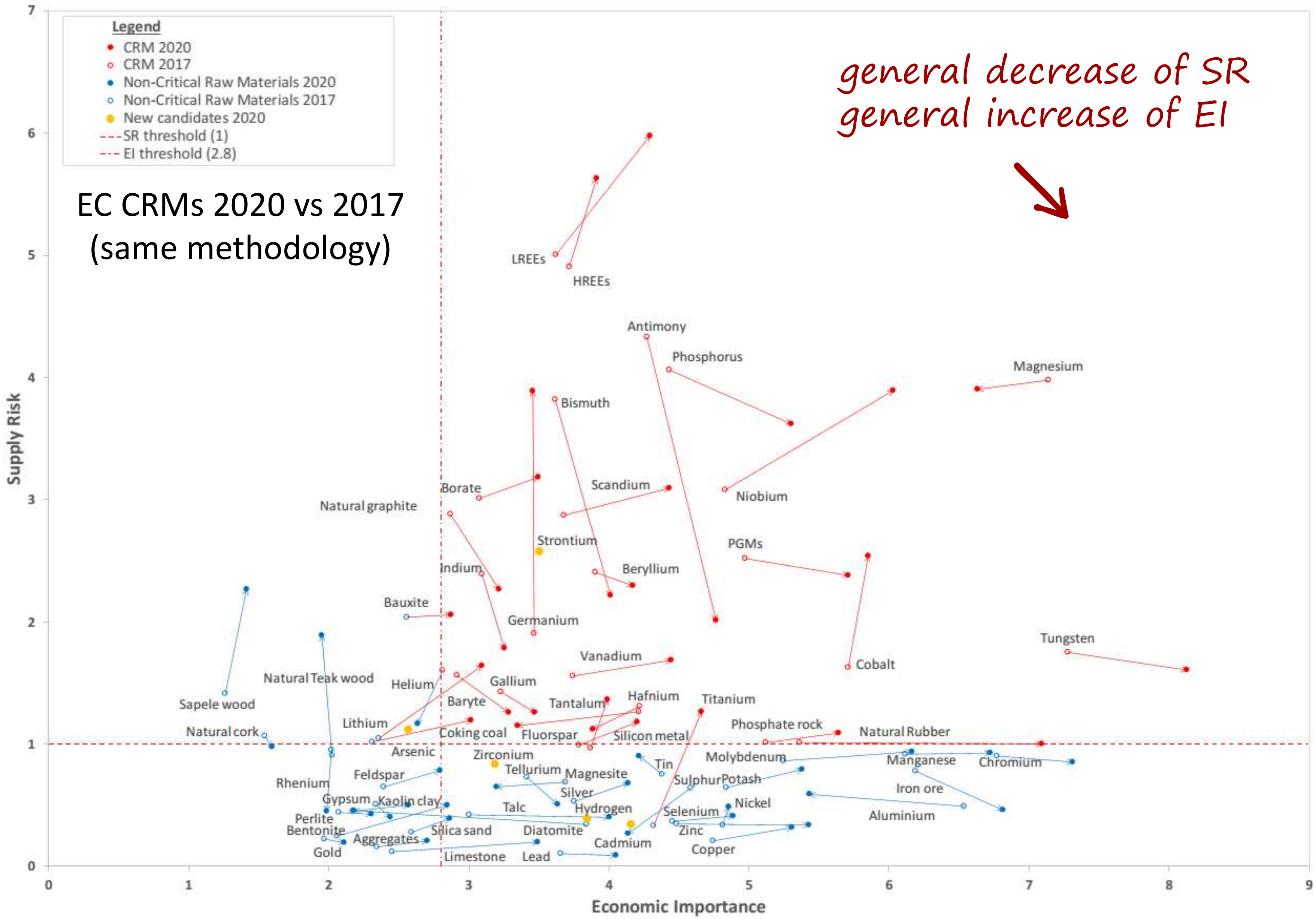
Coking Coal	PGMs		
Fluorspar	Phosphate rock	Strontium	
Gallium	Phosphorus		
Germanium	Scandium	~~Helium~~	
Hafnium	Silicon metal		
HREEs	Tantalum		

Table 7: Materials identified as critical in 2011, 2014, 2017 and 2020 assessments

Critical raw materials in 2011, 2014, 2017 and 2020		
Antimony	Germanium	Natural graphite
Beryllium	Heavy rare earth elements	Niobium
Cobalt	Indium	PGMs
Fluorspar	Light rare earth elements	Tungsten
Gallium	Magnesium	

consistent CRMs for EU

Criticality assessment comparison *over time*



Criticality assessment comparison *over time*

in the future, data at different times could be used to set up **predictive models** by using machine learning

(and considering uncertainty)

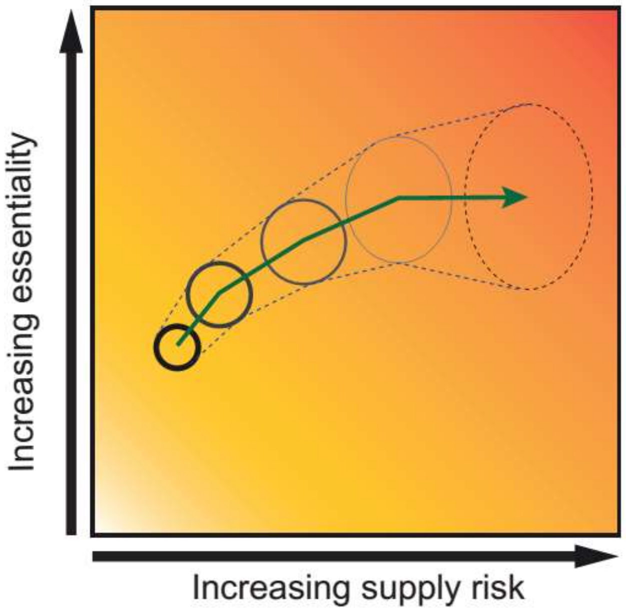
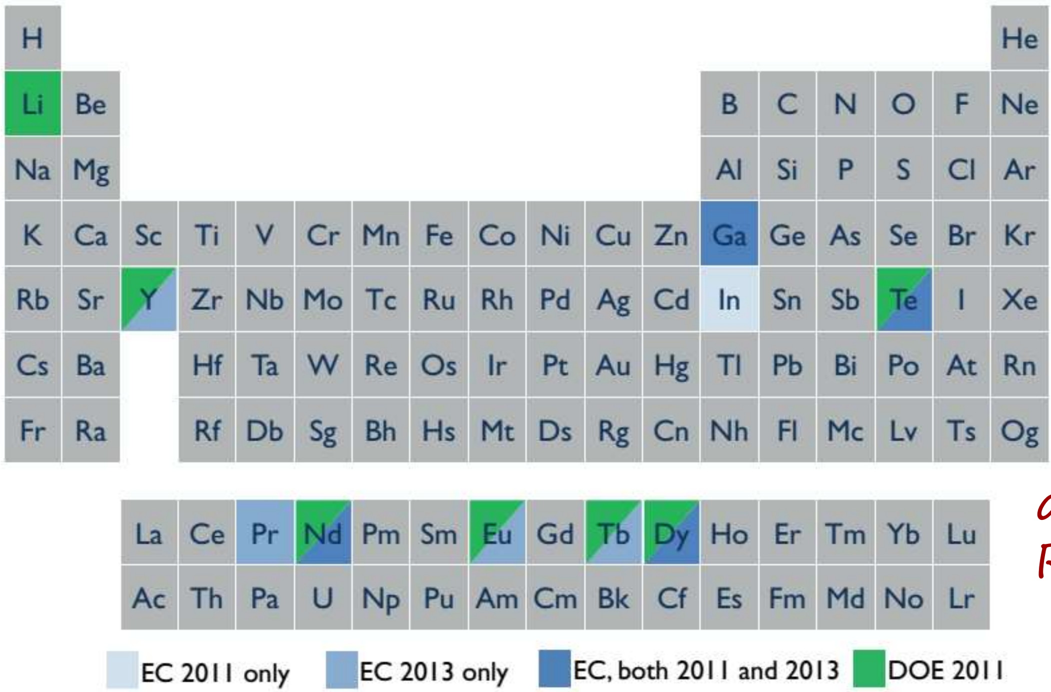


Fig. 5.1 A schematic forward-looking criticality analysis for a single material. The uncertainty of the analysis increases as it is projected further into the future, and there can be differing variations of uncertainty relative to the two axes of the diagram.

(A. King, Critical Materials, Elsevier 2021)

Criticality assessment comparison *: regional perspetives*

EU vs. *US* on **decarbonization-related** criticality



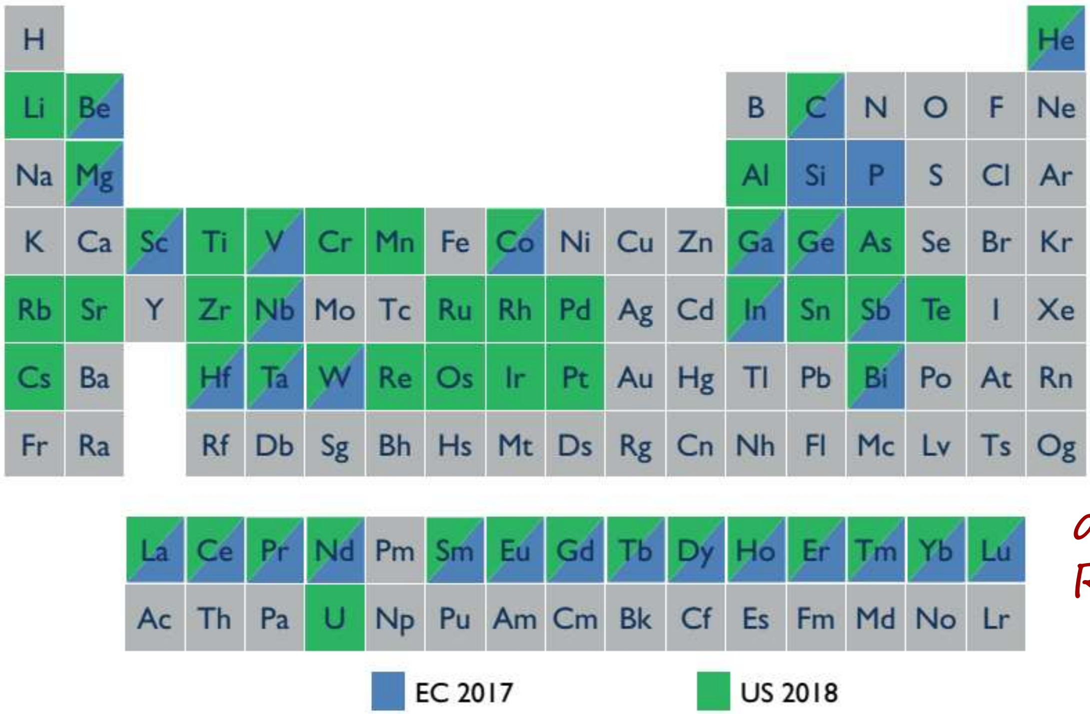
agreement on REEs as CRMs

Fig. 3.11 Comparison of the materials identified as critical in the EC studies of decarbonization and the US DOE's assessment of materials critical for the deployment of clean energy technologies. Of the six elements identified as critical in both the EU and the United States, five are rare earths.

(A. King, Critical Materials, Elsevier 2021)

Criticality assessment comparison *: regional perspetives*

EU vs. *US* on criticality in general

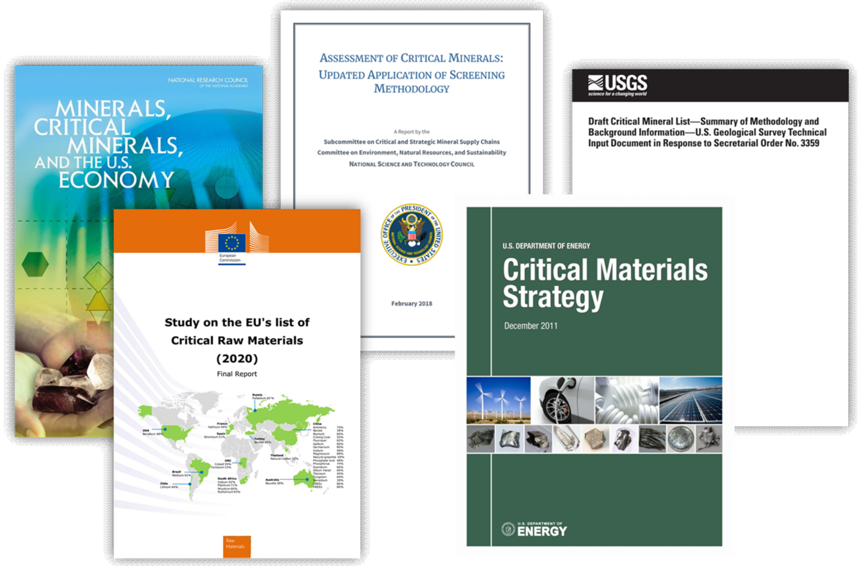


agreement on REEs as CRMs

Fig. 3.12 Comparison of the materials identified as critical to the economies of the EU and the United States.

(A. King, Critical Materials, Elsevier 2021)

Criticality assessment comparison : *criticality markers*

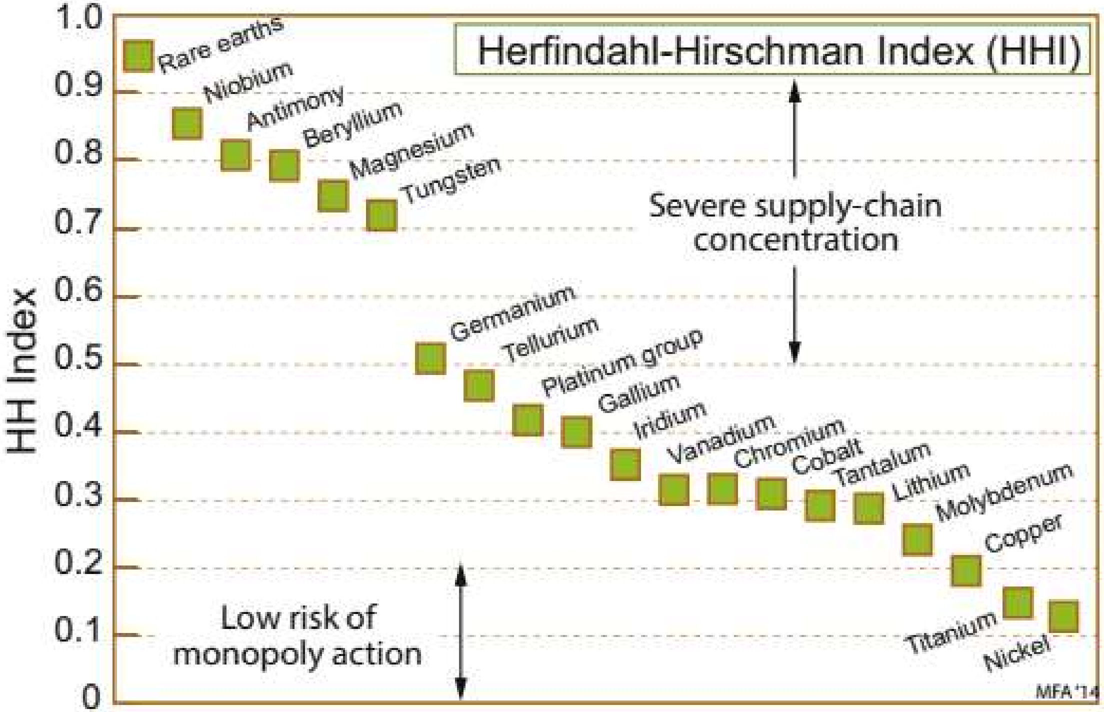


critical materials as identified
by **different assessments** share
some **common characteristics**

(criticalty markers
or indicators)

Criticality assessment comparison *: criticality markers*

- **limited supply diversity** (HHI)

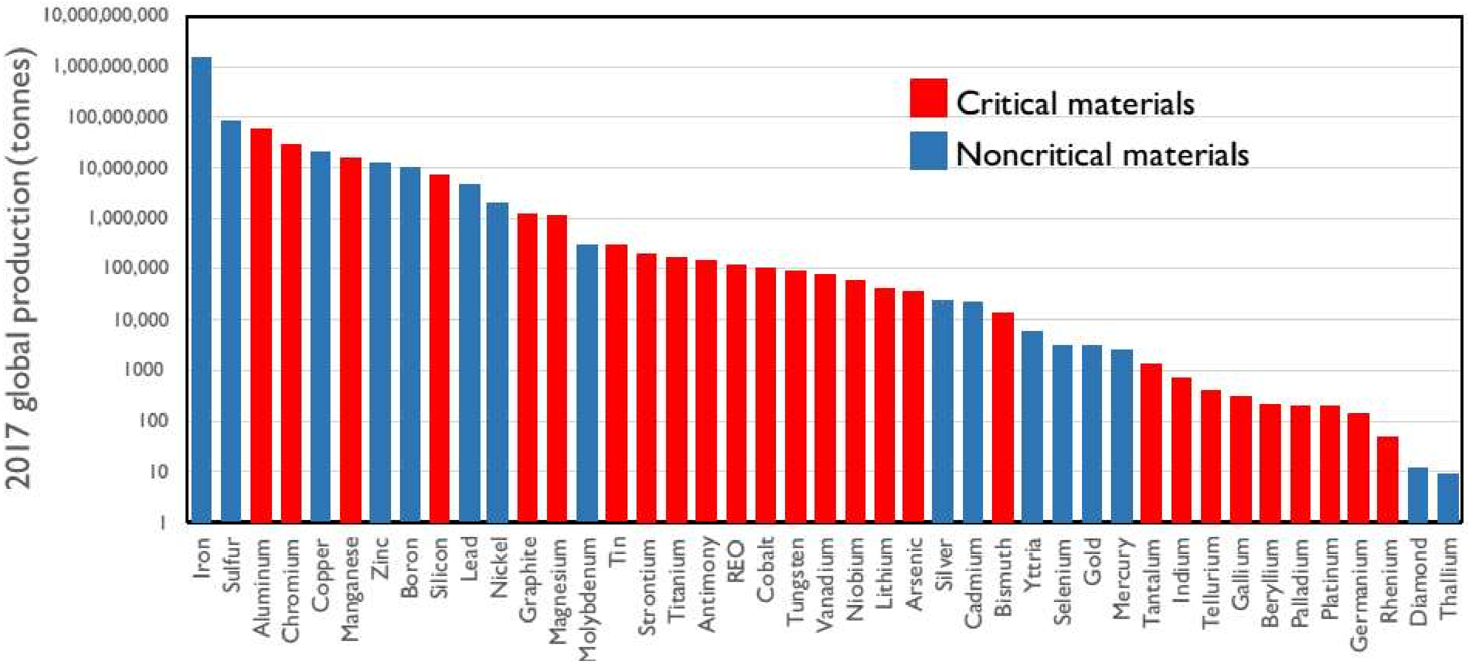


(from M.Ashby, “Materials and Sustainable Development”, Elsevier 2016)

Criticality assessment comparison *: criticality markers*

- limited supply diversity (HHI)
- **small markets** *(materials produced in small quantities)*

  - vulnerable to sudden increase in demand
  - harder to increase production upon increasing demand



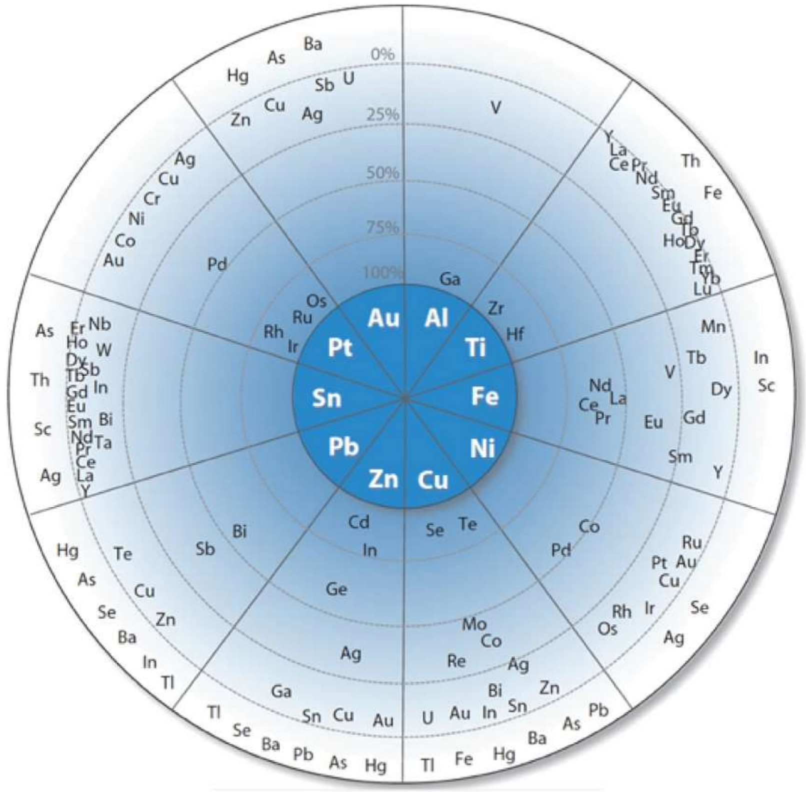
(A. King, Critical Materials, Elsevier 2021)

Criticality assessment comparison *: criticality markers*

- limited supply diversity (HHI)
- small markets *(materials produced in small quantities)*
- **co-production**

many elements are ***found together:***

- *hard to separate (separation costs)*
- *the «balance problem» (%s ≠ market demand)*



(A. King, Critical Materials, Elsevier 2021)

Fig. 3.15 The wheel of metal companionality. The principal host metals form the inner circle. Companion elements appear in the outer circle at distances proportional to the percentage of their primary production (from 100% to 0%) that originates with the host metal indicated. The companion elements in the white region of the outer circle are elements for which the percentage of their production that originates with the host metal indicated has not been determined.

Criticality assessment comparison *: criticality markers*

- limited supply diversity (HHI)
- small markets *(materials produced in small quantities)*
- **co-production**

typical of REEs

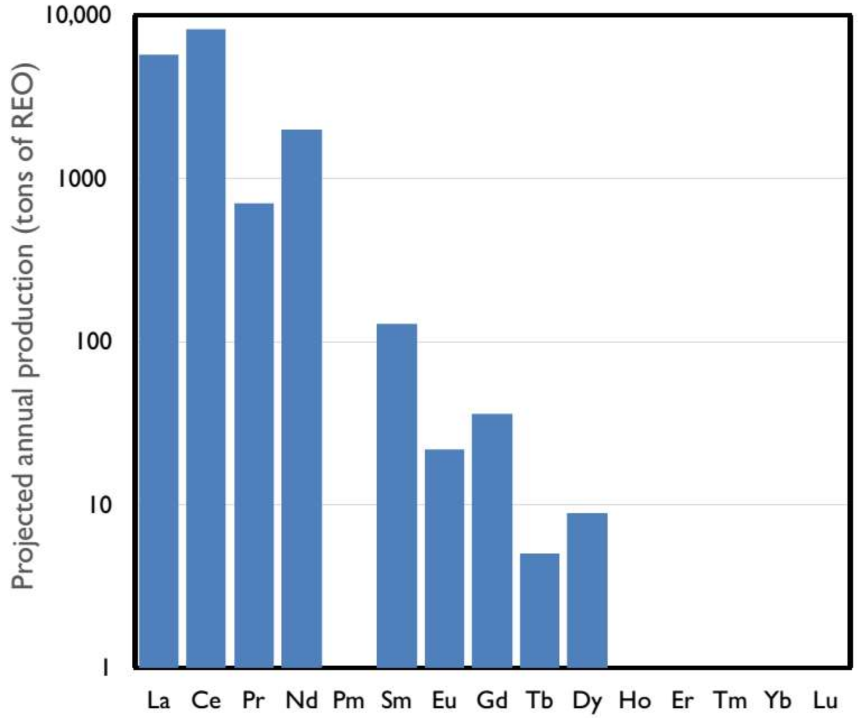


Fig. 3.14 Coproduction is typical of the rare earths. This is the mix of rare-earth oxide production, by mass, from a bastnaesite mine (these data represent the projected output from Mountain Pass after its reopening in 2012). In this case the mine predominantly produces light rare earths. Promethium does not occur naturally, and all of the elements heavier than dysprosium are present at concentrations too low to be of economic value.

(A. King, Critical Materials, Elsevier 2021)

Criticality assessment comparison : *criticality markers*

- limited supply diversity (HHI)
- small markets *(materials produced in small quantities)*
- co-production
- **lack of market transparency**

✓ *out of larger commodity markets (NYMEX, LME)*

✓ *no brokers (direct trade), no regulations, not open*

✓ *risks for price manipulation or mis-interpretation are increased*

"[...] rare metals are traded in backroom deals, often in small quantities and tailored grades for specific end uses."

"Illegal trading is endemic in China.«

D. Abraham
The Elements of Power,
Yale University Press, 2015

Criticality assessment comparison *: criticality markers*

- limited supply diversity (HHI)
- small markets *(materials produced in small quantities)*
- co-production
- lack of market transparency
- **demanding materials specification** *(es. purity)*

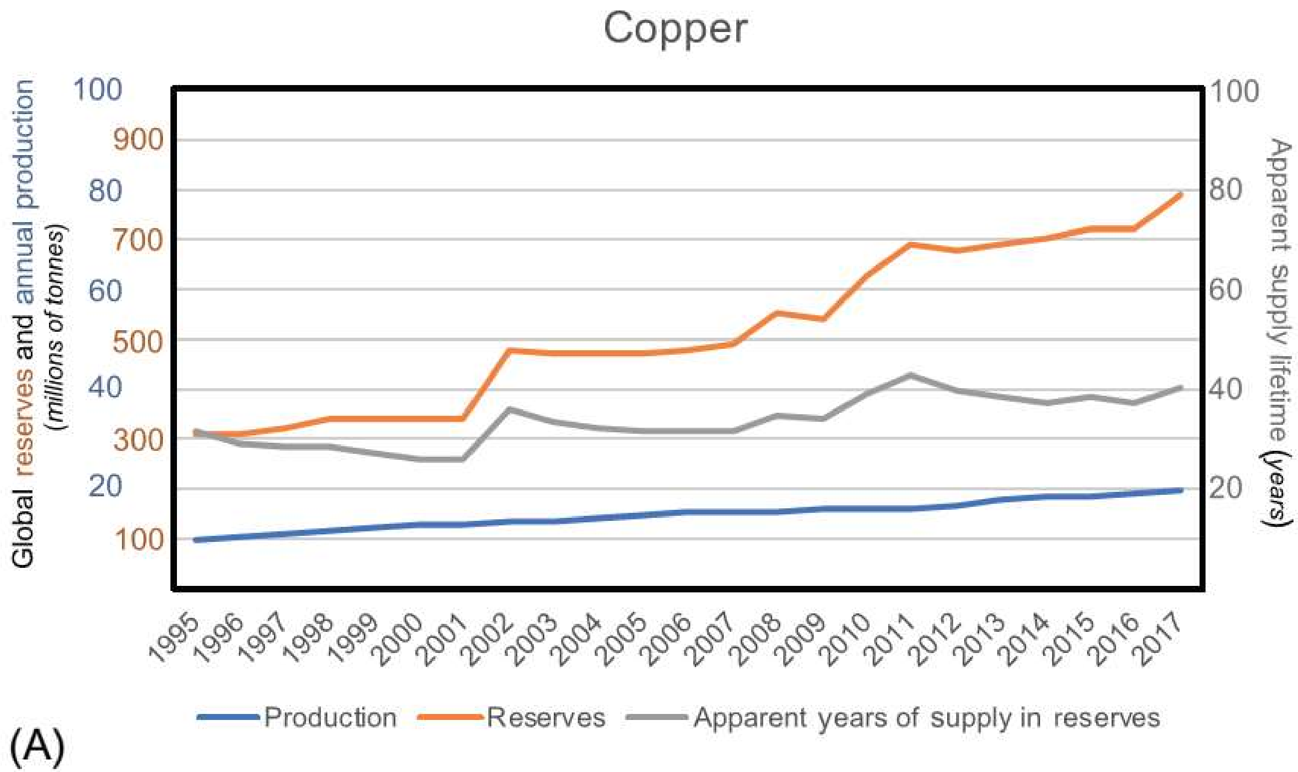
e.g. graphite

carbon highly abundant, but graphite is needed
extra pure for anodes in Li-ion batteries

Criticality assessment comparison : *misleading markers*

- price
- price variations
- crustal abundance
- **longevity of geological resources**

- new resources added
- new extraction technologies

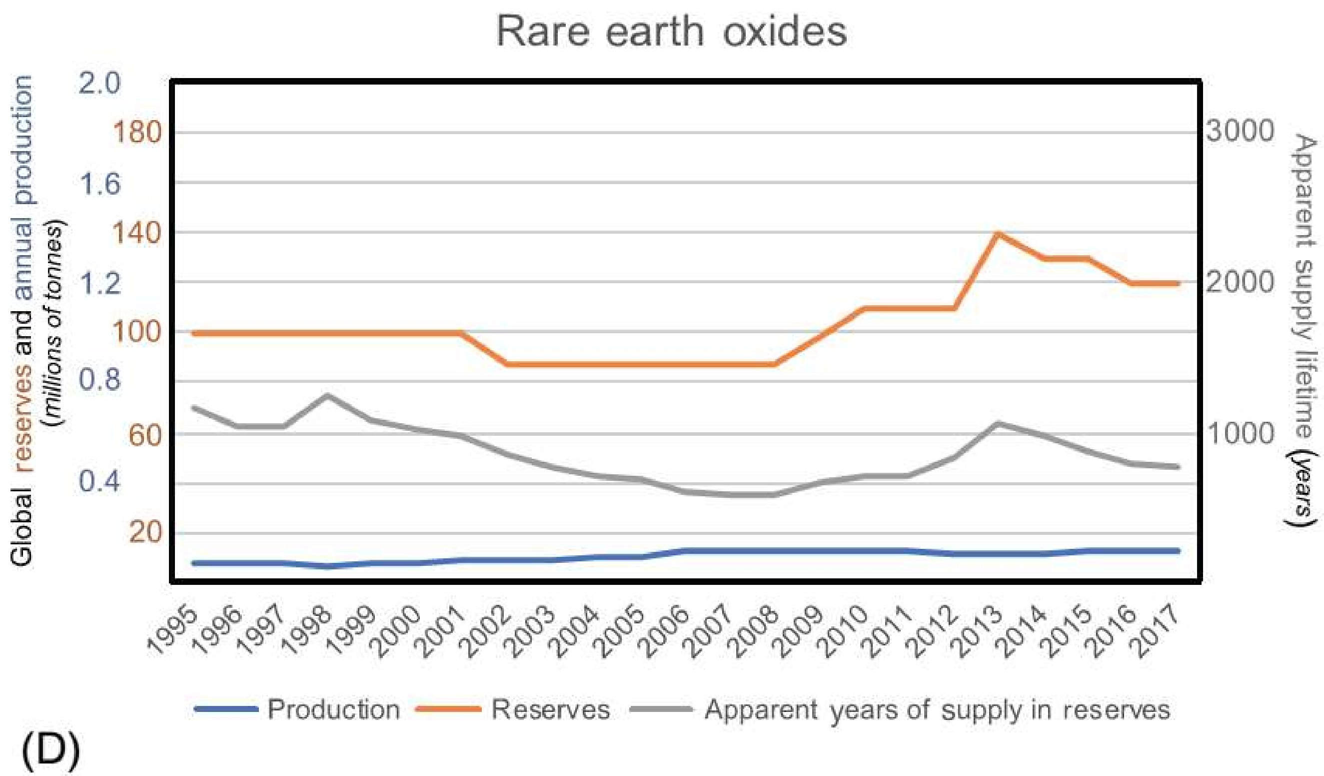


(A. King, Critical Materials, Elsevier 2021)

Criticality assessment comparison *: misleading markers*

- price
- price variations
- crustal abundance
- **<u>longevity of geological resources</u>**

- new resources added
- new extraction technologies



(A. King, Critical Materials, Elsevier 2021)

Environmental (and social) impact

- *some criticality assessment methodologies include environmental (and/or social) factors (e.g. Yale methodology)*
- *4 different **perspectives***

1. **Environmental/Social impacts as a source of supply risk**. *High or low probability of supply disruption due to potential regulations. (e.g. EC 2010)*

focus

2. **Vulnerability of the environment/social values to material use**. *The use of a material has a high/low impact on the environment. (e.g. Yale methodology)*
3. **Environmental/social risk.** *The disrupted availability of a material has a low or high impact on the environment or social values.*
4. **Reputational risk.** *The use of a material with a high environmental or social impact affects the reputation of a company (usually in assessment by companies).*

(D. Schrijvers et al., Resour. Conserv. Recycl. 2020)

Environmental impact

but relies on EC 2017 CRMs list

European Environment Agency
European Topic Centre on Waste and Materials in a Green Economy

(EIONET Report, december 2020)

https://www.eionet.europa.eu/

Eionet Report - ETC/WMGE 2020/5

Environmental aspects related to the use of critical raw materials in priority sectors and value chains

15/12/2020

*assessment on environmental impact of CRMs according to the OekoRess methodology**

*focused on **5 applications**:*

- *magnets*
- *batteries*
- *alloys*
- *fertilizers*
- *electronic components*

*Manhart et al. Mineral Economics 2019

(better than usual LCA, considers ecosystems degradation, impacts on water resources and disaster hazards)

Environmental impact

Table 8.1 Summary of the environmental hazard potential of the main critical raw materials in applications ([84])

Critical raw material			Beryllium	Rare-earth elements	Palladium	Cobalt	Phosphate	Boron	Gallium	Tantalum	Silicon	Niobium	Tungsten	Vanadium	Magnesium	Natural graphite
Application			Electronics	Magnets, batteries	Electronics	Magnets, batteries	Fertilisers	Magnets, fertilisers	Electronics	Electronics	Alloys	Alloys	Alloys	Alloys	Alloys	Batteries
	Goal	**Indicator**														
Geology	Avoiding pollution risks	Preconditions for acid mine drainage														
Geology		Paragenesis with heavy metals														
Geology		Paragenesis with radioactive components														
Technology	Limiting the direct impacts on ecosystems	Mining method														
Technology	Avoiding pollution risks	Use of auxiliary substances														
Natural environment	Avoiding natural accident hazards	Accident hazard due to floods, earthquakes, storms, landslides														
Natural environment	Avoiding competition in water usage	Water Stress Index														
Natural environment	Protection of valuable ecosystems	Protected areas and AZE sites														
Governance	Increased environmental performance in production country	Environmental Performance Index (EPI)														

[84] This table is based on one major mining site per critical raw material. The colour scale indicates the magnitude of the environmental hazard potential: green represents a low, yellow a medium and red a high potential for environmental hazard.

Environmental impact

Table 8.3. Summary of the environmental impact in the value chain of the main critical raw materials in the selected applications ([87])

	Application	Magnets			Batteries			Alloys					Fertilisers		Electronics			
	Environmental impact indicator	Rare-earth element	Cobalt	Boron	Rare-earth element	Cobalt	Natural graphite	Magnesium	Niobium	Vanadium	Silicon	Tungsten	Phosphate	Boron	Palladium	Tantalum	Beryllium	Gallium
Value chain	Carbon footprint (kton CO_2-eq/application)																	
	Cumulative energy demand ([88]) (TJ/application)																	
	Human toxicity, cancer and non-cancer (CTUh/application)																	
	Terrestrial acidification (kton SO_2-eq/application)																	
	Freshwater eutrophication (kton P-eq/application)																	

Particularly **high global environmental impacts** can be observed for those critical raw materials that are essential for producing **functional metal alloys** and those that are needed for **agricultural fertiliser** production, due to the **high production volumes** of these applications.

Environmental impact

(example: REEs)

just one site considered

The production of rare-earth elements causes **significant environmental damage**, as it is material and energy intensive and generates large amounts of emissions to air and water, and solid waste.

Their production in China, the largest producer, has raised environmental concerns with regards to heavy metal and radioactive emissions to groundwater, rivers, soil and the air around mine sites.

Additionally, the roasting phase of ores has an impact due to the large quantity of heat required, which in China is supplied by coal.

Most of these impacts are generated locally at the mining sites, often located in countries with medium or poor environmental performance.

Table 3.4 Evaluation of the environmental hazard potential of critical raw materials in magnets (8)

	Goal	Indicator	Rare-earth elements	Boron	Cobalt
			Bayan Obo, China	Bigadiç, Turkey	Katanga, DRC
Geology	Avoiding pollution risks	Preconditions for acid mine drainage	Lithophylic elements	Lithophylic element in colemanite, tincal and ulexite	Siderophilic element, mostly oxidised with sulphides in some sections
		Paragenesis with heavy metals	Soil in the mining area of Bayan Obo has been found to be contaminated with chromium, cadmium, lead, copper, and zinc	Groundwater in the mining area has been found to be contaminated with arsenic	Cobalt is associated with copper
		Paragenesis with radioactive components	0.16% thorium oxide, also uranium	No indications that boron is associated with elevated levels of uranium and thorium	No information found on levels of uranium and thorium in Mutanda, however, radioactive elements are present in other cobalt deposits in DR Congo
Technology	Limiting the direct impacts on ecosystems	Mining method	Open pit	Open pit	Open pit
	Avoiding pollution risks	Use of auxiliary substances	Extractants such as D2EHPA, TBP, and aliquat 336 have been widely used (9)	Extraction generally involves acid	Extraction involves acid
Natural environment	Avoiding natural accident hazards	Accident hazard due to floods, earthquakes, storms, landslides	China: high natural accident hazard	Turkey: medium natural accident hazard	DR Congo: low natural accident hazard
	Avoiding competition in water usage	Water Stress Index	Low water stress	High water stress	Low water stress
	Protection of valuable ecosystems	Protected areas and AZE sites	No relation to protected areas or AZE sites	No relation to protected areas or AZE sites	Very close to Marungu Highlands AZE site
Governance	Increased environmental performance in production country	Environmental Performance Index (EPI)	China: medium Environmental Performance Index	Turkey: medium Environmental Performance Index	DR Congo: low Environmental Performance Index
Value chain	Carbon footprint (Kton CO_2-eq/application)		5.6E+02	4.1E-01	5.6E+01
	Cumulative Energy Demand (TJ/application)		1.1E+04	7.5E+00	8.7E+02
	Human toxicity, cancer and non-cancer (CTUh/application)		2.6E+02	7.7E-02	2.6E+01
	Terrestrial acidification (Kton-SO_2 eq/application)		2.4E+00	1.8E-03	6.0E-01
	Freshwater eutrophication (Kton P-eq/application)		2.2E-01	1.5E-04	2.7E-02

Environmental impact

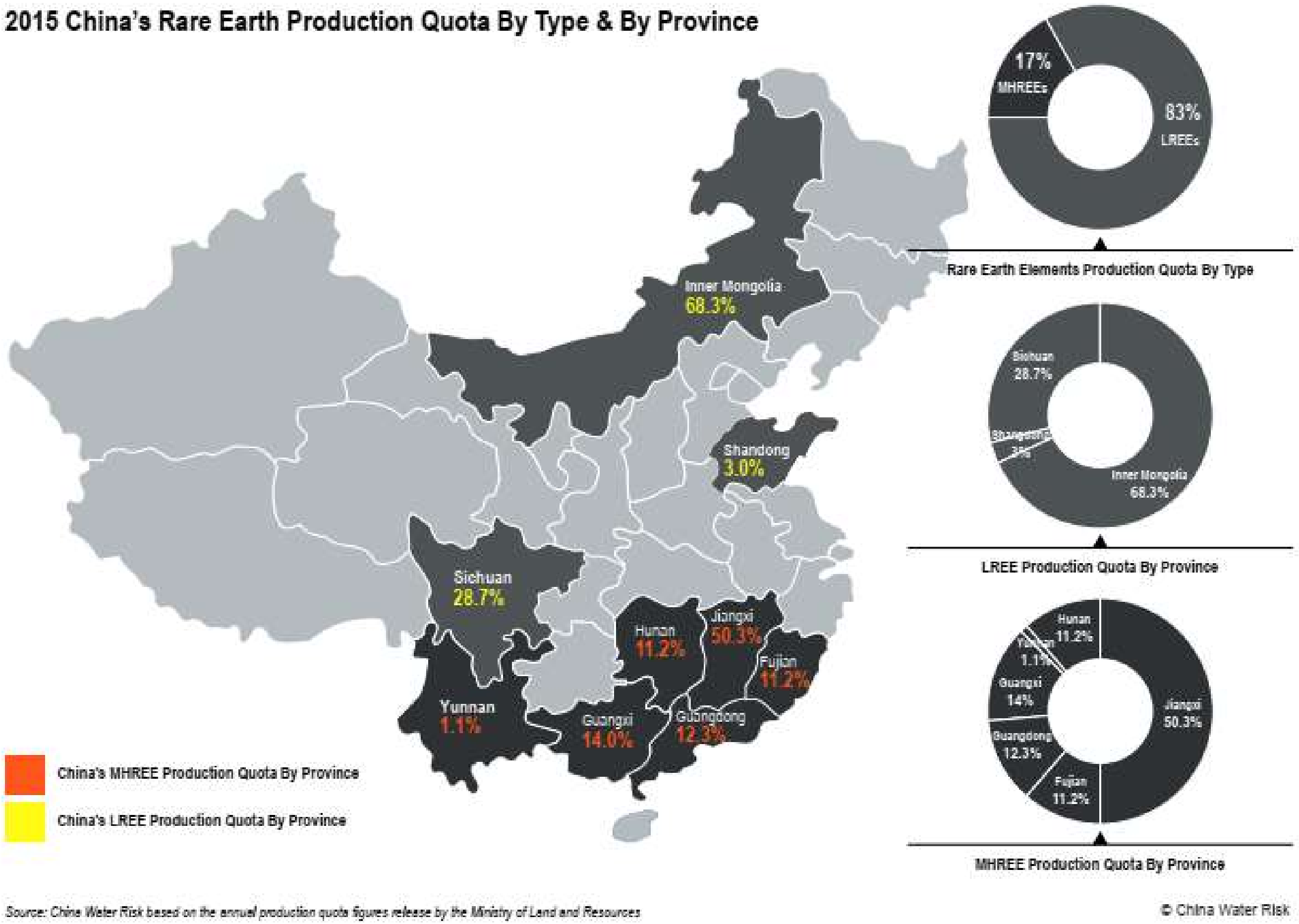
CHINAWATER RISK

(2016 report, www.chinawaterrisk.org)

report from Chinese NGO about water pollution in China due to REEs

Environmental impact

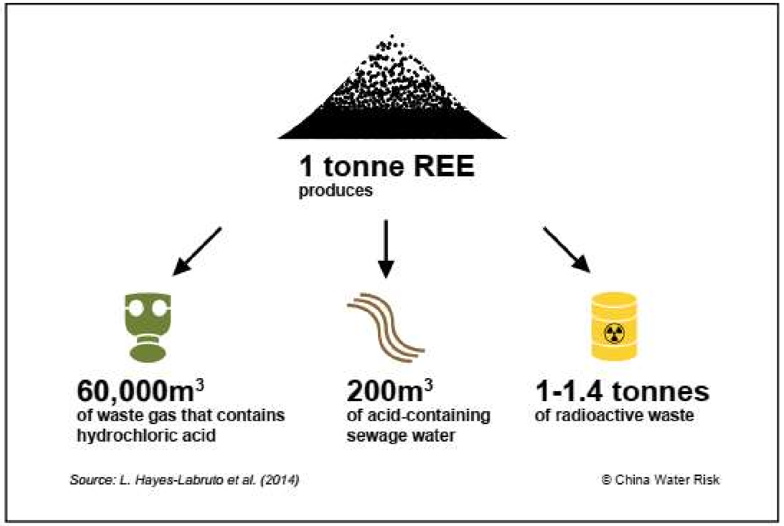
(2016 report, www.chinawaterrisk.org)



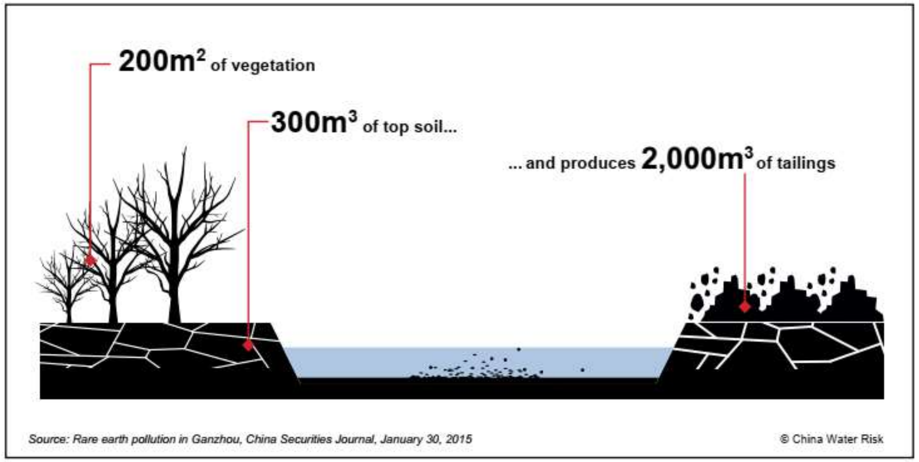
Environmental impact

REEs extraction is highly polluting

Rare Earth Production Comes With Toxic Waste



Pond Leaching for 1 Tonne of REOs Destroys



Environmental impact

CHINAWATER RISK (2016 report, www.chinawaterrisk.org)

- widespread **black market** (lower prices, lower or absent environmental standards)
- “good chances” that we are using products that contains illegally mined and trafficked RE
- efforts to stop illegal mining from China, but not from beneficiary countries and companies (i.e. purchasers)
- **6 billion USD** to clean-up the polluted REE mines in Ganzhou (8.6 % of total China REEs production)
- extraction costs in Ganzhou are **4.500 USD/ton**, while they should be (taking into account environmental remediation) about **30.000 USD/ton**
- Rare earths paradox: “clean” low-carbon technologies fueled by local pollution

Environmental impact

Environmental impact

Satellite images of a rare earth mining site in Ganzhou on April 14, 2005, (left) and February 9, 2009 (right) (Guo, 2012).

(Guo, W., 2012. The rare earth development can no longer overdraw ecological cost. China Environment News, July 2. China Environmental Press, Beijing & Environmental Development 8 (2013) 131–136)

Environmental impact

Apple 2019

Rare earth elements

Elements like neodymium, praseodymium, and dysprosium are used in magnets for audio applications, in cameras, and in haptics technology. Traditional recyclers don't recover these rare earth elements, because they are used in small quantities and technology has not advanced sufficiently to recover them. However, Daisy recovers the small components that contain rare earth elements from iPhone. By consolidating these sources, we're creating an opportunity for new technology to efficiently recover these materials.

Components and materials Daisy recovers

For every 100,000 iPhone devices, Daisy has the potential to recover:*

Aluminum	1,500 kg
Gold	1.1 kg
Silver	6.3 kg
Rare earth elements	32 kg
Tungsten	83 kg
Copper	1,000 kg
Tin	29 kg
Cobalt	790 kg
Steel	1,400 kg

Social impact

Amnesty report 2016

"THIS IS WHAT WE DIE FOR"

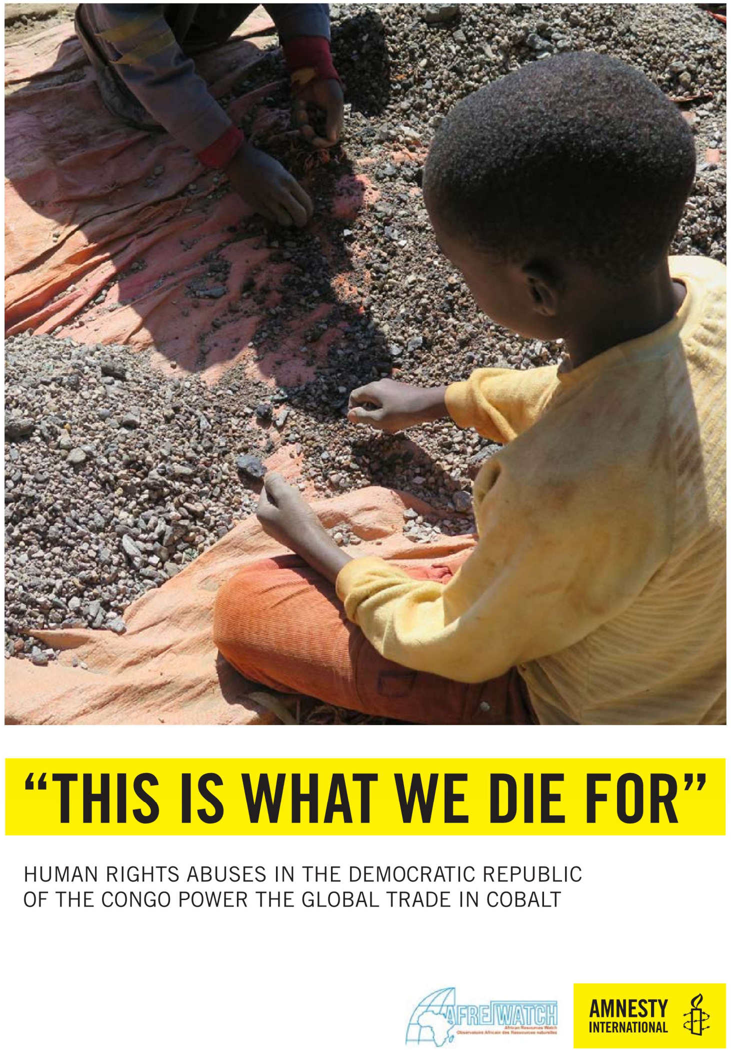
HUMAN RIGHTS ABUSES IN THE DEMOCRATIC REPUBLIC
OF THE CONGO POWER THE GLOBAL TRADE IN COBALT

AFREWATCH

AMNESTY INTERNATIONAL

Provinces in the Democratic Republic of the Congo pre-2015

Social impact



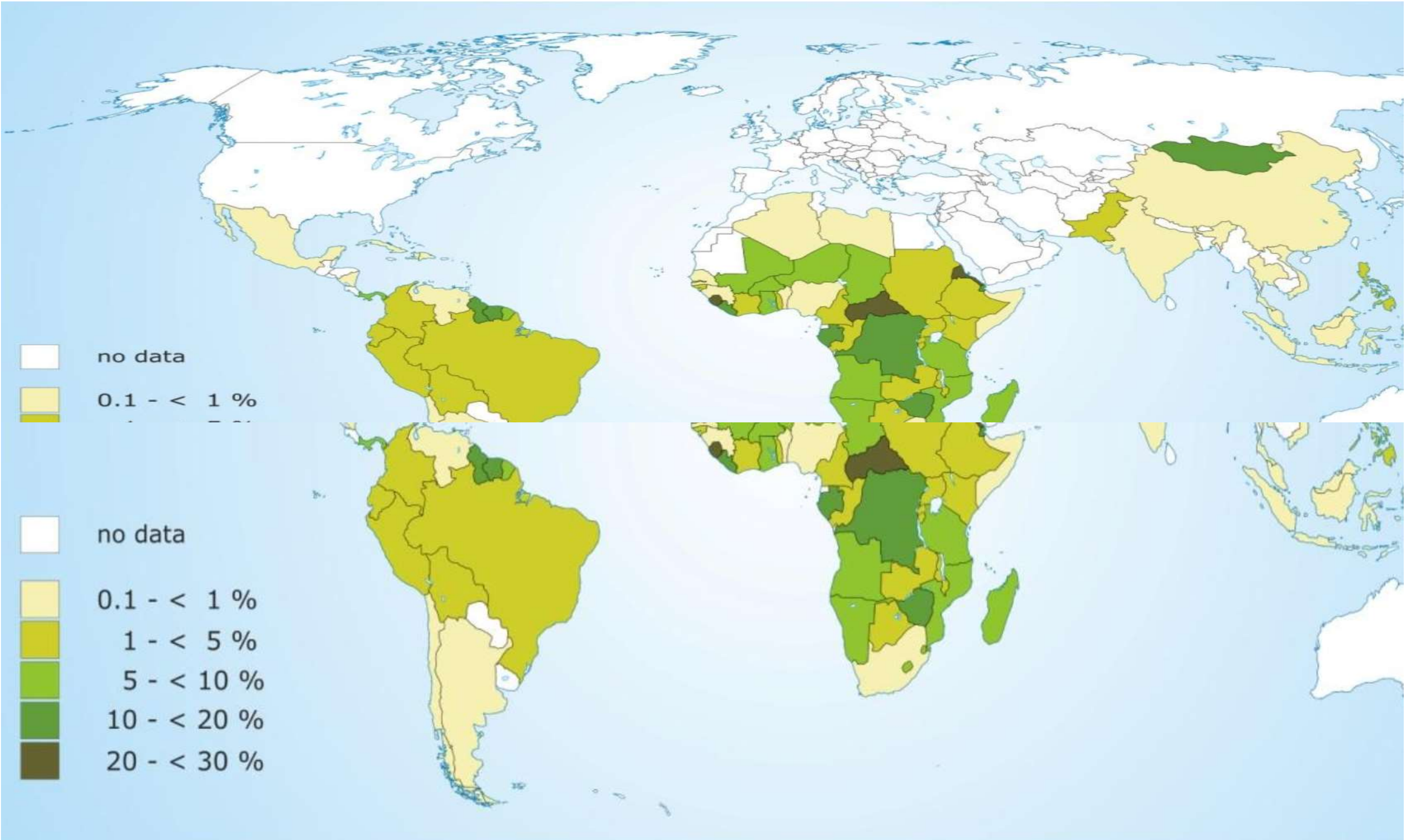
- more than half of the world's total supply of cobalt comes from the **Democratic Republic of the Congo** (DRC).
- 20% of the cobalt currently exported from the DRC comes from **artisanal miners**
- artisanal miners mine by hand using the most basic tools to dig out rocks from tunnels deep underground
- artisanal miners include **children** as young as seven
- chronic exposure to dust containing cobalt can result in a **potentially fatal diseases**, yet vast majority of miners do not have the most basic of protective equipment
- most children indicated that they earned between 1-2 USD per day.

Social impact

100 million people were directly engaged in artisanal and small-scale mining

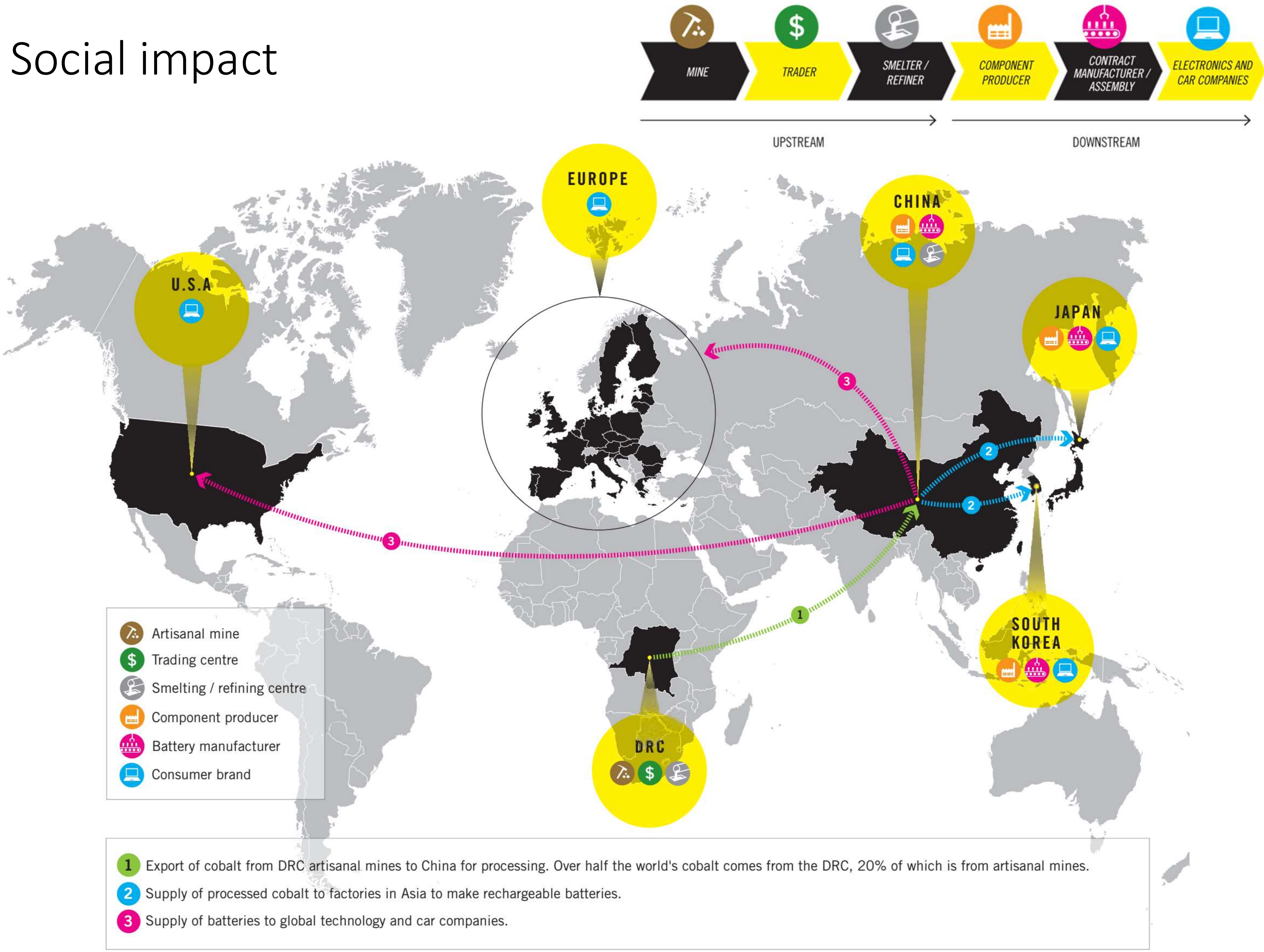
(World Bank, 2013)

Percentage of population dependent on artisanal mining



(Dorner, U., Franken, G., Liedtke, M. & Sievers, H. (2012). *Artisanal and small-scale mining (ASM)* (Polinares Working Paper 19). Polinares. Retrieved from http://pratclif.com/2015/mines-ressources/polinares/chapter7.pdf – Data from 2009)

Social impact

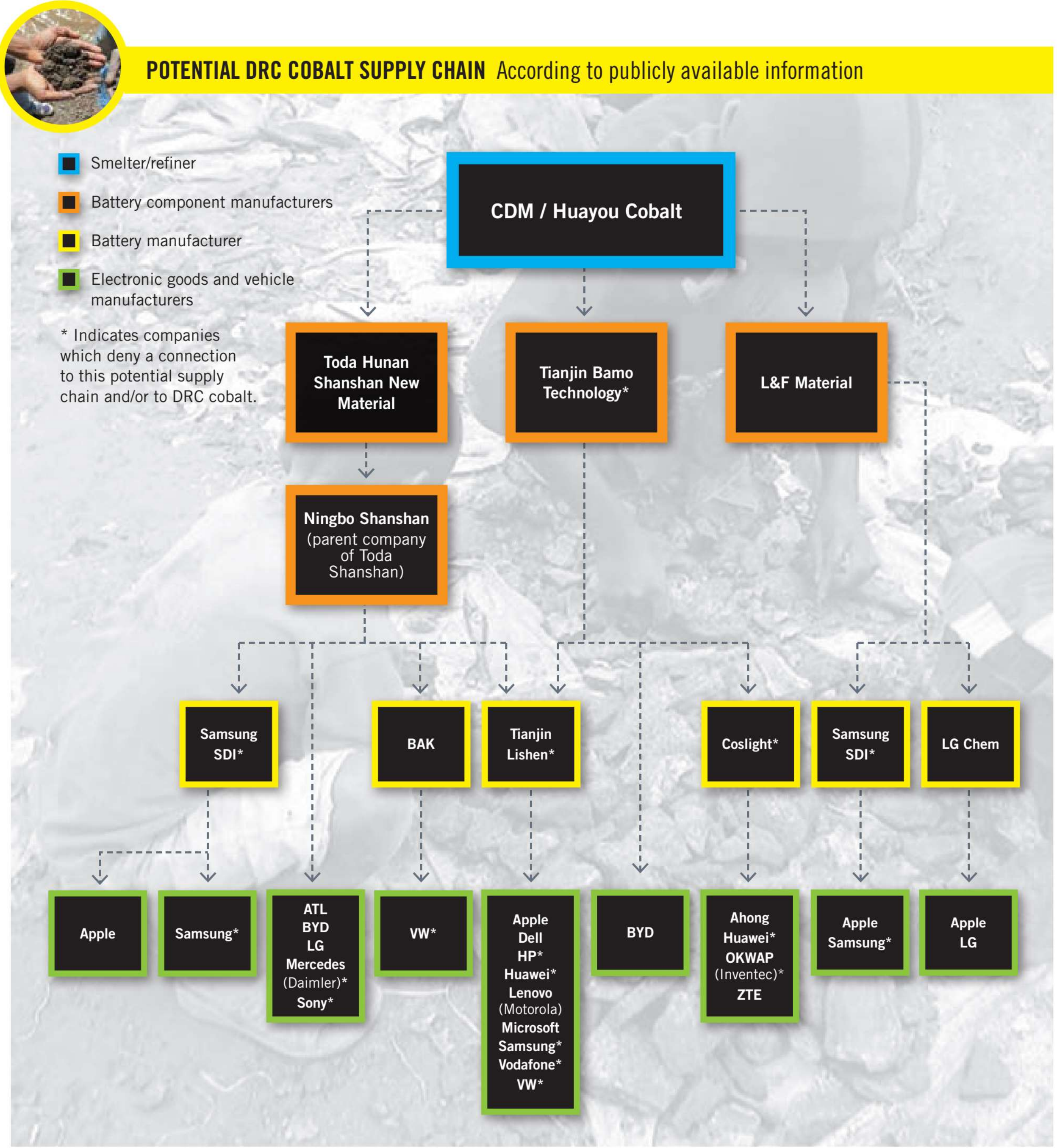


Social impact

Complex supply chain

Flow chart of the cobalt supply chain

Social impact



Social impact

conflict minerals

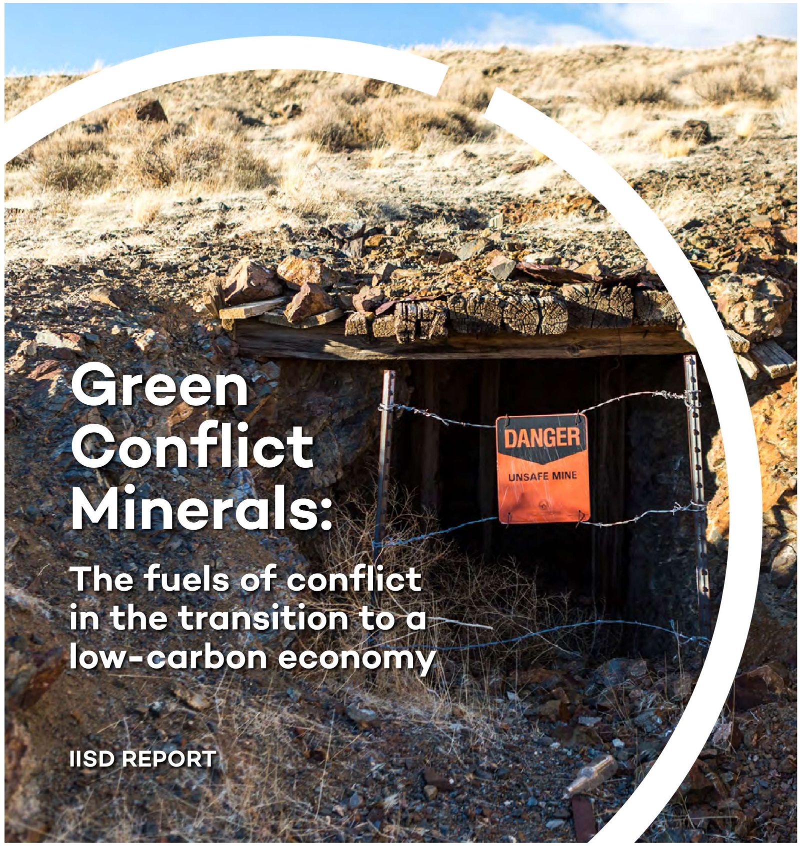
Conflict minerals are minerals used to finance armed groups, fuel forced labour and other human rights abuses, and support corruption and money laundering.

As defined by the US legislation, they currently include the metals **tantalum, tin, tungsten and gold** (3TG), which are the extracts of the minerals cassiterite, columbite-tantalite (coltan) and wolframite, respectively.

Concept extended to all resources whose extraction is associated with social problems (conflicts, human rights, child labour, etc.)

Social impact

2018 Report



IISD
International Institute for Sustainable Development

Clare Church
Alec Crawford

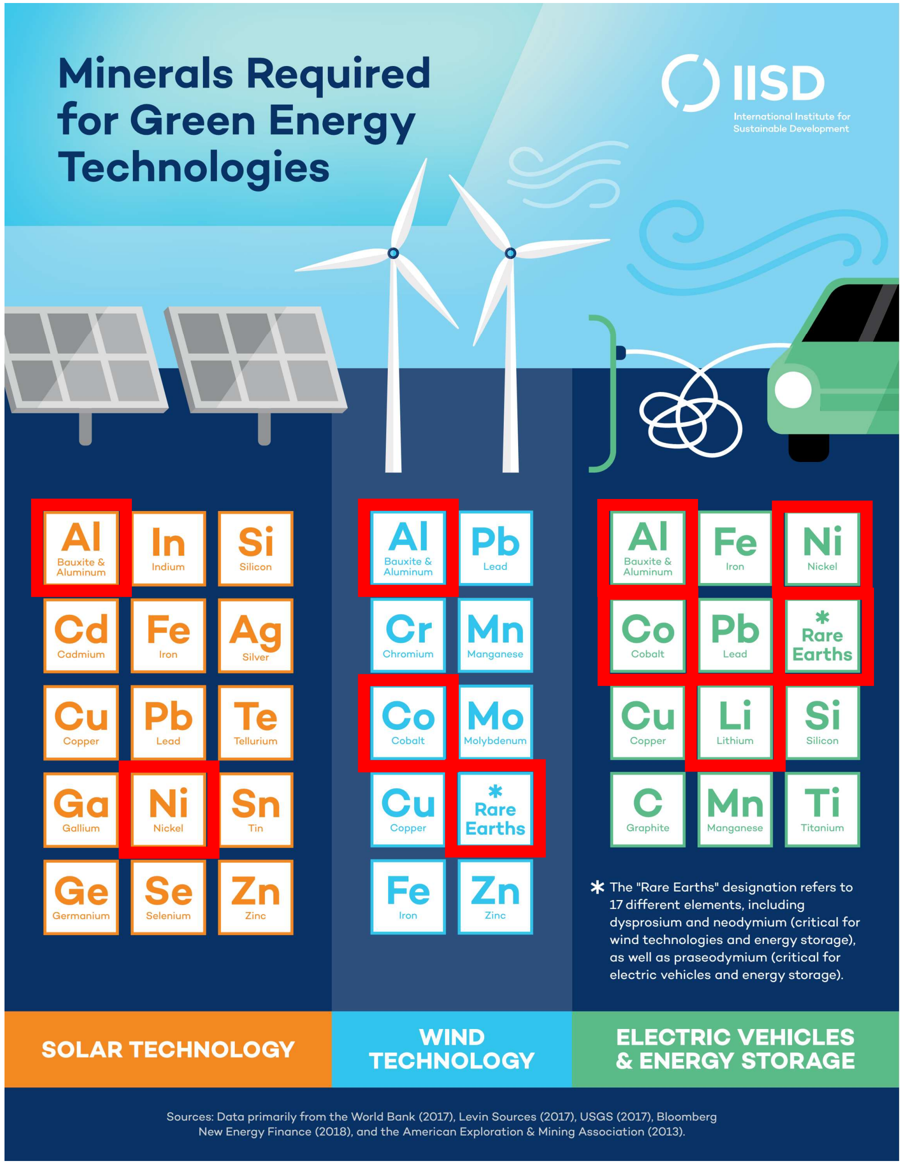
August 2018

IISD
International Institute for Sustainable Development

(Canadian Charity)

- Significant reserves of all of minerals used for the transition to a low-carbon economy are found in **states perceived to be both fragile and corrupt**
- The increased extraction of many of the identified minerals has been linked with **local grievances, tensions and violence**

Social impact



5 CASE STUDIES:

- **Cobalt** in DRC
- **Rare earths** in China
- **Nickel** in Guatemala
- **Bauxite** in Guinea
- **Lithium** in Zimbabwe

Social impact

(pollution → social tensions)

Rare earths in China

- Coupled with the growth of environmental activism, highly polluting rare earths mining in China could lead to **increasing tensions** at the local level. (RISK)
- Illegal mines are cited to sell to **organized crime** syndicates and **exploit workers**, some of which are **children**.

Bauxite in Guinea

- Villages near the mines suffer from the **negative consequences** of extraction: fertility of fields is decreasing, threatening local food security, contaminated local waterways, livestock endangered, respiratory problems.
- Steady rise in **local tensions and violence**, multiple riots broke out in 2017 leaving one dead and 20 injured.

Social impact

Australian REE processing in Malaysia

(social tensions)

https://www.scmp.com/week-asia/geopolitics/article/3011749/malaysia-snag-us-search-alternative-chinese-rare-earths

REUTERS

https://www.reuters.com/article/us-lynas-corp-malaysia/malaysia-environment-groups-lynas-workers-rally-over-rare-earths-plant-idINKCN1RM0AD

ENVIRONMENT APRIL 10, 2019 / 5:34 AM / UPDATED 2 YEARS AGO

Malaysia environment groups, Lynas workers rally over rare earths plant

By Liz Lee

3 MIN READ

KUALA LUMPUR (Reuters) - Malaysian environmental groups and Lynas Corp workers held rival demonstrations in Kuala Lumpur on Wednesday over concerns about radioactive waste from the company's rare earths processing plant in the country.

Social impact

Possible solutions

- National regulations (producing countries)
- National regulations (beneficiaries)
- Corporate responsibility (producers)
- Corporate responsibility (buyers)
- Consumer awareness (end users)

pressure

Social impact

EU passed a **new regulation** in May 2017 to stop

- conflict minerals and metals from being exported to the EU;
- global and EU smelters and refiners from using conflict minerals;

It requires EU companies to ensure they import these minerals and metals **from responsible sources** only.

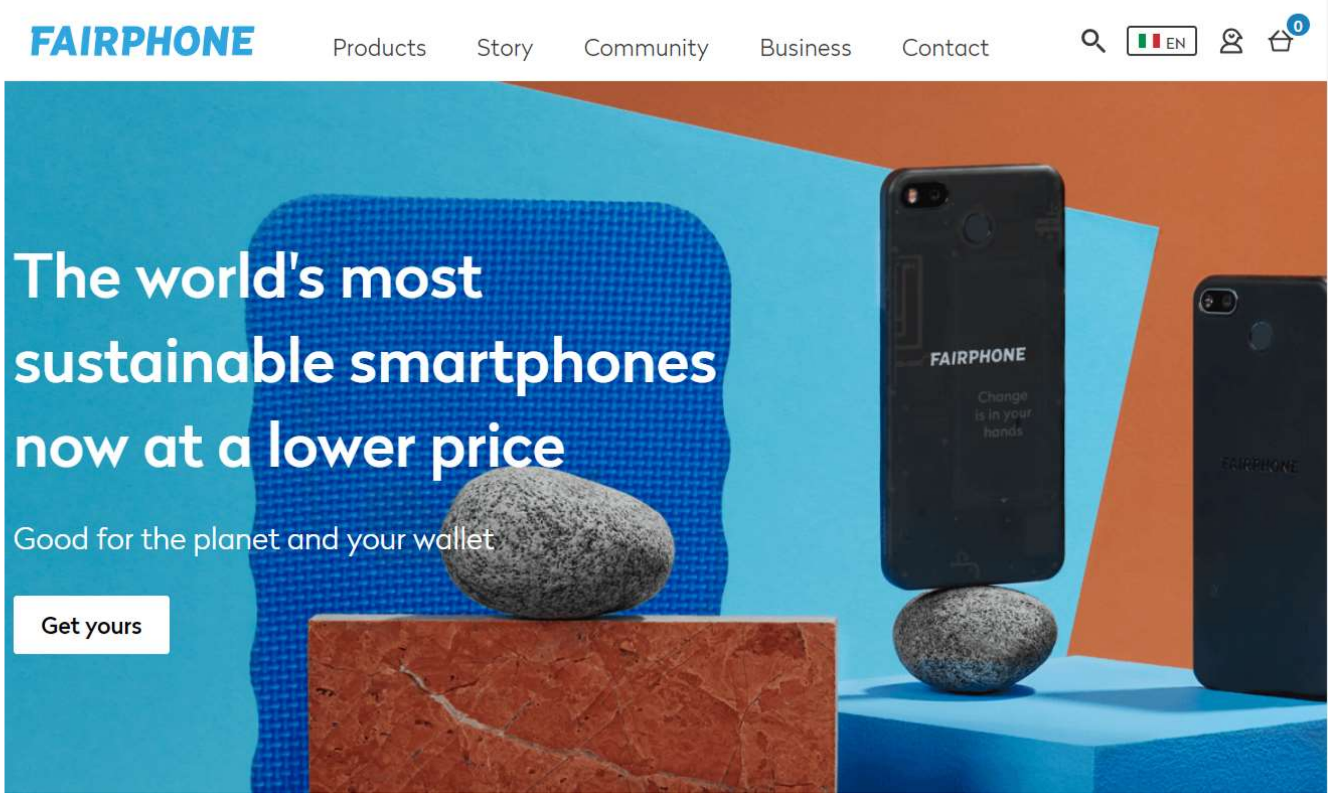
The requirements start to apply on 1 January 2021.

(likely expanded to include cobalt besides 3TG)

(https://ec.europa.eu/trade/policy/in-focus/conflict-minerals-regulation/index_en.htm)

Social impact

an example



- **Responsibly sourced materials (certified supply chain)**
- Recycled materials
- Modular design (replaceable parts/upgrades, extended life)

CRMs in strategic technologies and sectors

what now?

need to evaluate
the ***impact*** of CRMs
on ***strategic sectors***

(a different kind of assessment)

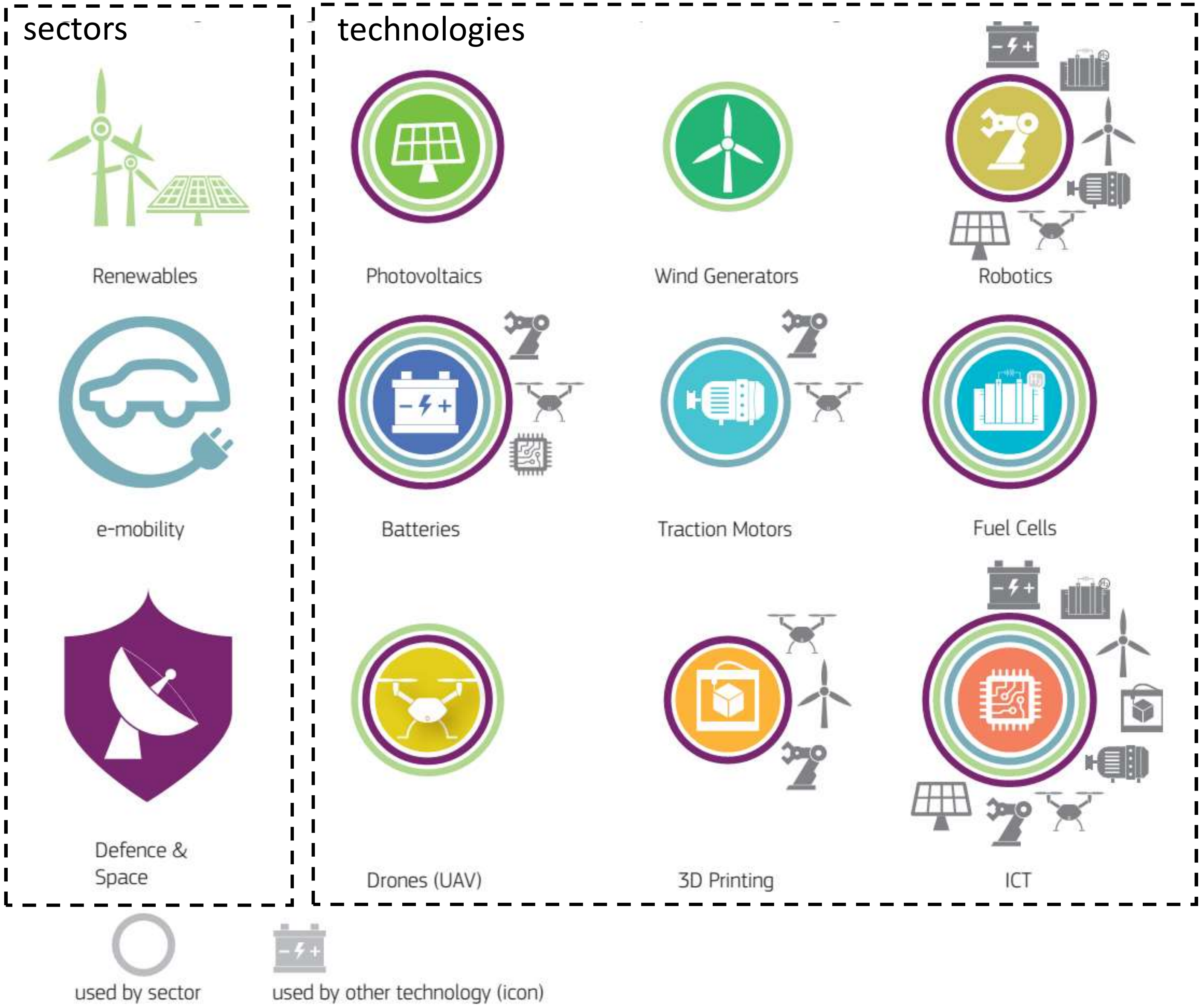
CRMs in strategic technologies and sectors

European Commssion report late 2020

foresight study

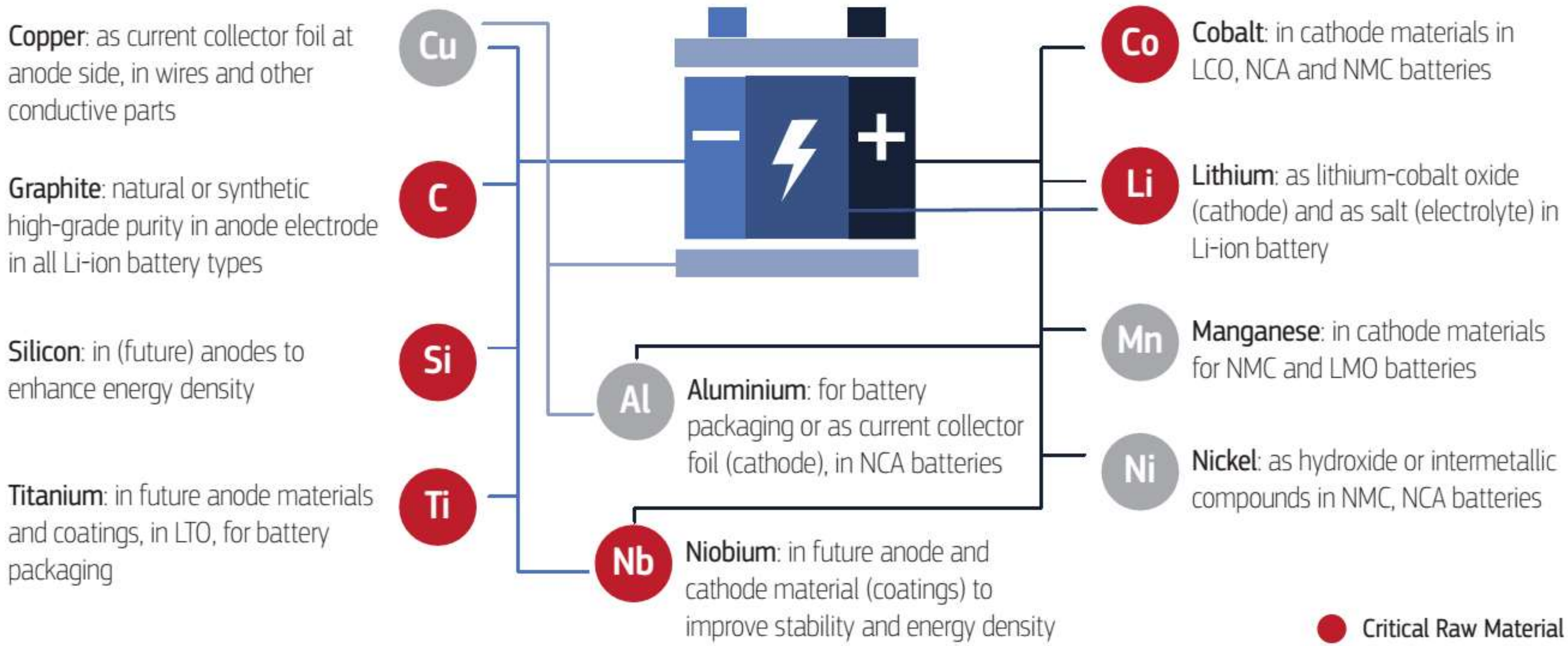
how CRMs will impact on strategic technologies and sectors

CRMs in strategic technologies and sectors



CRMs in strategic technologies and sectors

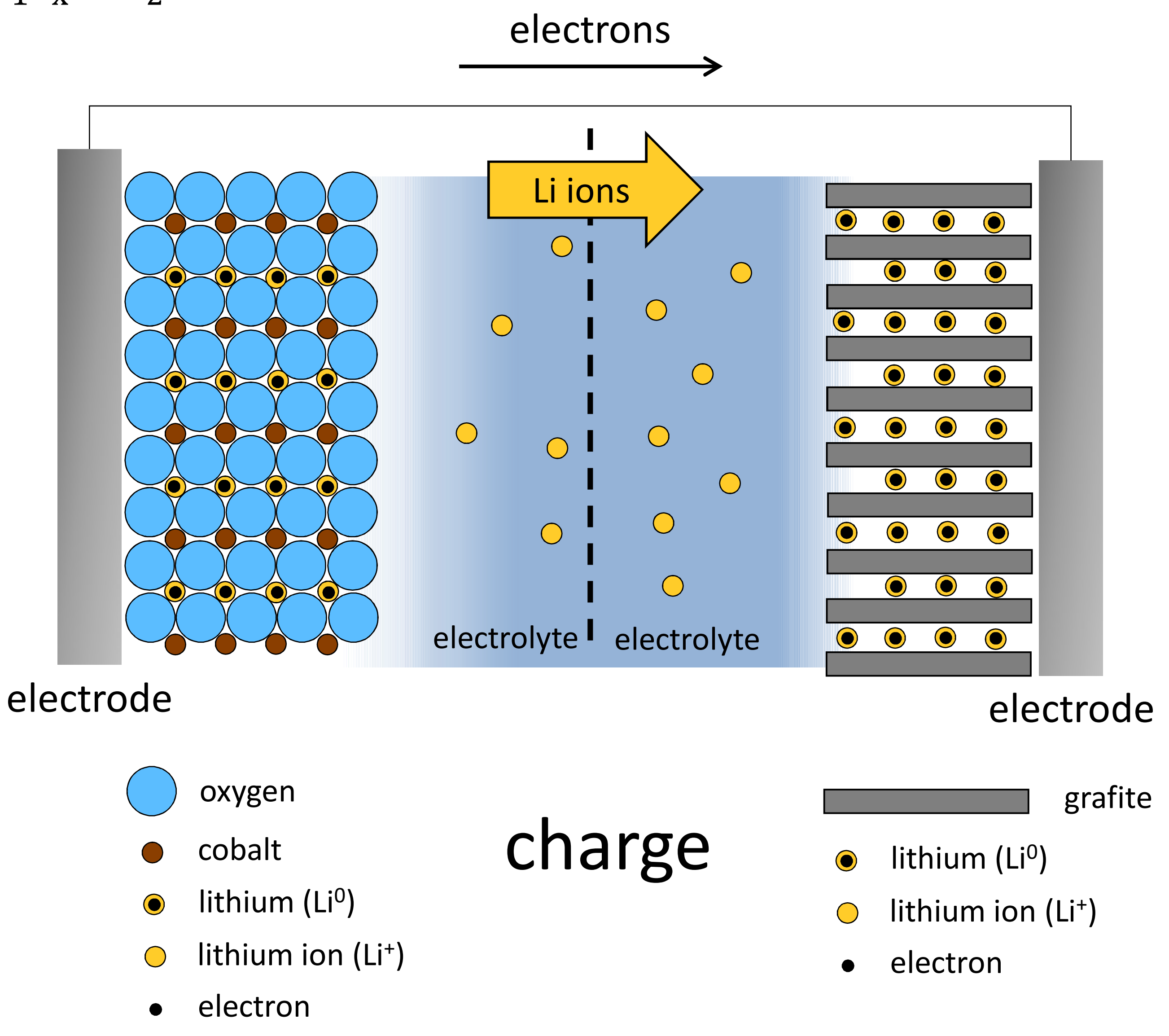
Li-ion battery technology



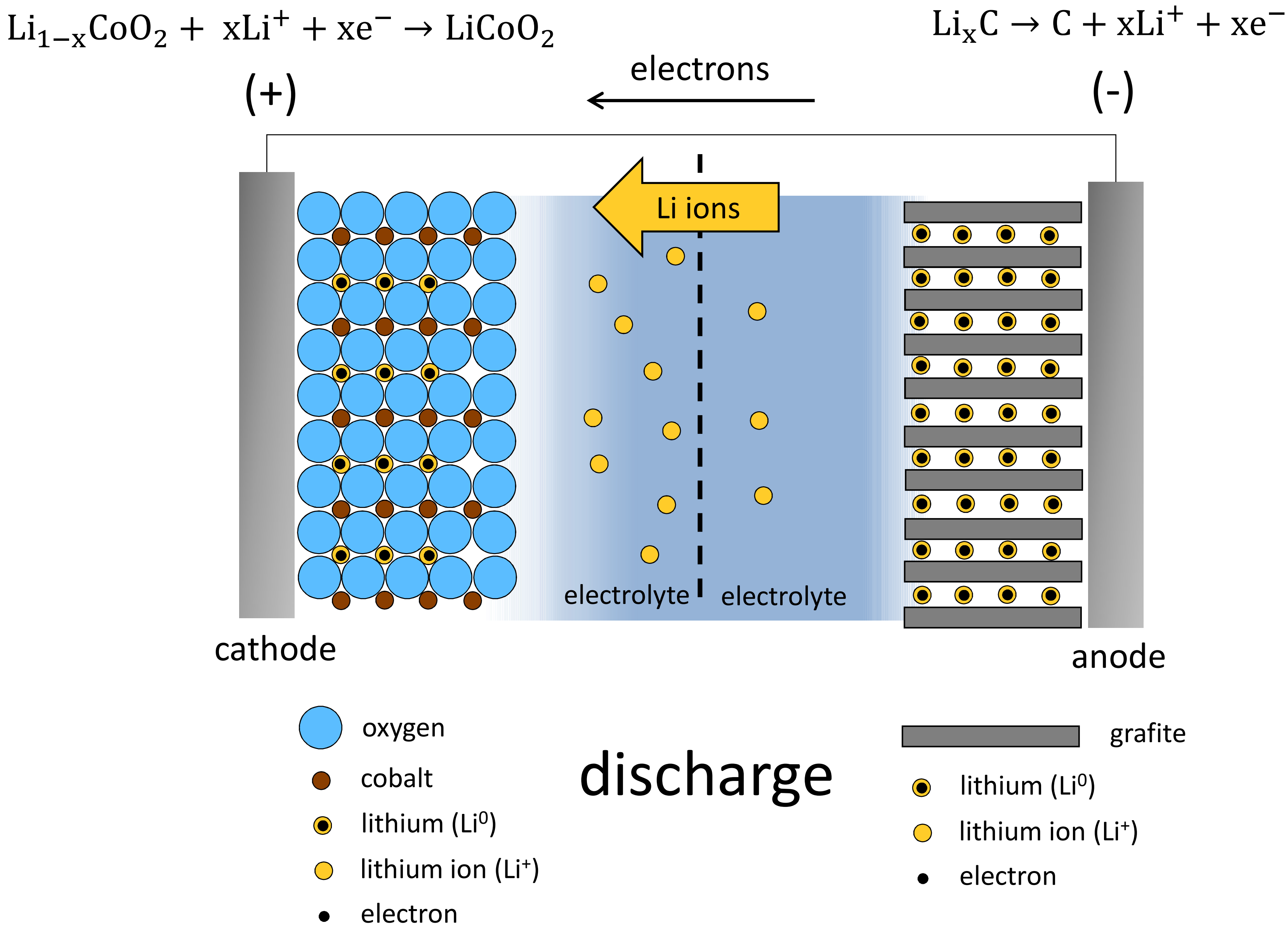
CRMs in strategic technologies and sectors

$$LiCoO_2 \rightarrow Li_{1-x}CoO_2 + xLi^+ + xe^-$$

$$C + xLi^+ + xe^- \rightarrow Li_xC$$

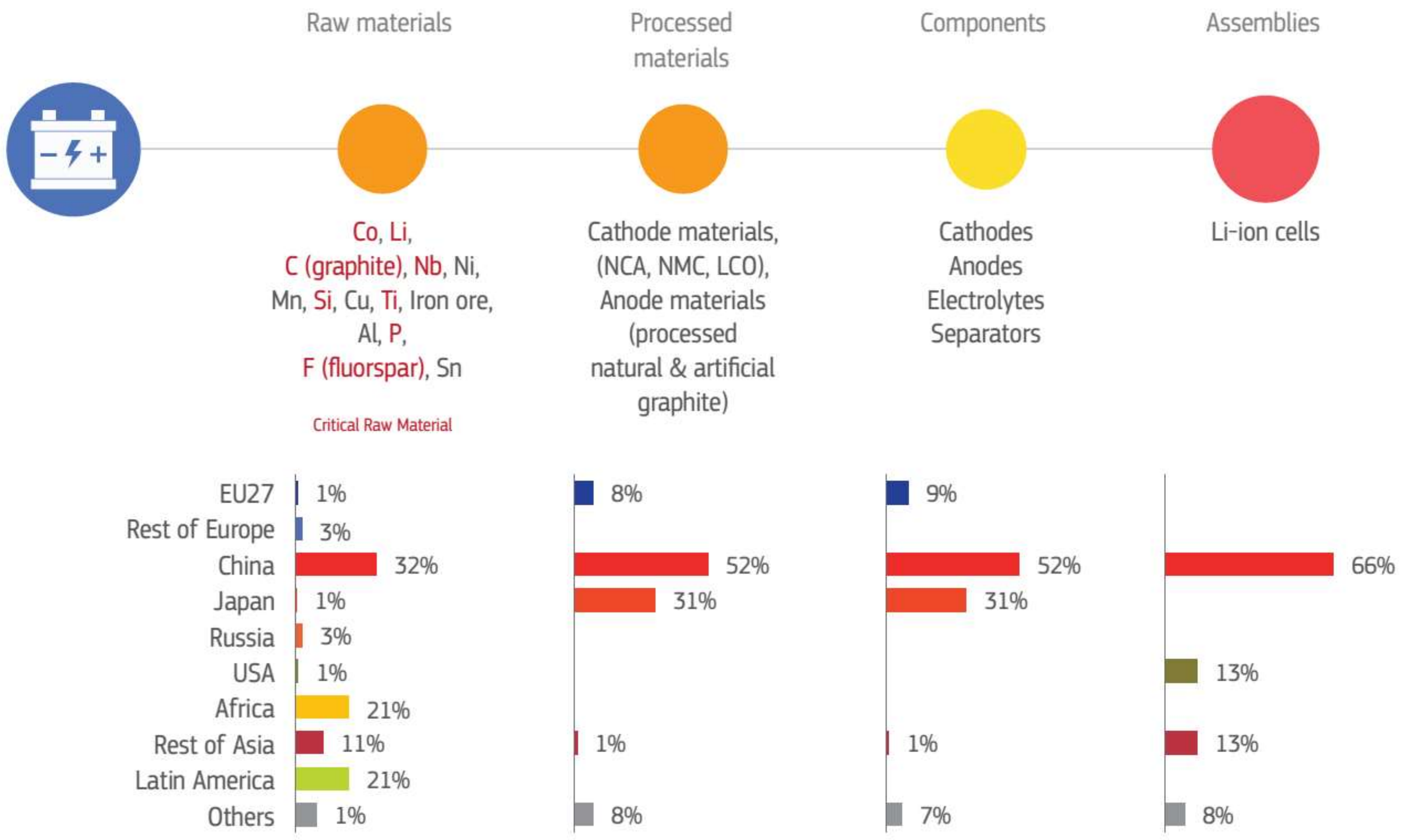


CRMs in strategic technologies and sectors



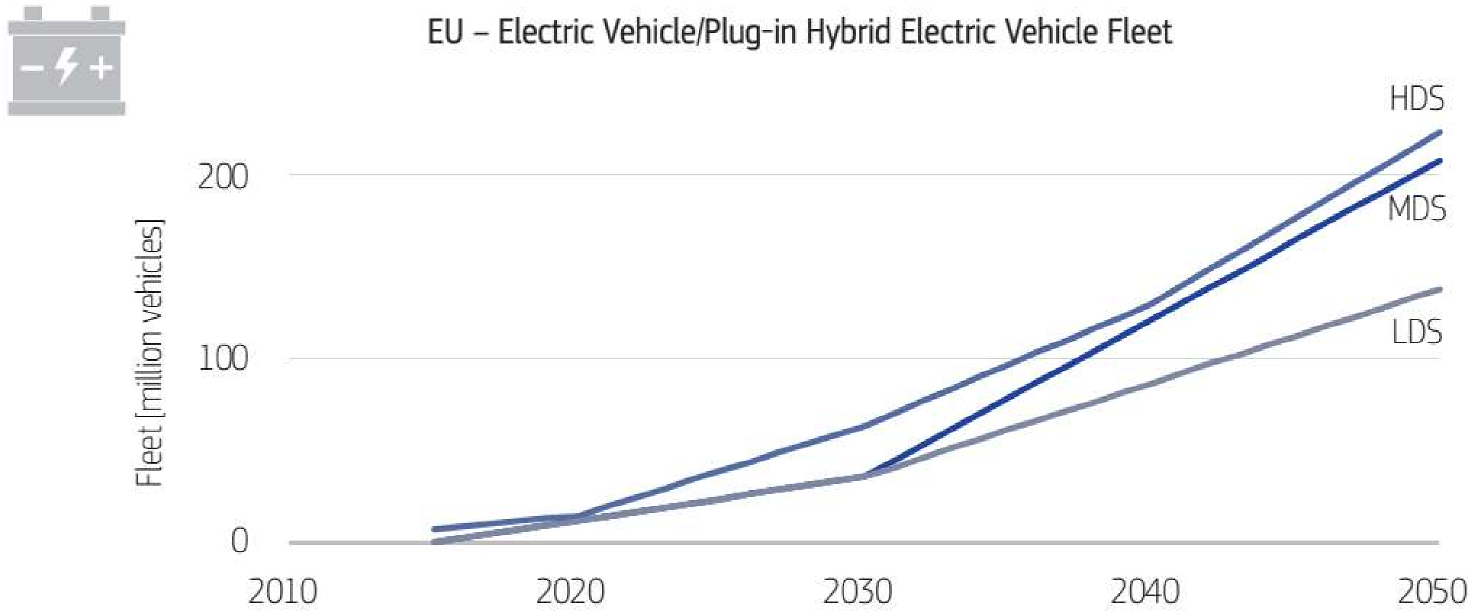
CRMs in strategic technologies and sectors

Figure 8. Li-ion batteries: an overview of supply risks, bottlenecks and key players along the supply chain. (See the Glossary for the acronyms used)



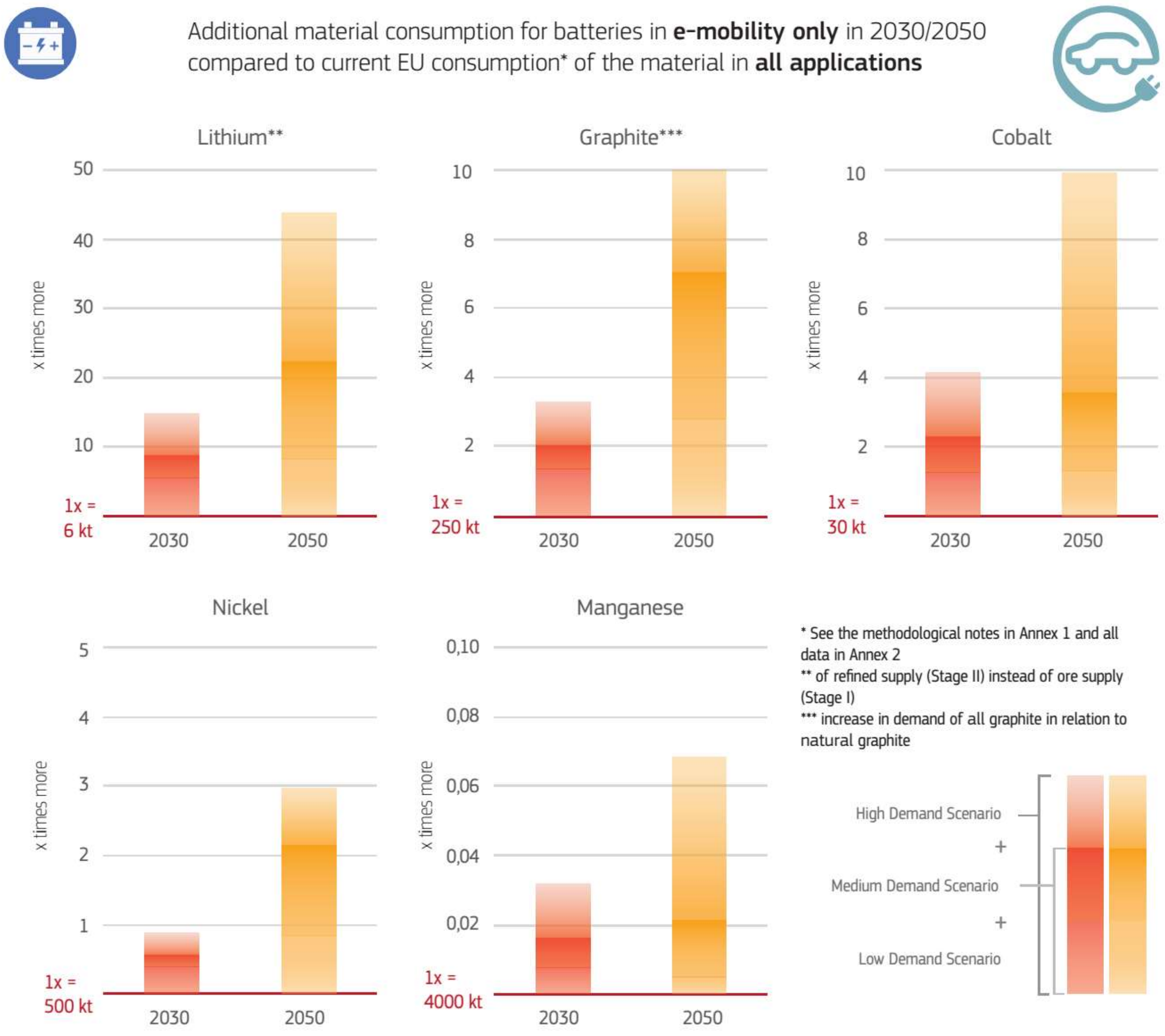
CRMs in strategic technologies and sectors

Figure 9. EU fleet of electric vehicles containing batteries according to the three explored scenarios



CRMs in strategic technologies and sectors

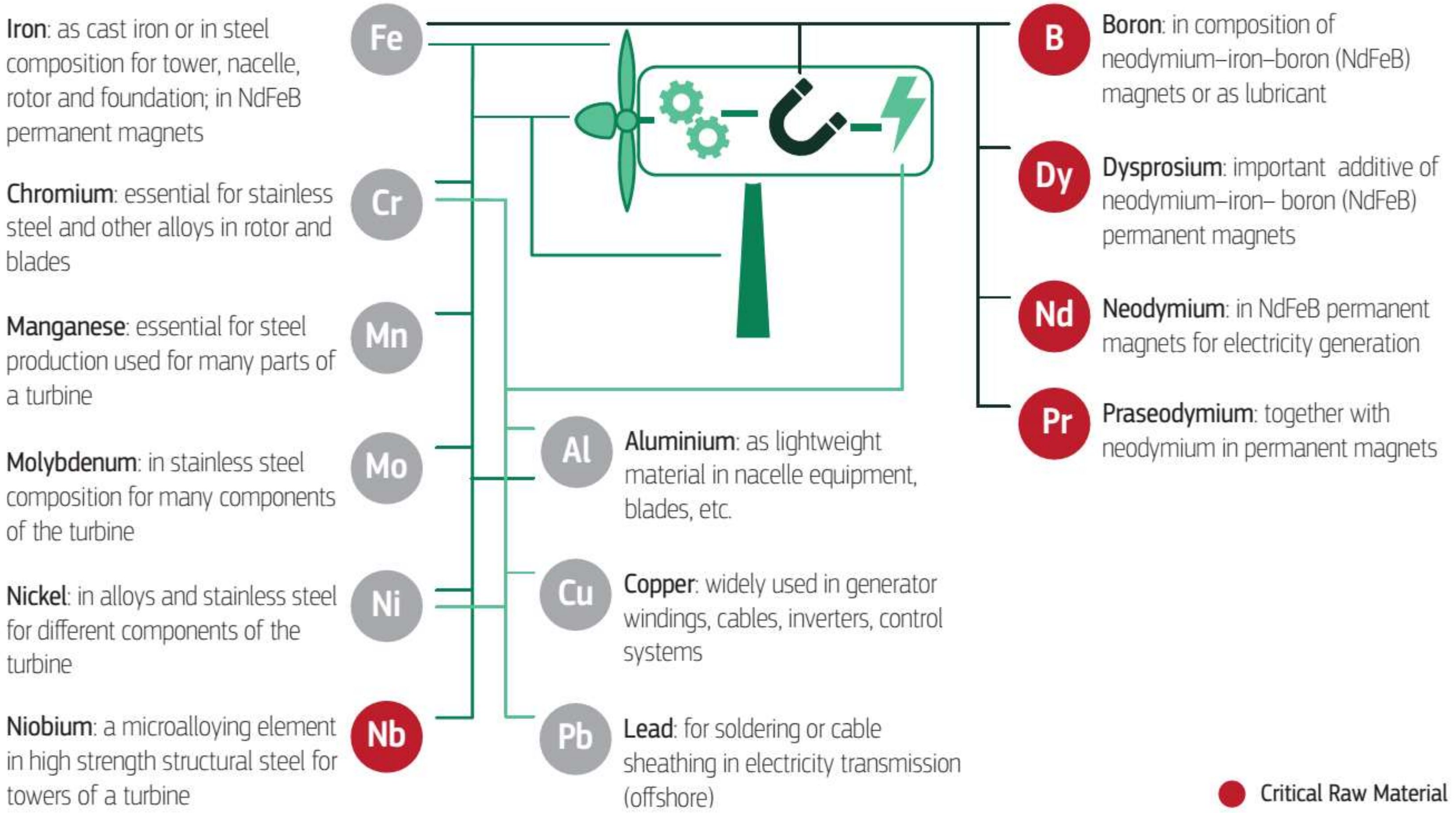
Figure 10. EU annual material demand for batteries in EVs in 2030 and 2050



CRMs in strategic technologies and sectors

Wind turbines generators

Figure 18. Raw materials used in wind turbines



CRMs in strategic technologies and sectors

two categories of wind turbines

1. Geared turbines

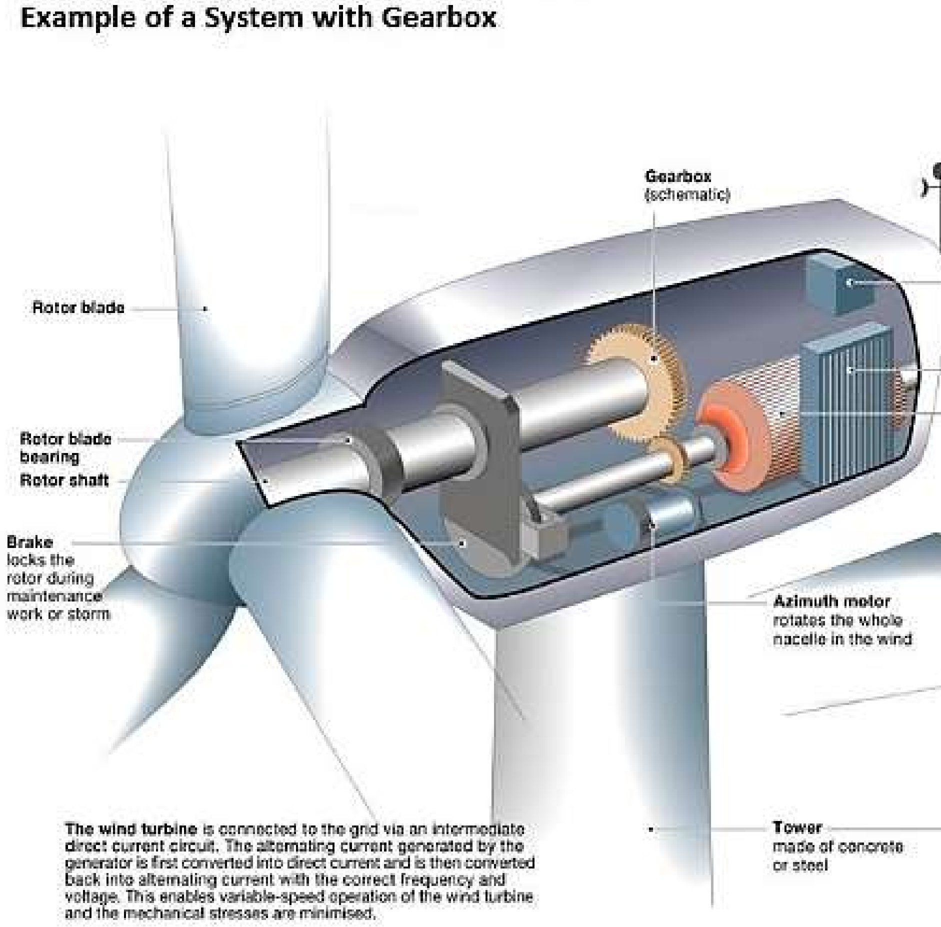
- most common (80%)
- use gearbox to convert low rotational speed to much higher speed
- use induction generators (with significant amounts of Cu and Fe)
- low costs
- require more frequent mantainance
- dominate on-shore installations

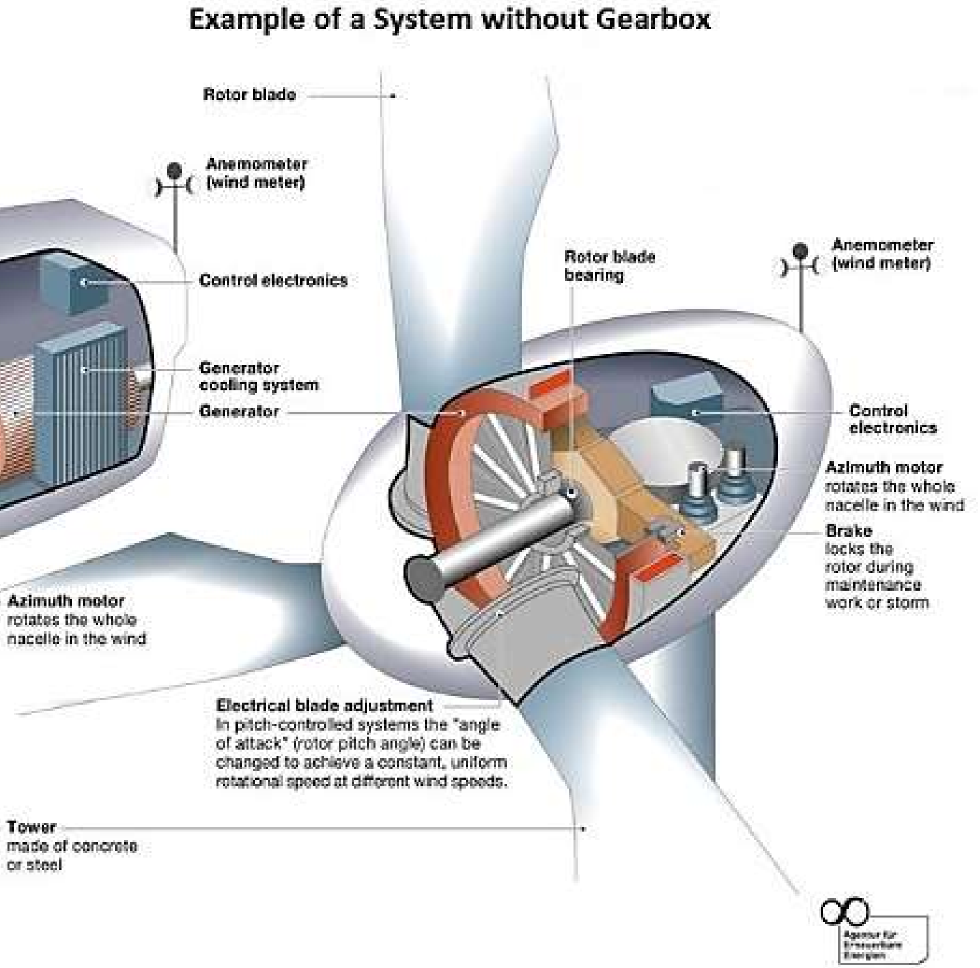
2. Direct drive turbines

- less common (20%)
- use generators directly fixed to the rotors (same speed)
- use induction generators or **permanent magnets (REEs)**
- more expensive
- require **less mantainance**
- mostly use **off-shore**

CRMs in strategic technologies and sectors

two categories of wind turbines





(https://ei-spark.lbl.gov/generation/onshore-wind/turb/nacelle/innov/)

CRMs in strategic technologies and sectors

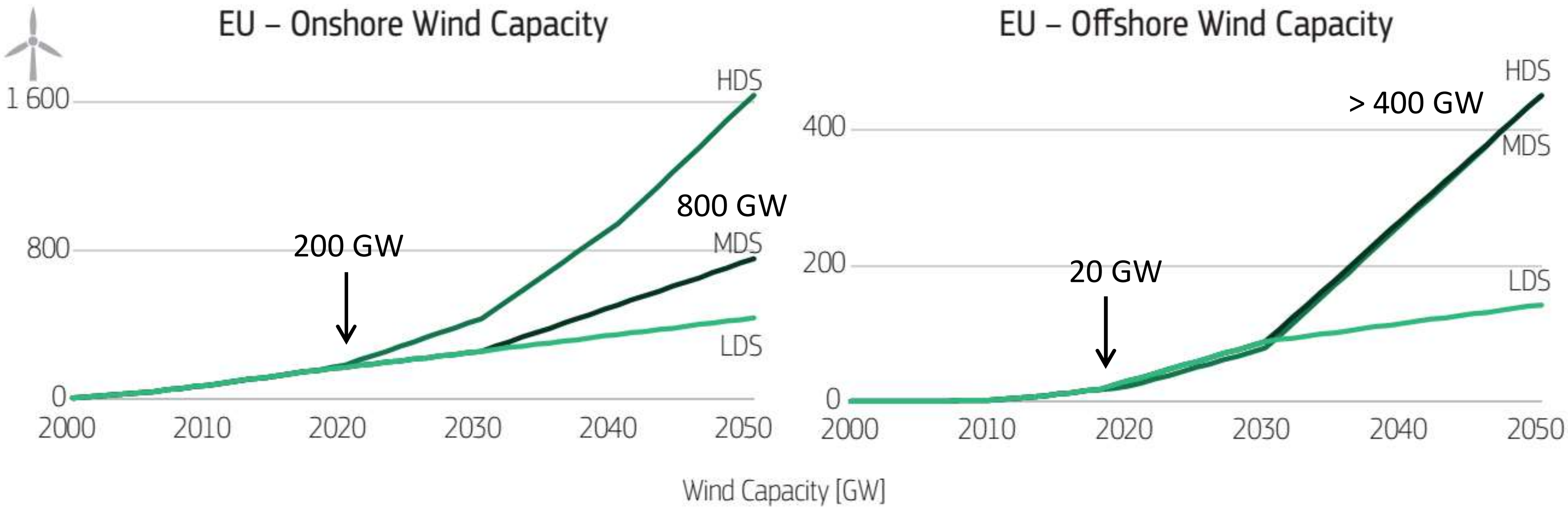
Table 3.3 Share of Subtechnology Penetration in Wind Market Compared with Base Share

2050 share	Onshore Geared	Onshore Direct drive	Offshore Geared	Offshore Direct drive
Base share (2DS)	75%	25%	25%	75%
High share: **Geared**	**90%**	10%	**40%**	60%
High share: **Direct drive**	60%	**40%**	10%	**90%**

(World Bank, Minerals for Climate Action, 2020)

CRMs in strategic technologies and sectors

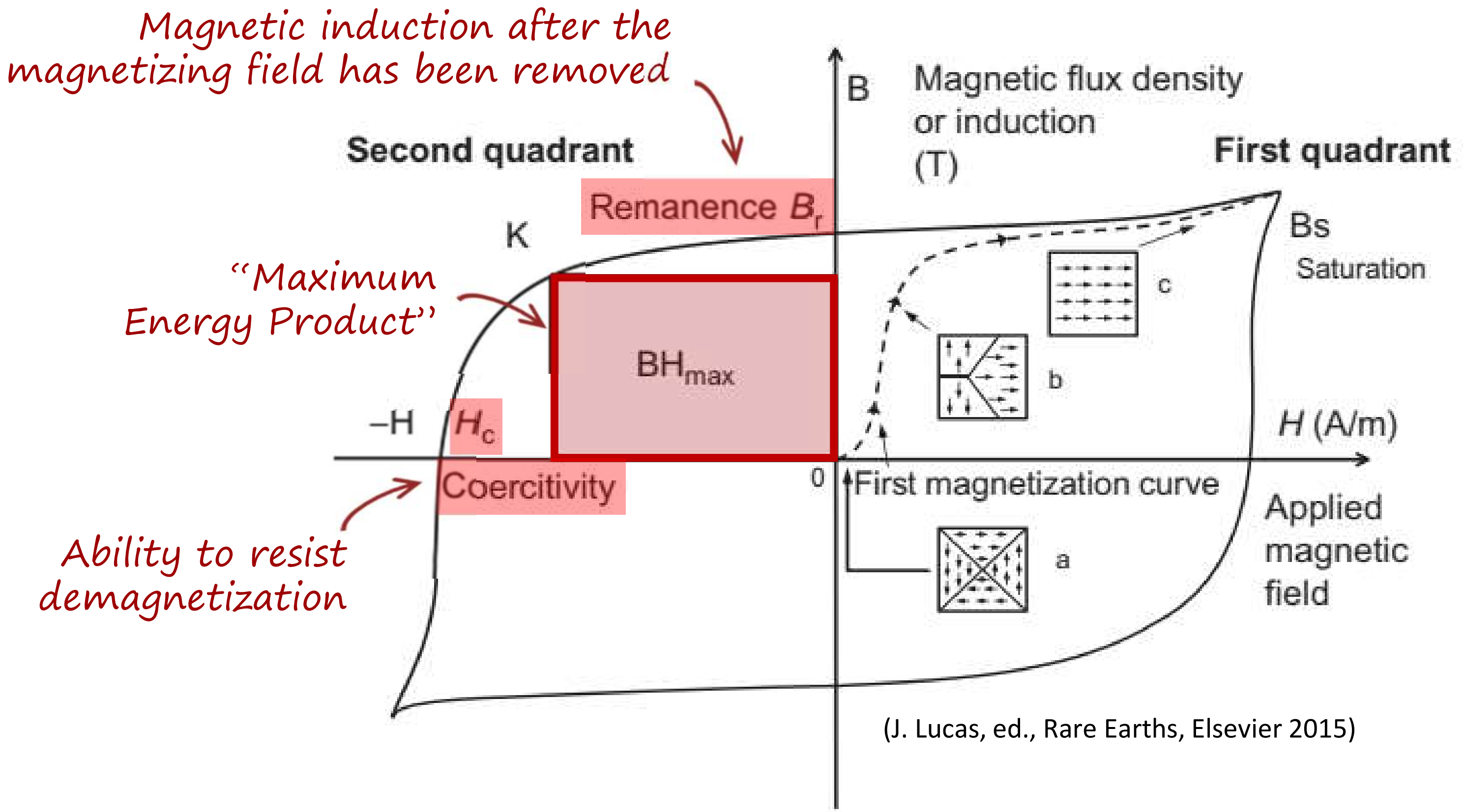
Figure 20. Onshore and offshore wind capacity in the three explored scenarios.



off-shore installations are expected to grow more

CRMs in strategic technologies and sectors

Hysteresis loop of a ferromagnetic material

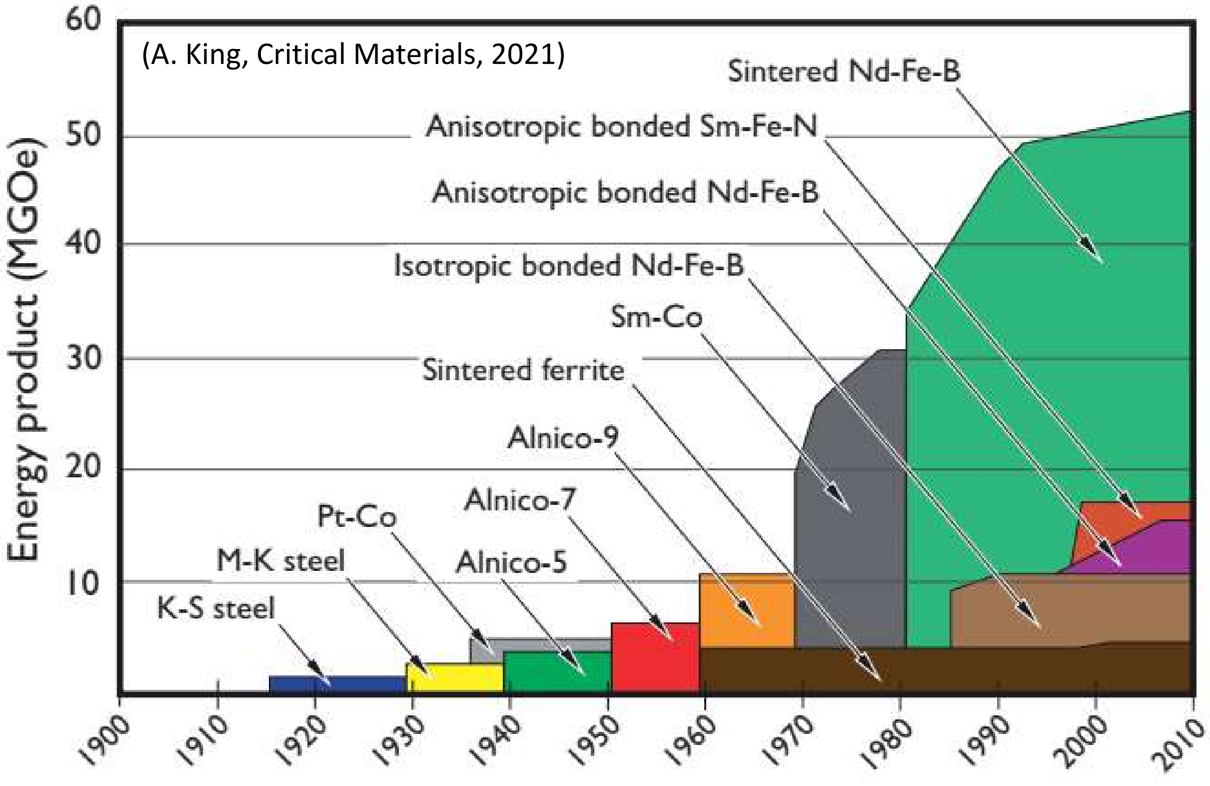


(J. Lucas, ed., Rare Earths, Elsevier 2015)

Large values of B_r and H_c (i.e. BH_{max}) are important for permanent magnets

CRMs in strategic technologies and sectors

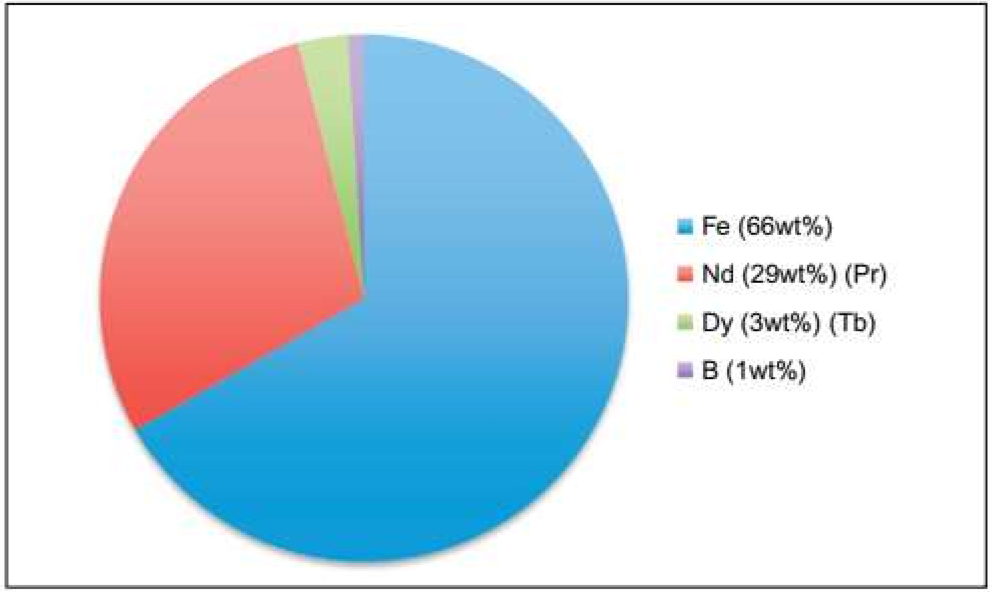
superiority of Nd-Fe-B magnets



???
breakthrough
expected
(*new material*)

CRMs in strategic technologies and sectors

Composition of a NdFeB magnet



(J. Lucas, ed., Rare Earths, Elsevier 2015)

1/3 in weight
is Neodymium!

in an electric car: 1-2.5 kg magnet (725 g Nd)

in a wind turbine with a direct drive generator (low-speed PMSG 3MW):
2 tonnes magnet (~560 kg Nd)*

*Pavel et al. Resources Policy 52 (2017) 349–357

CRMs in strategic technologies and sectors

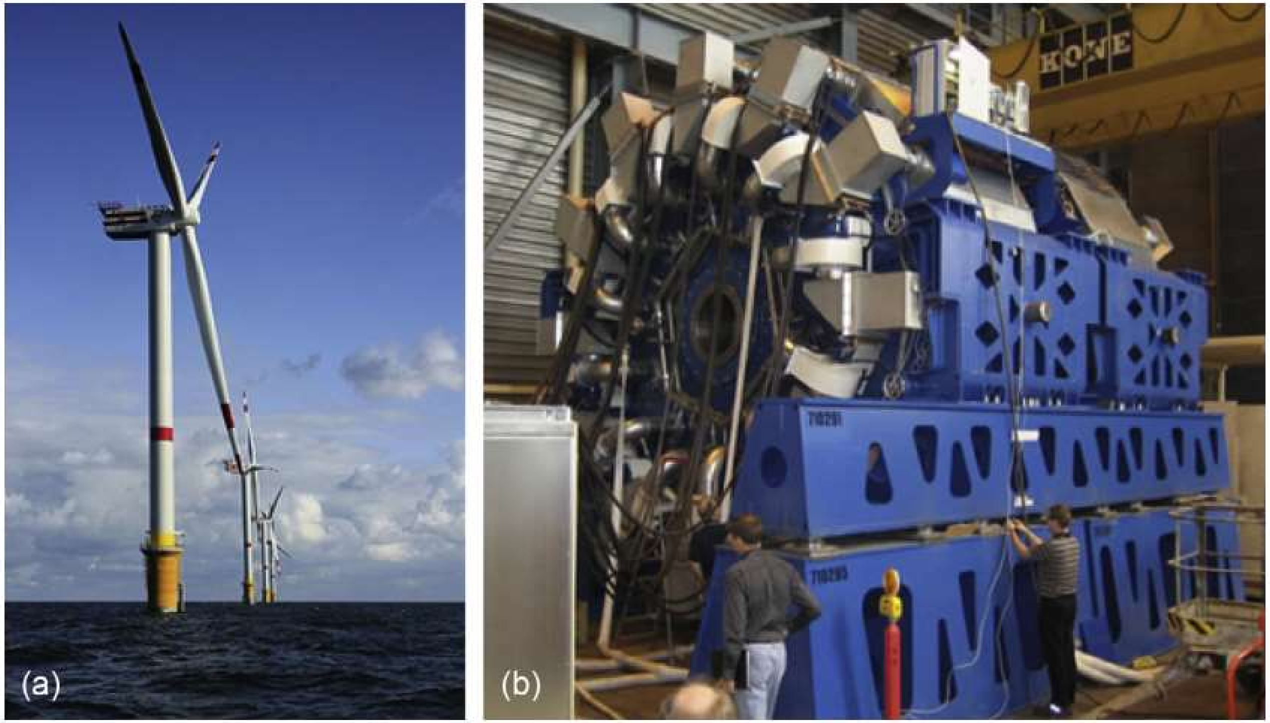


FIG. 14.15

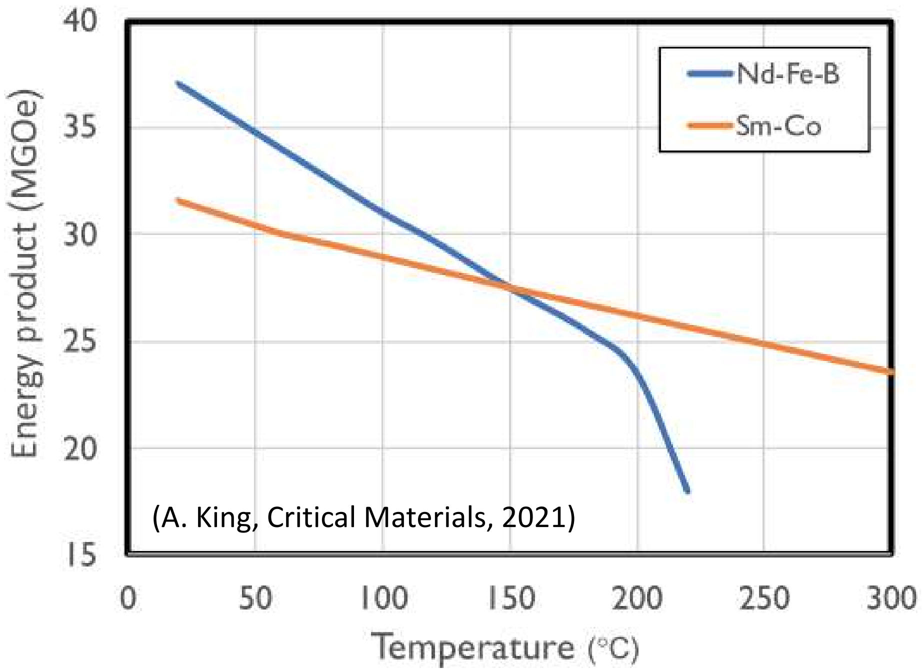
(a) Photography of offshore wind turbines equipped with permanent magnet generator (PMG). These turbines produce 3.5 MW of power using about 2 t of magnets, which correspond to 0.6 kg of NdFeB alloys for the production of 1 kW. Rotor blades are up to 80 m long (Wikipedia commons photo). (b) PMG of a wind turbine using NdFeB magnets. Strong magnets enable gearbox-free generators to improve reliability and lower maintenance. Technicians give the size of the generator.

Courtesy of The Switch.

(J. Lucas, ed., Rare Earths, Elsevier 2015)

CRMs in strategic technologies and sectors

Fig. 4.9 General features of the thermal performance of rare-earth magnets. All magnets lose strength with increasing temperature, but this effect is much more significant for neodymium-iron-boron than for samarium-cobalt magnets.

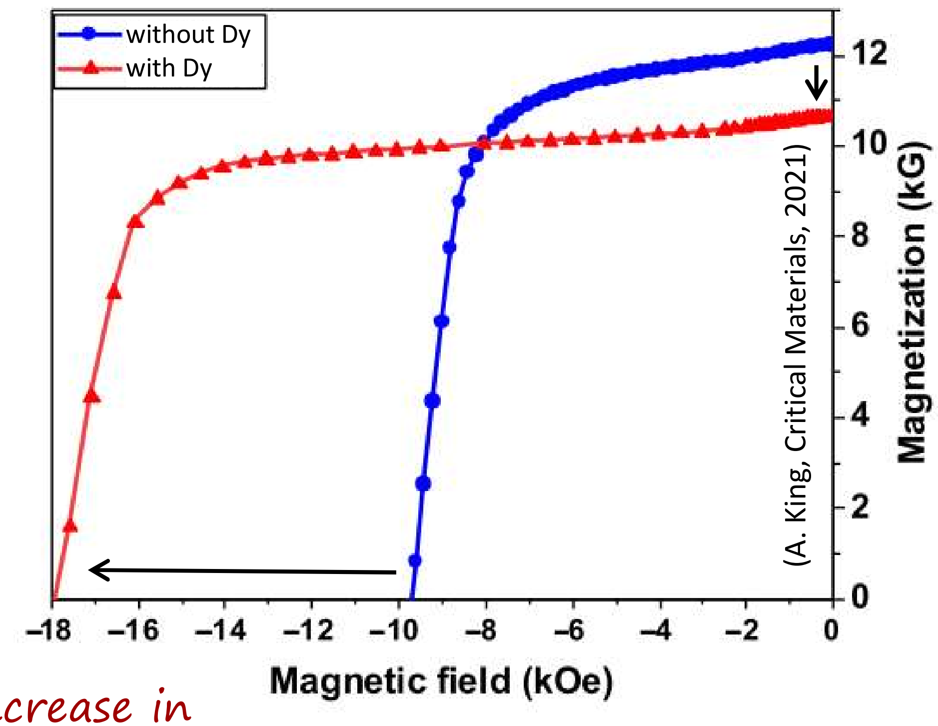


can be improved by adding Dy

- **NeFeB magnets** more efficient at **low temperatures**
- **SmCo magnets** more efficient at **higher temeperatures**

CRMs in strategic technologies and sectors

Effect of replacing some of the Nd with Dy in NdFeB magnets

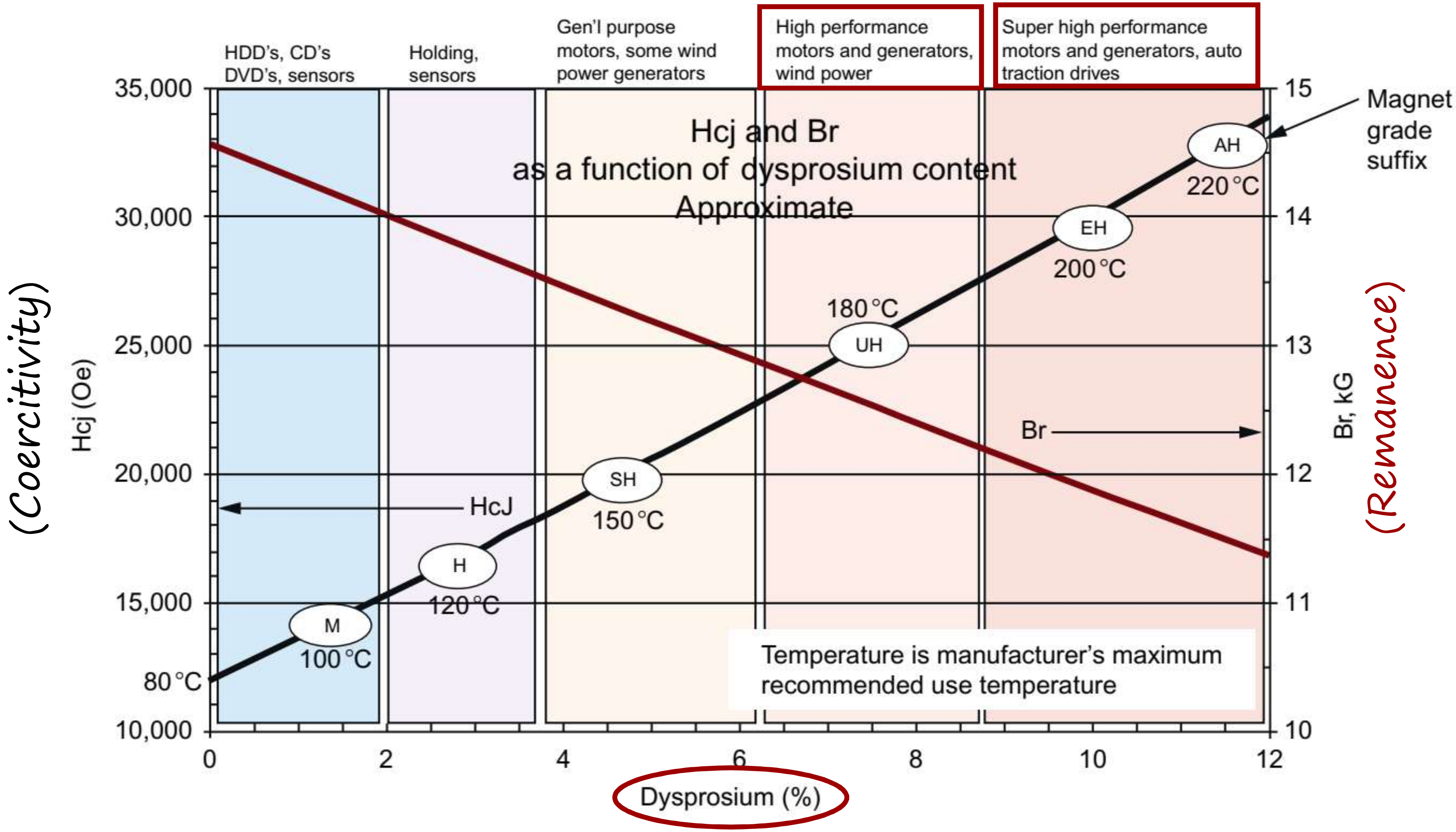


slight decrease in Remanence B_r

large increase in Coercivity H_c

better performances at ***higher temperatures***

CRMs in strategic technologies and sectors



(J. Lucas, ed., Rare Earths, Elsevier 2015)

CRMs in strategic technologies and sectors

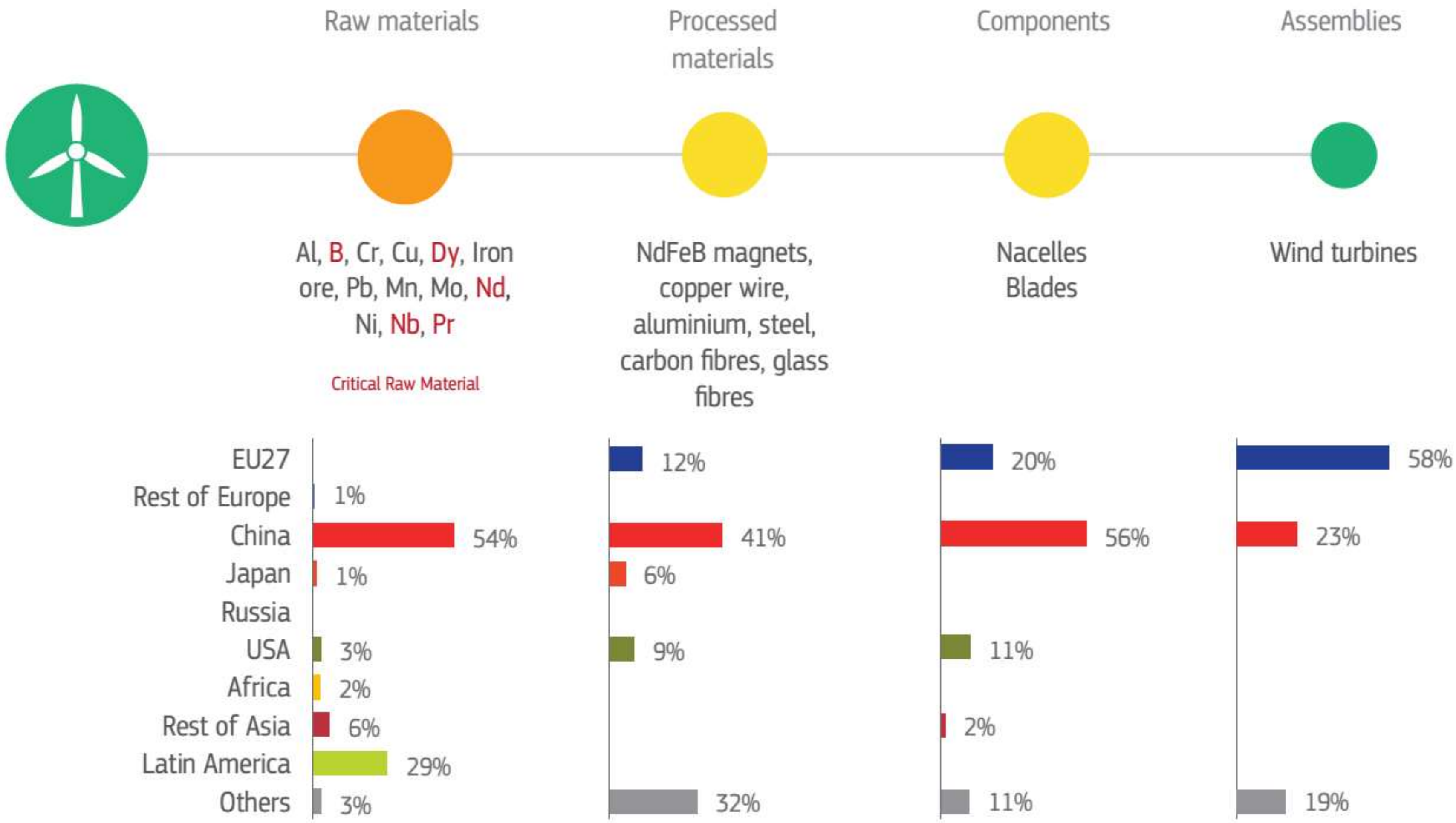
Curie and **working temperatures** for permanent magnets

Magnet type	Max. Working Temperature (deg. C)	Curie Temperature (deg. C)
NdFeB-s		
N	80	310
M	100	340
H	120	340
SH	150	340
UH	180	350
EH	200	350
AH	230	350
SmCo-s		
SmCo5	250	750
Sm2Co17	250-350	800
AlNiCo		
Sintered	450	760-890
Cast	450-550	810-890
Ferrite-s	250	450

(https://www.hsmagnets.com/blog/curie-temperature-of-permanent-magnets/)

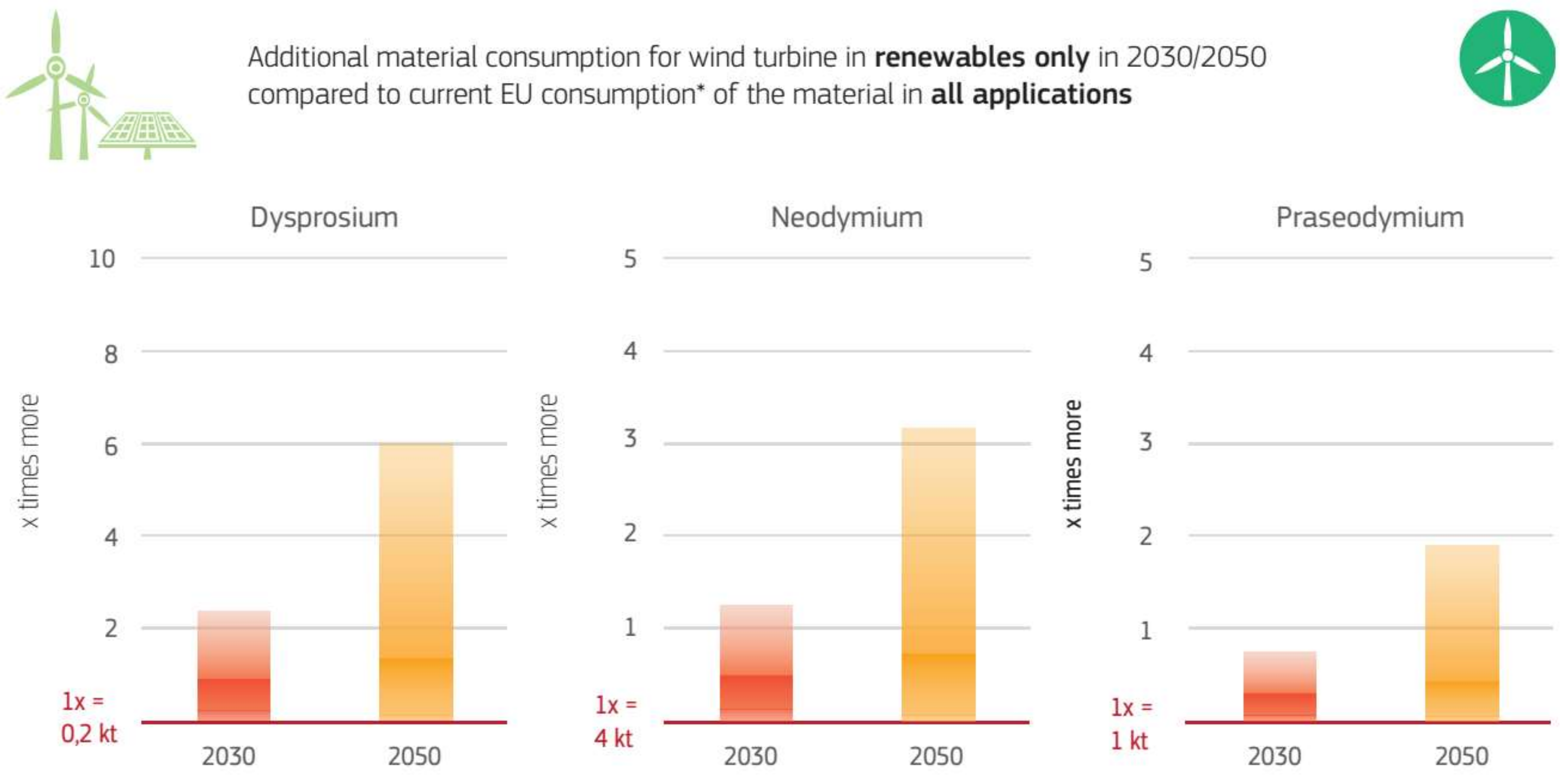
CRMs in strategic technologies and sectors

Figure 19. An overview of supply risks, bottlenecks and key players along the supply chain of wind turbines.



CRMs in strategic technologies and sectors

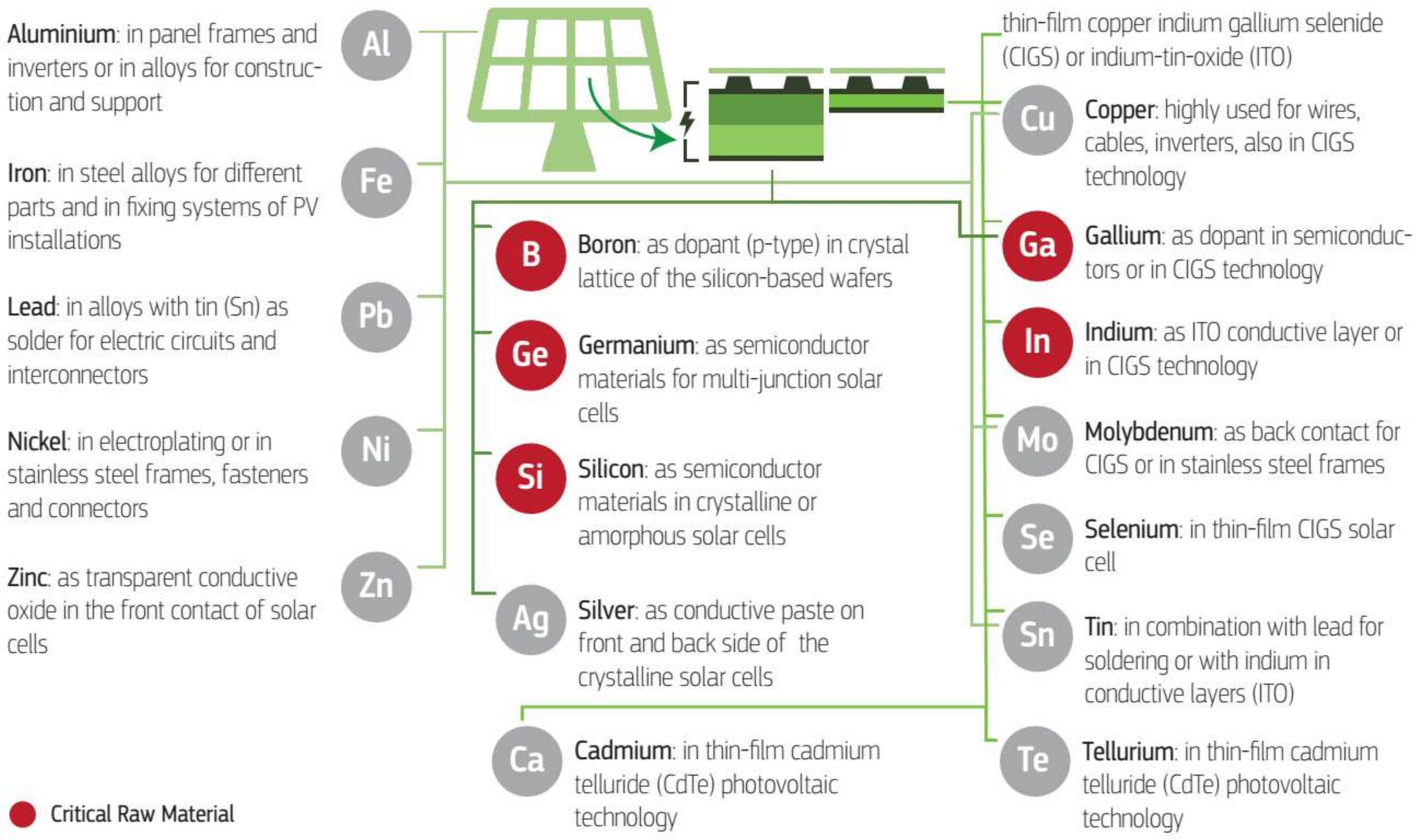
Figure 22. EU annual material demand for wind power in 2030 and 2050.



CRMs in strategic technologies and sectors

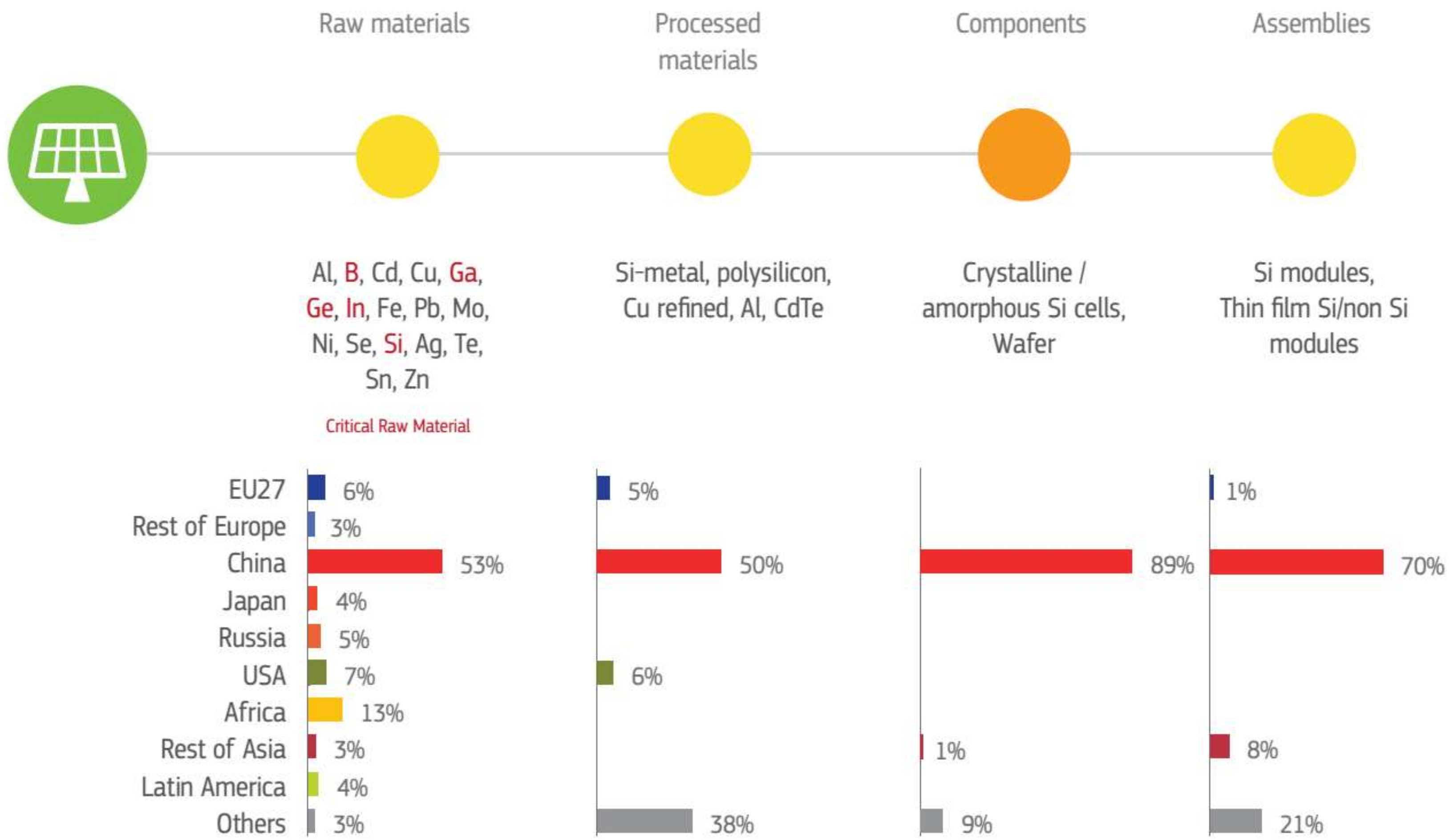
Photovoltaics

Figure 27. Raw materials used in solar PV technologies



CRMs in strategic technologies and sectors

Figure 28. Solar PV: an overview of supply risks, bottlenecks and key players along the supply chain.



CRMs in strategic technologies and sectors

Robotics, drones and digital technologies are most **metal intensive**

B, Si, Cu are elements present in all/most technologies

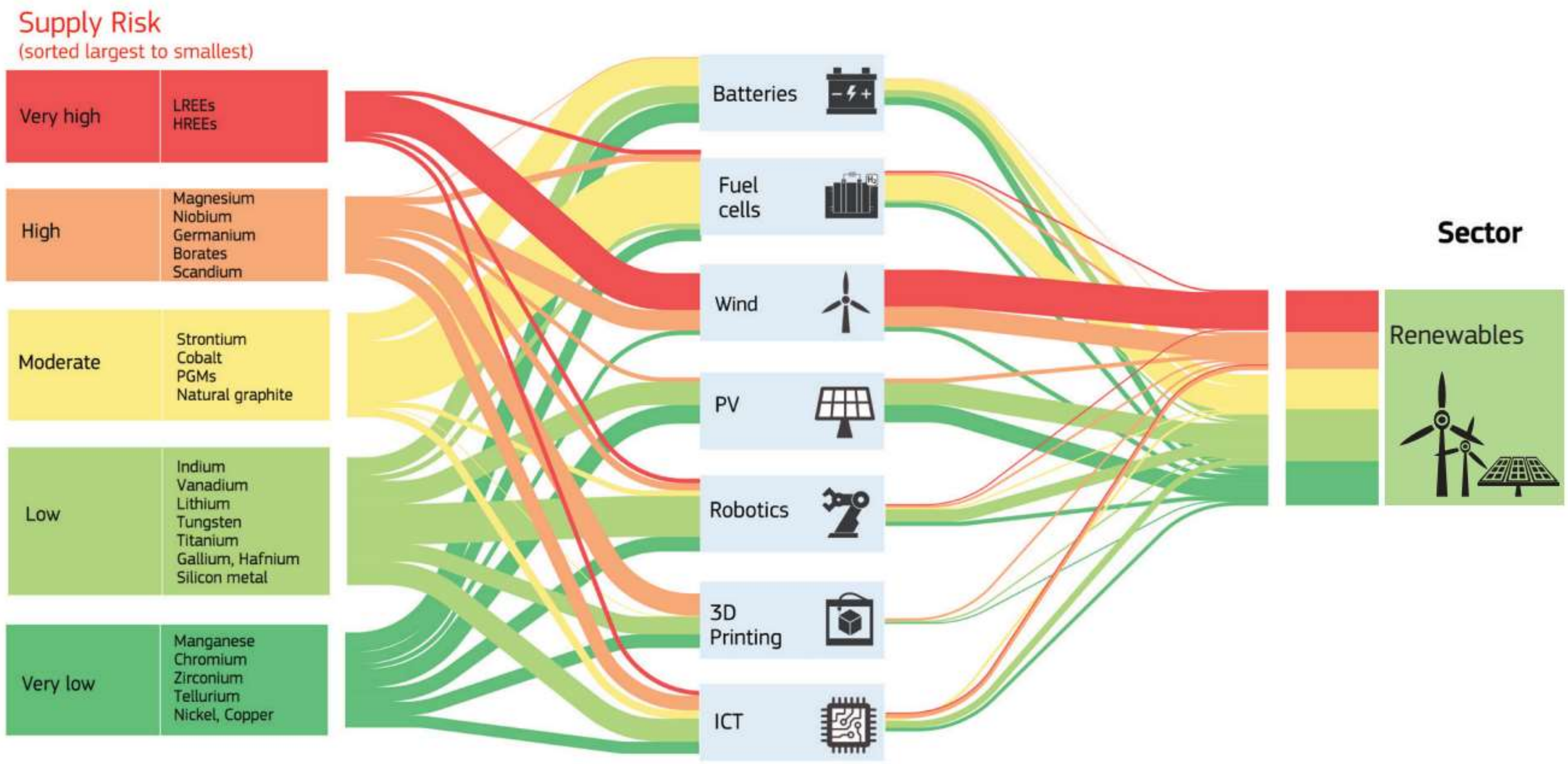
Supply Risk	Material									
●	LREEs		●	●	●		●	●		●
●	HREEs		●	●	●		●	●		
●	Magnesium		●				●	●	●	●
●	Niobium	●		●				●	●	
●	Germanium					●		●		●
●	Borates		●	●	●	●	●	●	●	●
●	Scandium							●	●	
●	Strontium		●				●	●		
●	Cobalt	●	●	●			●	●	●	●
●	PGMs		●				●	●		●
●	Natural graphite	●	●				●	●		●
●	Indium					●	●	●		
●	Vanadium		●				●	●	●	●
●	Lithium	●	●				●	●		
●	Tungsten						●	●	●	
●	Titanium	●	●				●	●	●	●
●	Gallium					●	●	●		●
●	Silicon metal	●	●		●	●	●	●	●	●
●	Hafnium							●	●	
●	Manganese	●	●	●			●	●	●	●
●	Chromium		●	●			●	●	●	●
●	Zirconium		●				●	●	●	●
●	Silver		●			●	●	●		●
●	Tellurium					●	●	●		●
●	Nickel	●	●			●	●	●	●	
●	Copper	●	●	●	●	●	●	●	●	●

CRMs in strategic technologies and sectors

CRMs in strategic technologies and sectors

sector analysis

Figure 47. Materials and technologies relevant to the renewable energy sector

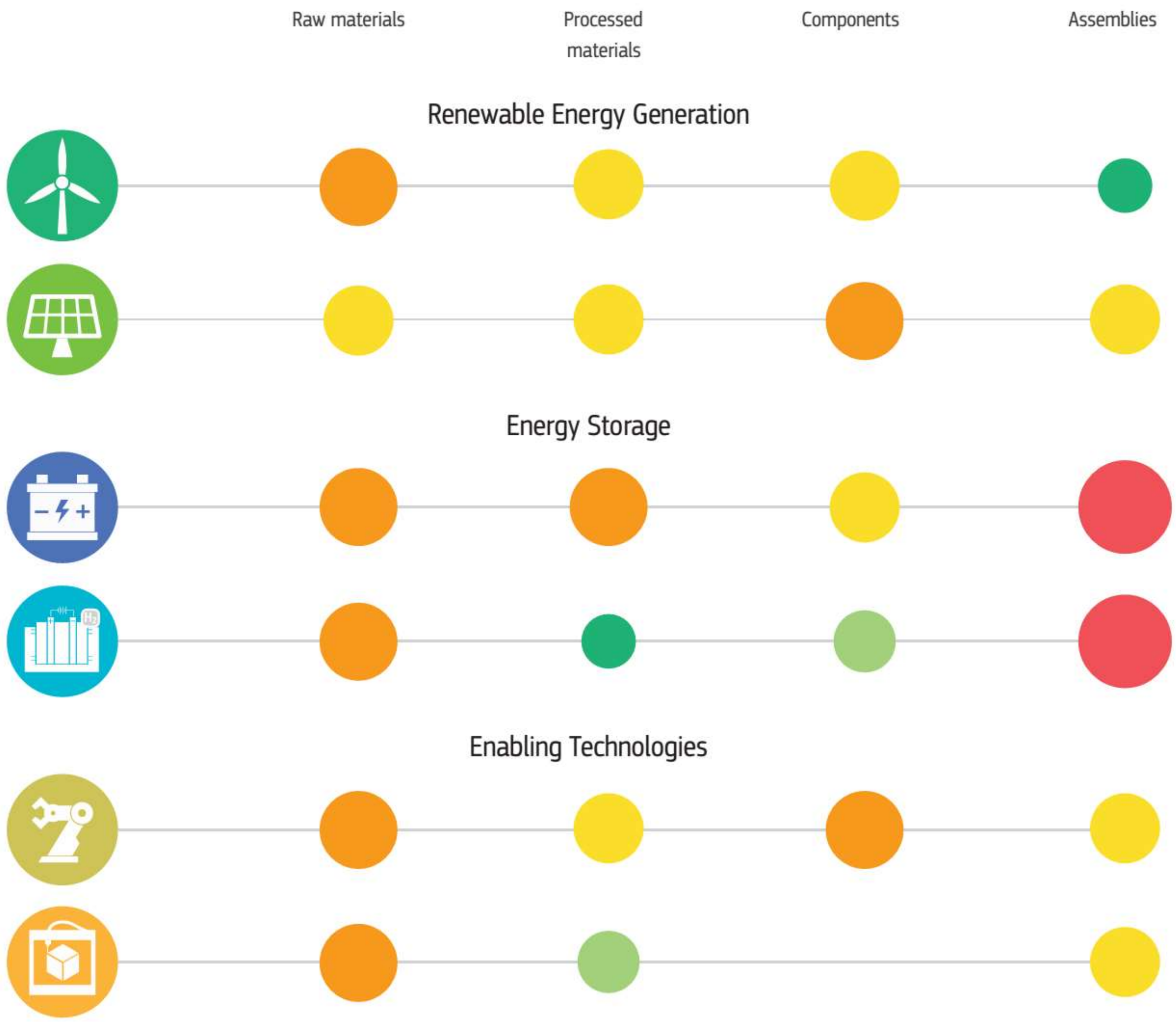


CRMs in strategic technologies and sectors

Figure 48. List of critical and non-critical raw materials used for renewables ranked by their 2020 supply risk

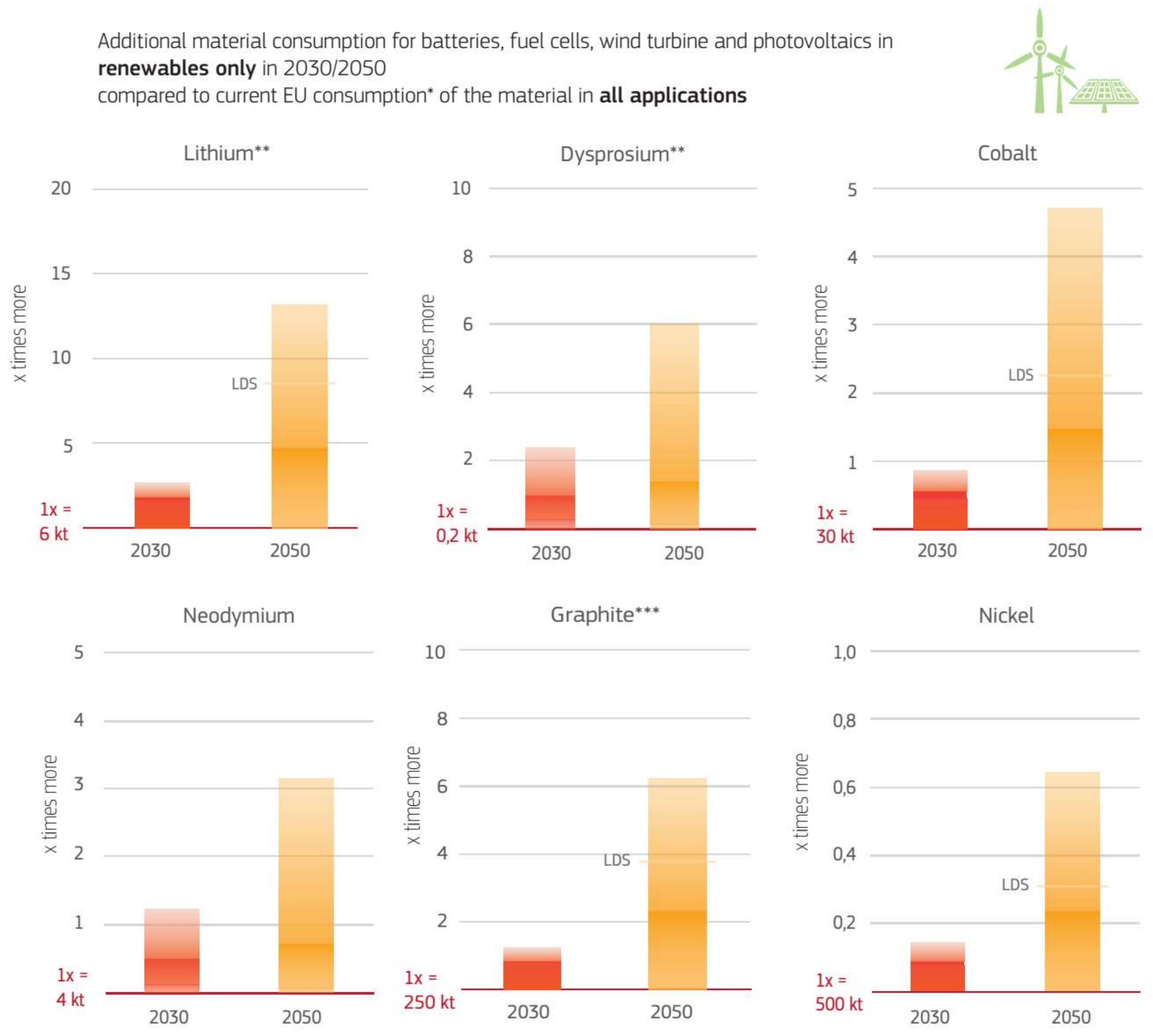
CRMs in strategic technologies and sectors

Figure 49. Supply bottlenecks for seven technologies relevant to the renewable sector



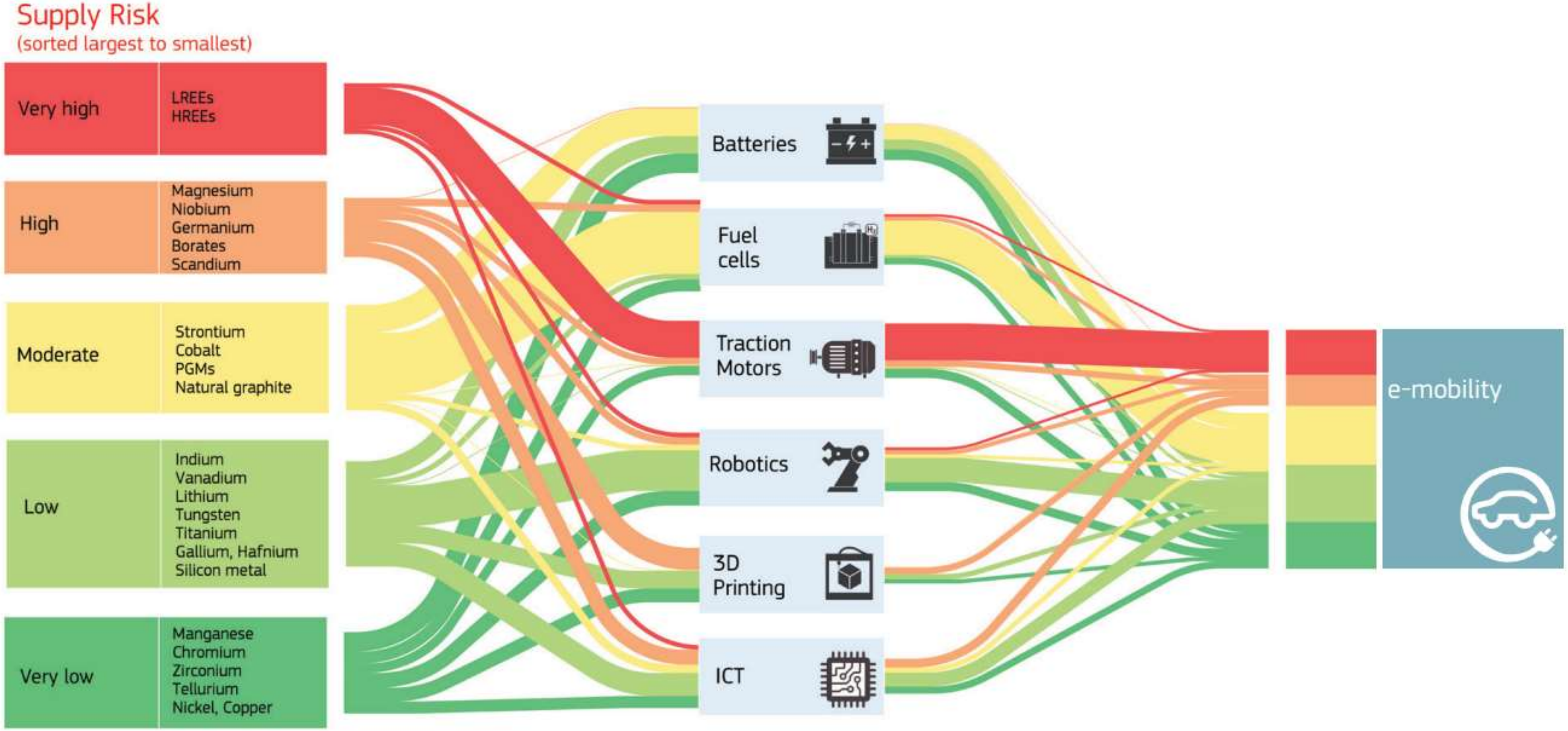
CRMs in strategic technologies and sectors

Figure 50. EU annual material demand for renewables in 2030 and 2050



CRMs in strategic technologies and sectors

Figure 52. Relevant materials and technologies to the e-mobility sector

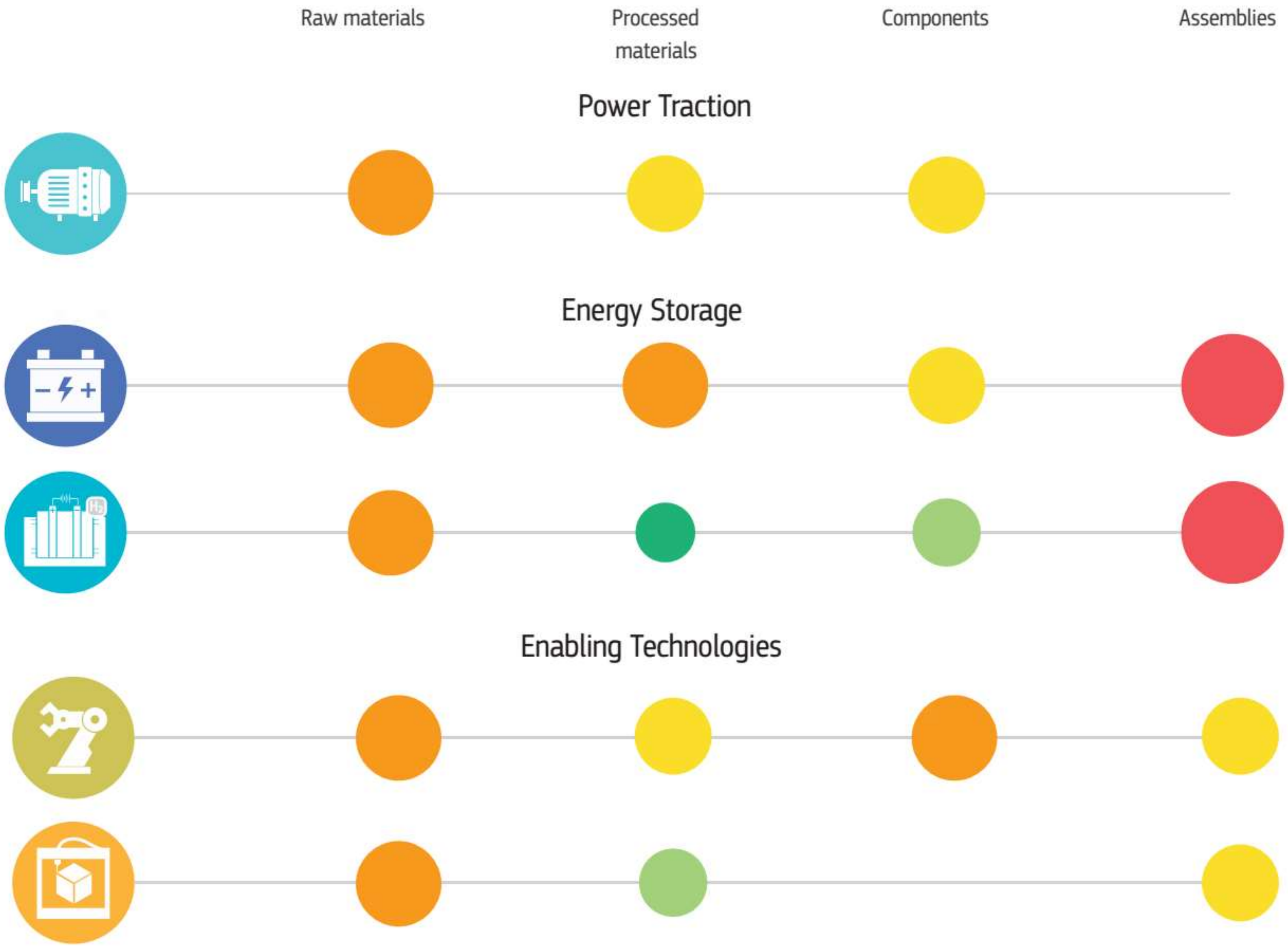


CRMs in strategic technologies and sectors

Figure 53. List of materials used in e-mobility with their 2020 supply risk

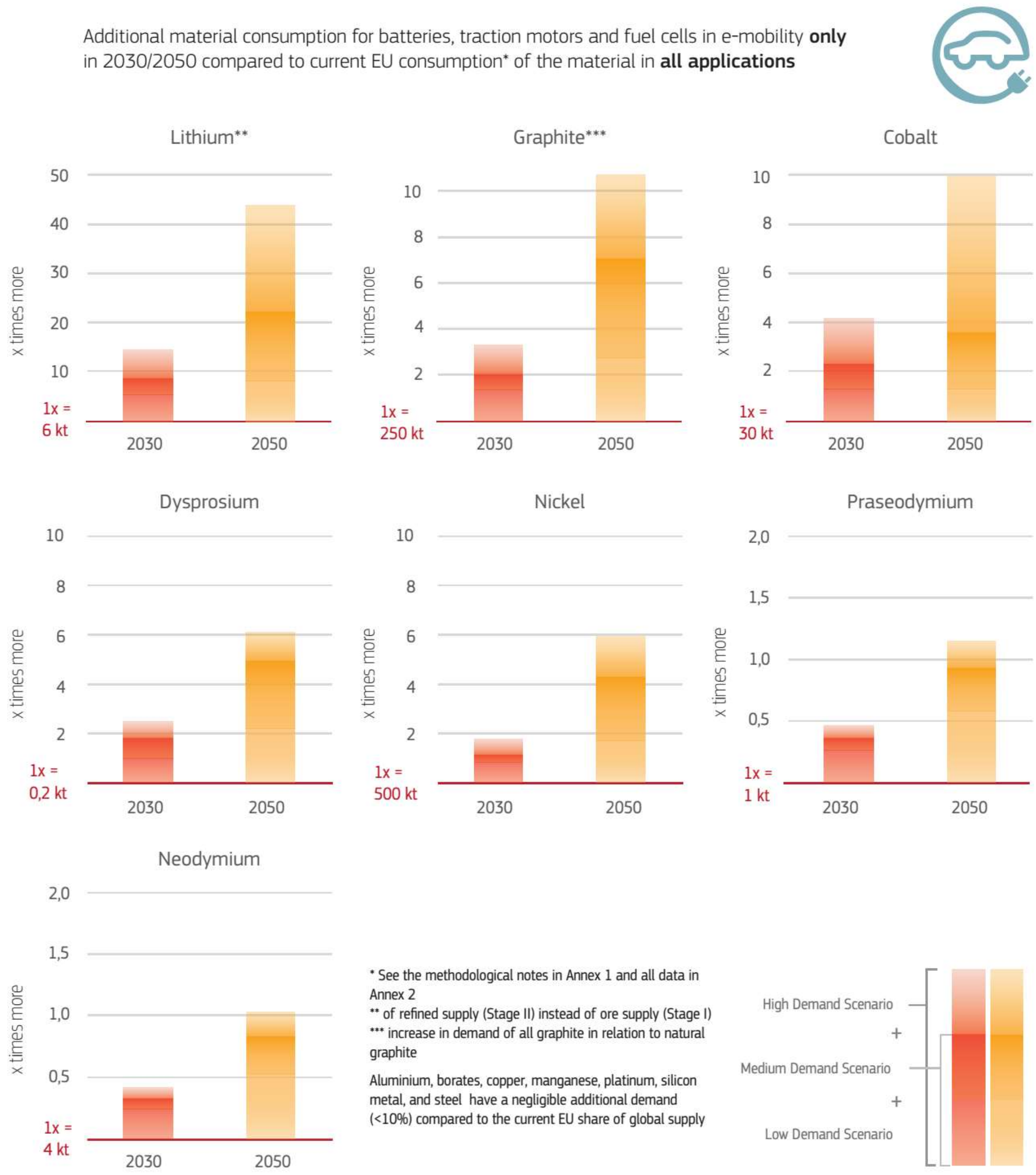
CRMs in strategic technologies and sectors

Figure 54. Potential supply risks in the value chains of emerging technologies relevant to the EU e-mobility sector: Li-ion batteries, fuel cells and traction motors



CRMs in strategic technologies and sectors

Figure 55. EU annual material demand for e-mobility sector in 2030 and 2050



* See the methodological notes in Annex 1 and all data in Annex 2

** of refined supply (Stage II) instead of ore supply (Stage I)

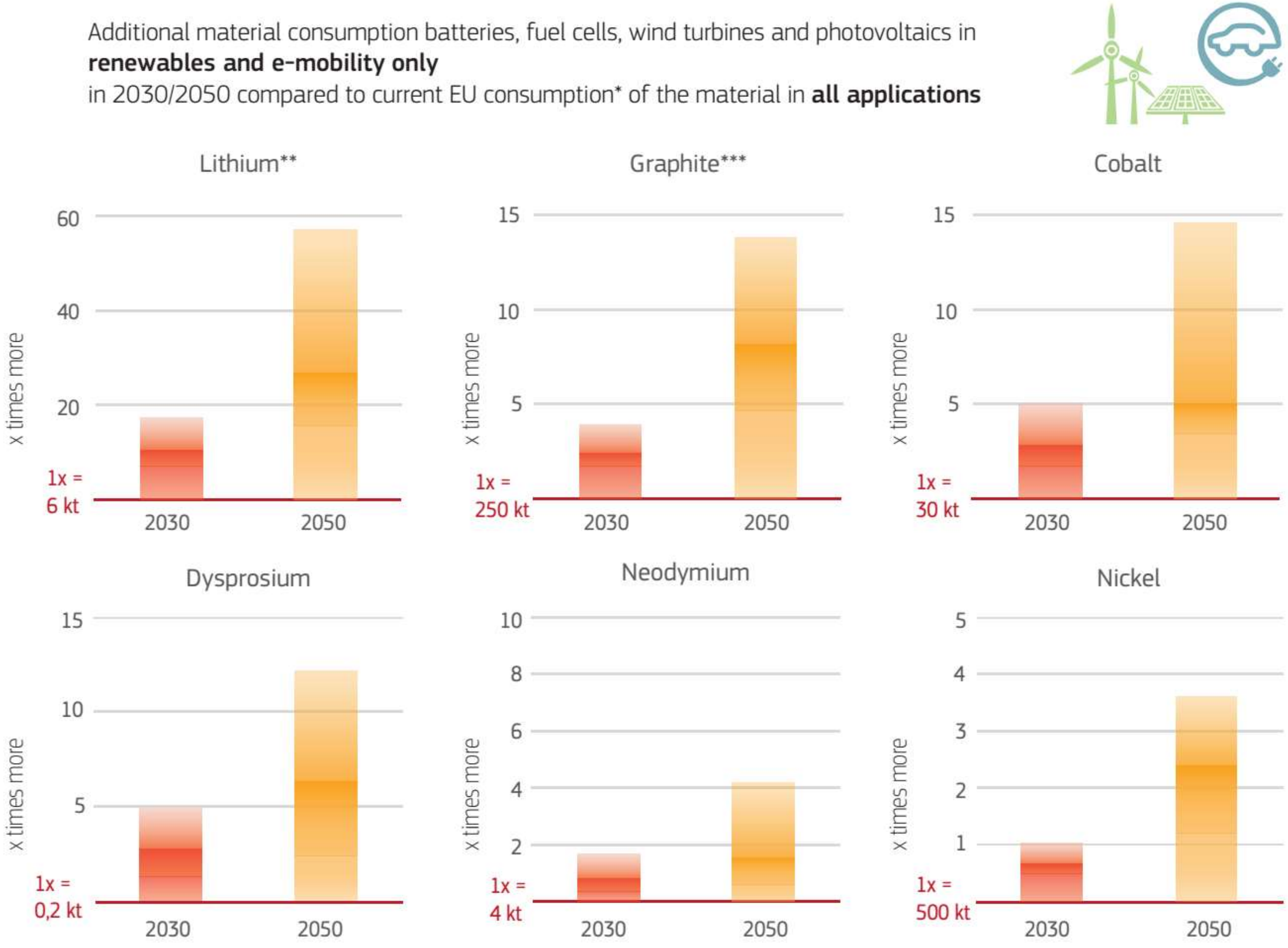
*** increase in demand of all graphite in relation to natural graphite

Aluminium, borates, copper, manganese, platinum, silicon metal, and steel have a negligible additional demand (<10%) compared to the current EU share of global supply

CRMs in strategic technologies and sectors

combined!

Figure 63. EU annual material demand for e-mobility and renewables combined in 2030 and 2050



CRMs in strategic technologies and sectors

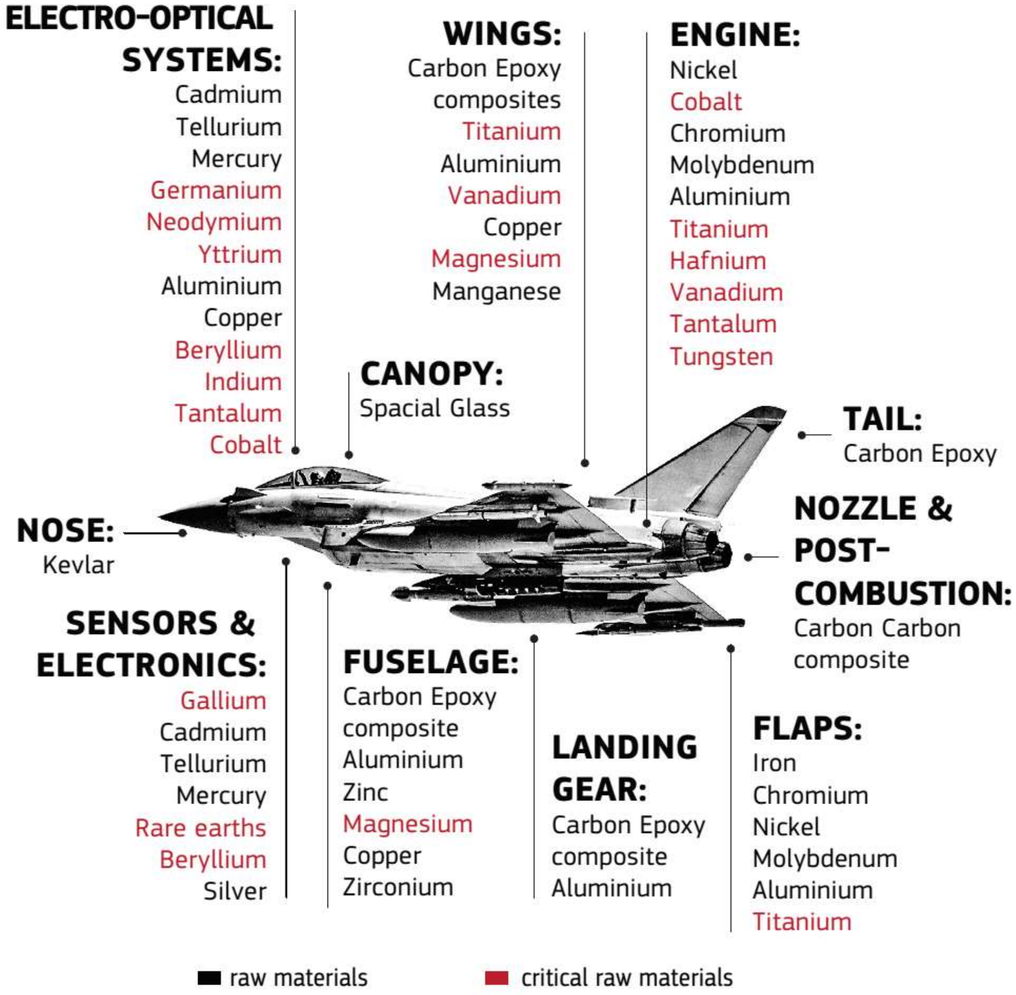


Figure 60. Materials used in different parts of the combat aircraft Rafale

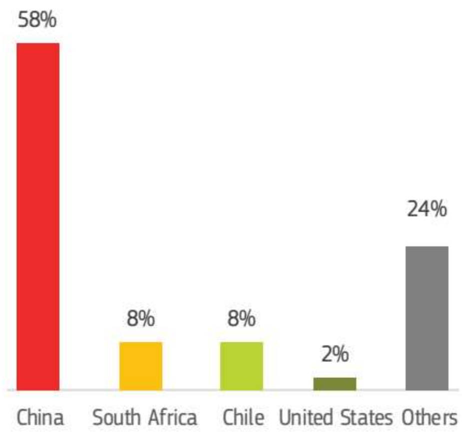
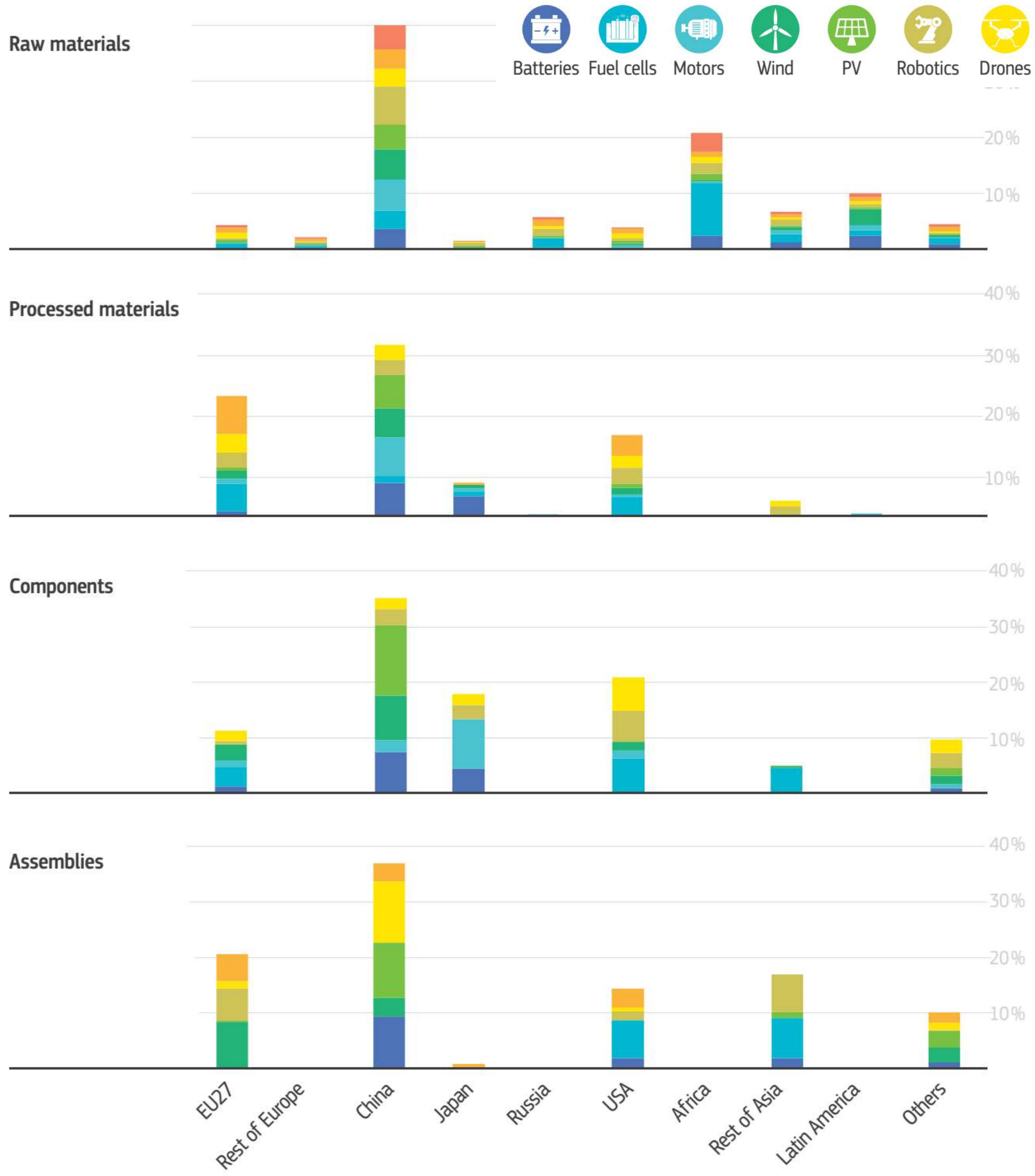


Figure 62. Key players in the supply of raw materials used in defence sector

Defence & Space

CRMs in strategic technologies and sectors



key suppliers for each stage *(country shares)*

CRMs in strategic technologies and sectors

KEY FINDINGS

→ **REEs** supply chain extremely vulnerable because of China's market dominance.

→ **Dy** critical because of higher rate of demand growth and lower proportion in ores.

→ **Co** remains a concern because of large share of DRC

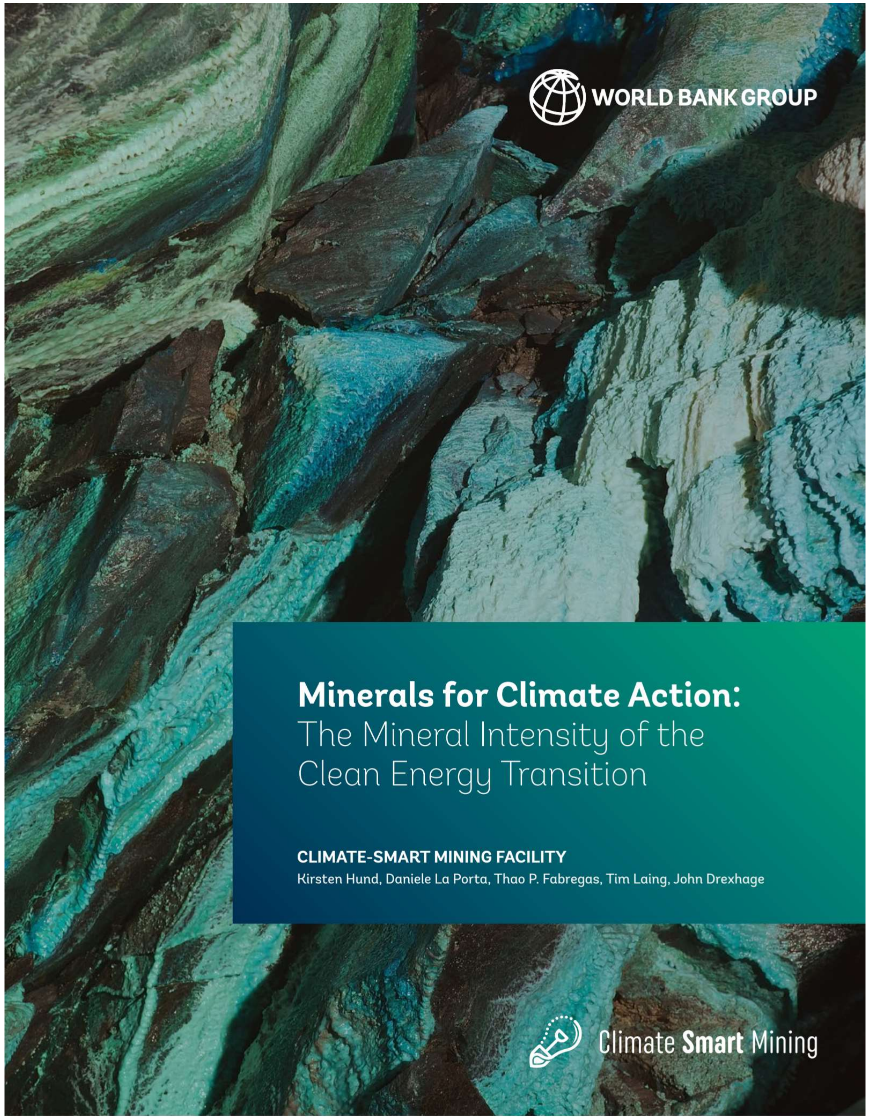
→ **Wind energy and traction motors** will compete for REEs and borates

→ **Fuel cells and Digital tech** will require large amounts of PGM

→ **PV and Digital tech** will compete for Ge, In, Ga, Si

→ **Bottlenecks** for EU are mostly in the raw materials stage

CRMs in strategic technologies and sectors



World Bank, 2020
(another interesting report)

Part 4

Mitigation

After the rare earths crisis

FINANCIAL TIMES

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The Big Read | Rare earths | + Add to myFT

US-China: Washington revives plans for its rare earths industry

Other nations intend to reduce deper
from wind turbines to F-35 jets

Save

Jamie Smyth in Sydney SEPTEMBER 14 2020

It is five years since the giant trucks
California's Mojave desert fell silent
the US, had just collapsed under the
investors and left the nation almost
metallic elements that are embedde
electric vehicles and F-35 fighter jet

Now, as relations between Washing
government is supporting the resur
the world's biggest producer of rare
Covid-19 pandemic has underscore
they are not reliant on a single coun
and goods.

THE WALL STREET JOURNAL.

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China Still Dominates Rare-Earth Processing

Few Countries Have the Industrial Capacity to Turn the Minerals Into Something Useful

The Washington Post
Democracy Dies in Darkness

Opinions | Editorial Board | The Opinions Essay | Global Opinions | First 100 Days | D.C.

The Post's View

Loosening China's grip on rare-earth metals

By **Editorial Board**
March 15, 2012

THE PEOPLE'S REPUBLIC of China controls 97 percent of the world's supply of rare-earth metals. Lucky for China — but not so lucky for the rest of the world, because these 17 minerals, with names like europium and neodymium, are used in the manufacture of everything from clean-energy devices to the U.S. military's precision-guided munitions. That gives China more market power in more critical areas than the United States, Europe and Japan can comfortably afford. The risks

awareness

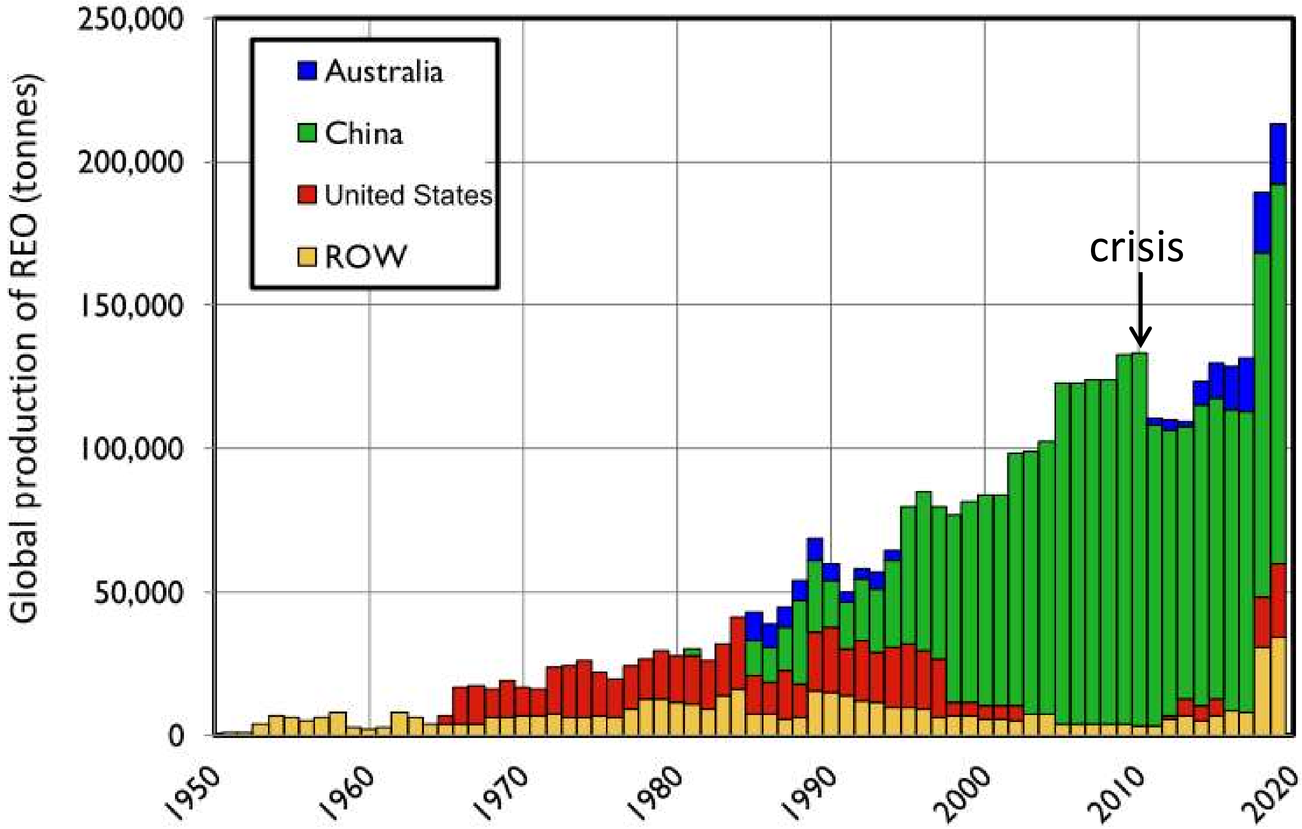
After the rare earths crisis

WORLD TRADE
ORGANIZATION

WTO trade dispute

- **March 2012**, the **United States, Japan**, and the **European Union** jointly initiated a World Trade Organization (WTO) dispute settlement case against China's restrictive policies on REEs
- China responded that restrictions were issued for environmental reasons
- **March 2014**, a WTO dispute panel ruled that China's REE restrictions were inconsistent with its WTO obligations
- **August 2014**, the ruling was largely upheld by WTO Appellate Body
- **May 2015**, China announced that it had removed the restrictions

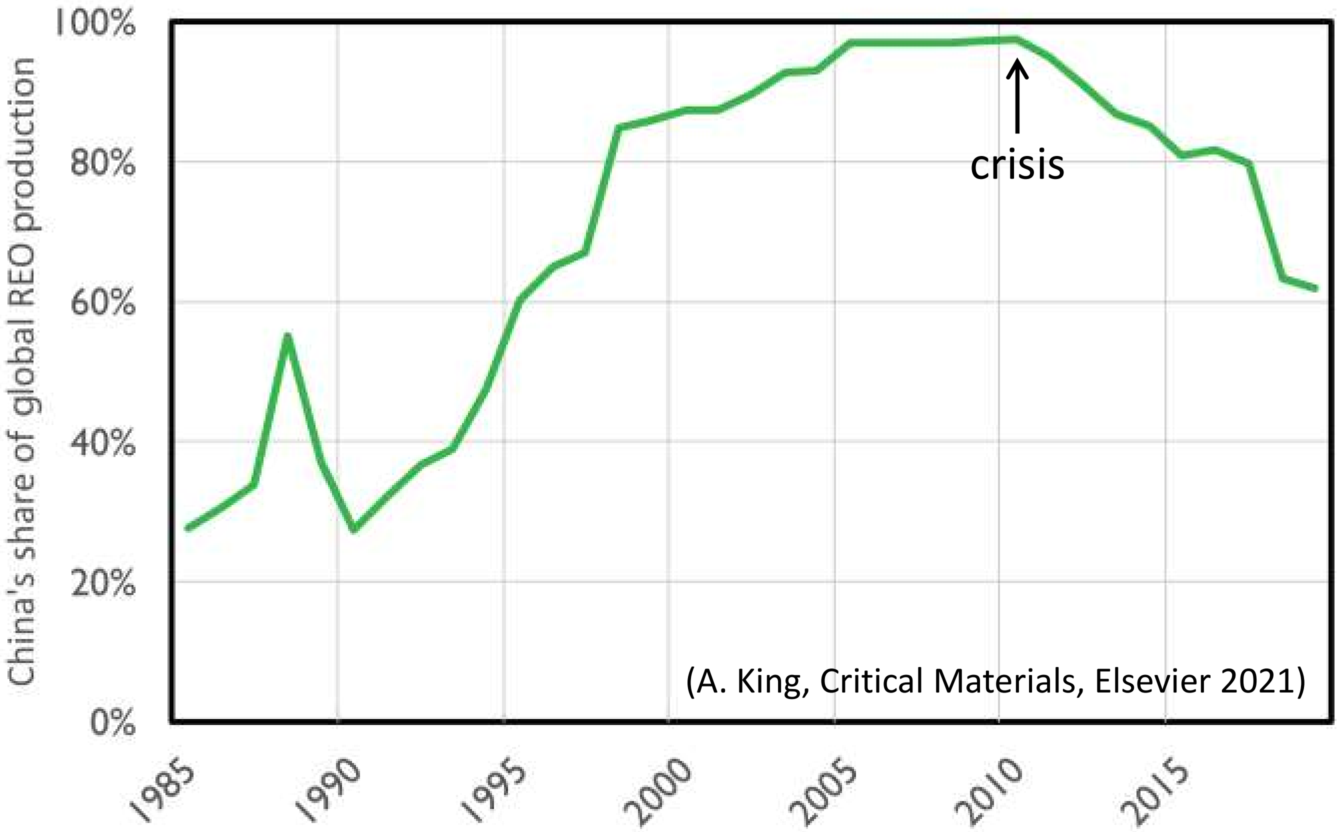
After the rare earths crisis



(A. King, Critical Materials, Elsevier 2021)

after the crisis, the number of producers increased

After the rare earths crisis

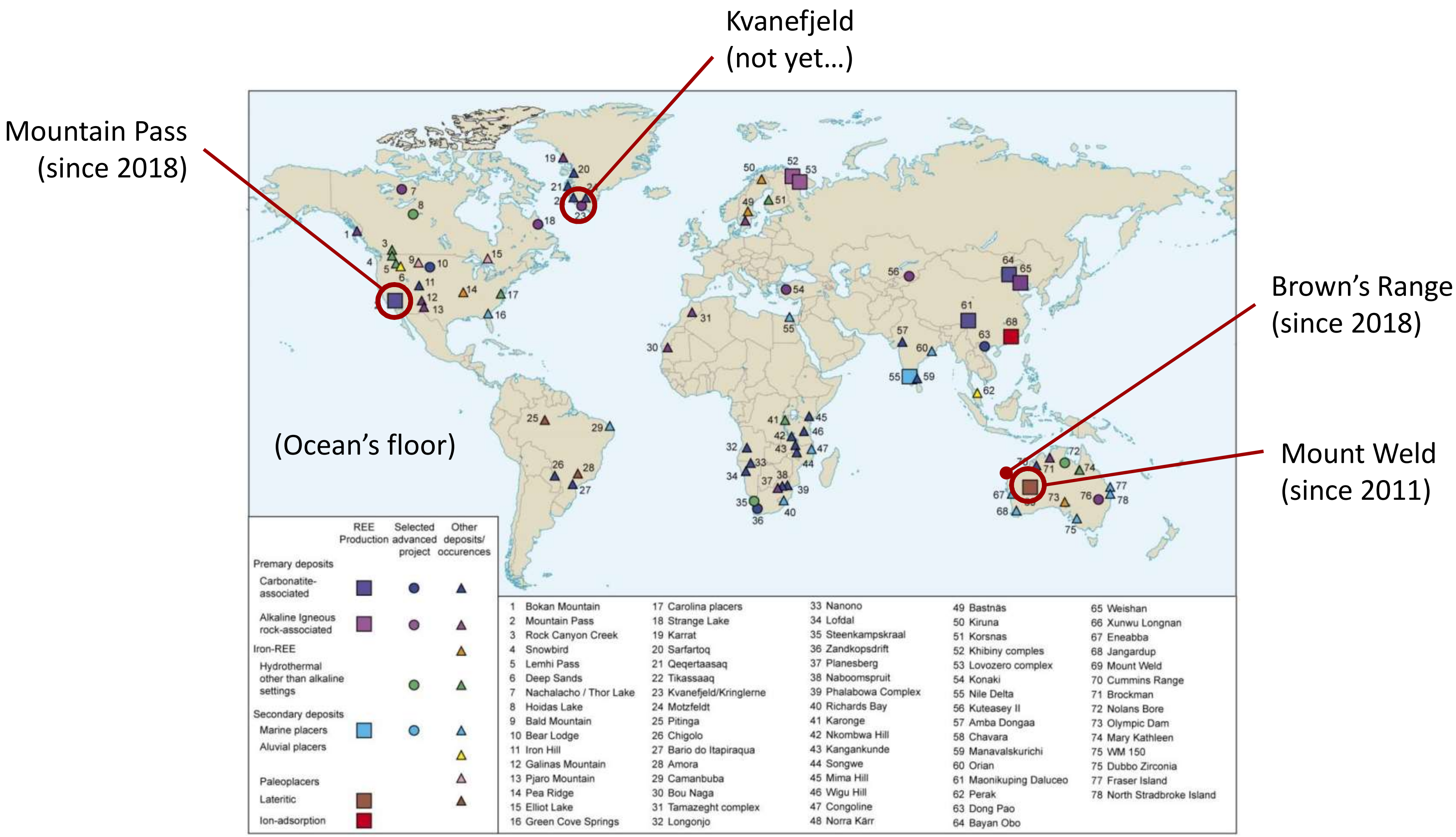


after the crisis, China's share decreased

*(however, most US production **still processed in China!**)*

After the rare earths crisis

Stimulation of new mining projects



(source: British Geological Survey 2011)

After the rare earths crisis

Technology responses
(to decrease amount of REEs needed)

Grain Boundary Diffusion (GBD) in NdFeB magnets

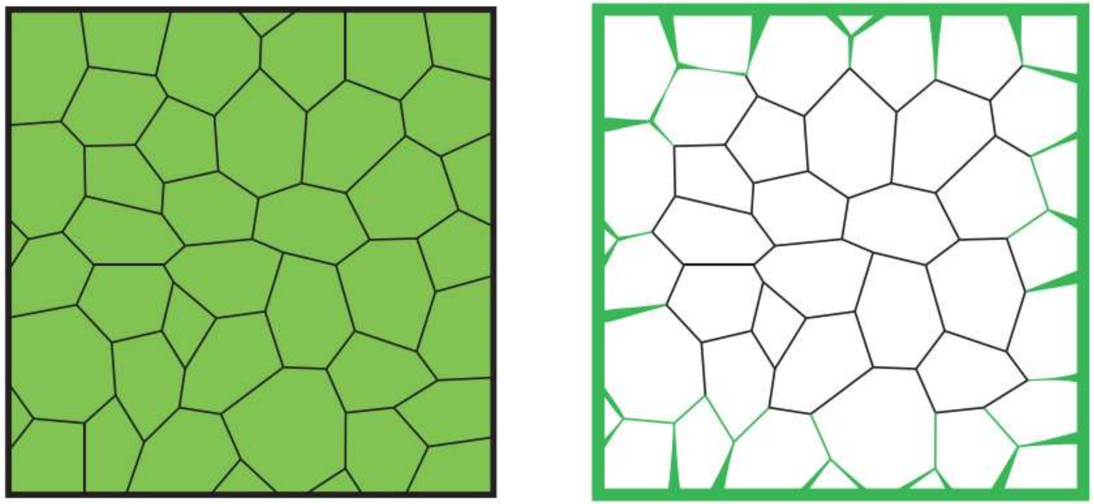


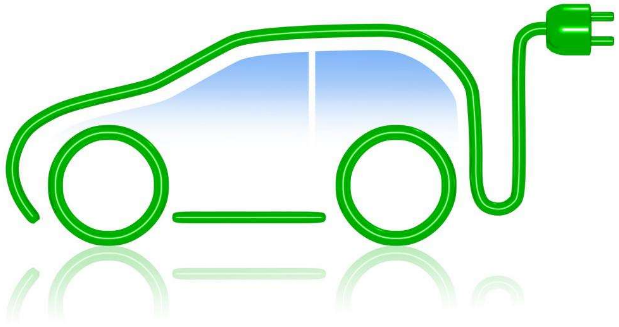
Fig. 4.13 The principle of the grain boundary diffusion method for dysprosium addition. In traditional processing, dysprosium is substituted for neodymium before the alloy is melted, and after solidification, it is uniformly distributed through the material. For the grain-boundary diffusion method the dysprosium is added after the magnet is formed, by coating the surface with a dysprosium source and then annealing at a low temperature. The dysprosium diffuses into the magnet via the grain boundaries, which operate as fast-diffusion paths. The resulting dysprosium distribution is as shown on the right. This results in lower usage of dysprosium and smaller impact on the remanence.

(A. King, Critical Materials, Elsevier 2021)

Advantages

- 70-90% Dy reduction
- no decrease in remanence
- improved coercitivity

After the rare earths crisis



*Investments/research to **reduce** amount of REEs in motors*

- Ford redesigned motors to reduced operating temperatures (less Dy needed)
- Toyota announced the development of a new magnet material with 50% less HREEs
- Honda similar approach to reduce dependence from HREEs

but…

- Tesla model 3 (2017) switched to REE-based magnets instead of induction motors

After the rare earths crisis

Investments/research to ***reduce*** *amount of REEs in wind turbines*

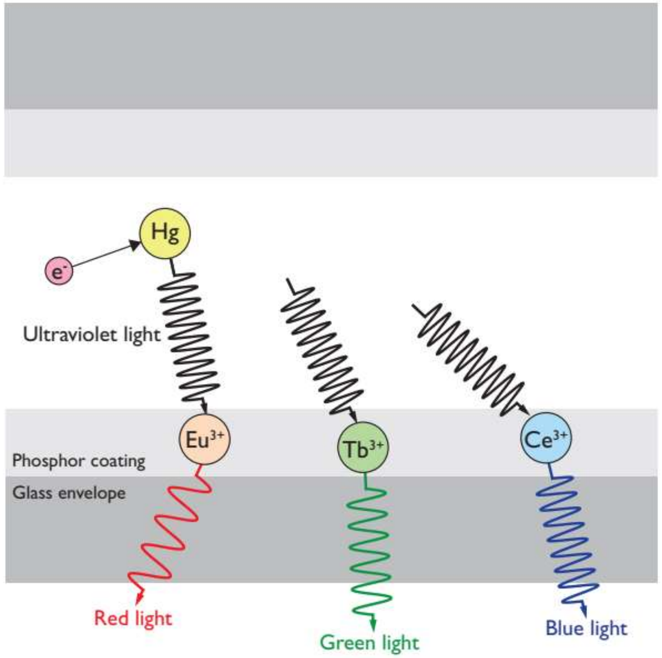
- Siemens Gamesa announced it “dramatically reduced” the need for HREE in its 7 MW offshore generators.

(King, Critical Materials 2011)

After the rare earths crisis

A technology shift in lighting

Fluorescent lamps are heavily dependent on REEs



(A. King, Critical Materials, Elsevier 2021)

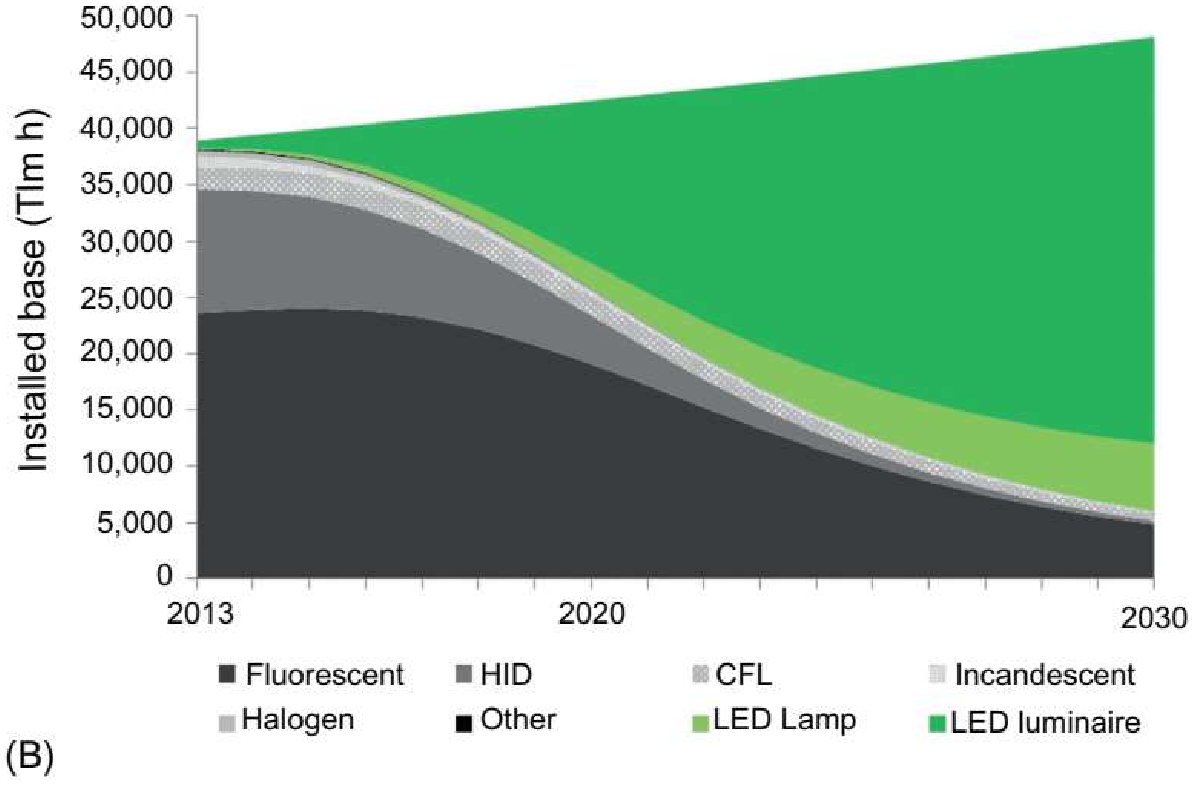
After the rare earths crisis

A technology shift in lighting

(accelerated by REE crisis)

Rapid growth of LED and decline of fluorescent lighting

(less dependent on REEs)



(A. King, Critical Materials, Elsevier 2021)

Mitigation

How to address criticality?

- New technologies *(e.g. LED)*
- Reduced use via technological improvements *(e.g. GBD)*
- Material substitution *(e.g. ...later...)*
- Source diversification
  - New mines development
  - Unconventional sources
- Recycling

Development of new technologies

…20 years (time needed to market)

Table 5.1 Time from discovery to commercialization for selected materials innovations.

Material	Invention	Commercialization	Time lag
Vulcanized rubber	1839	Late 1850s	30 years
Low-cost aluminum	1886	Early 1900s	20 years
Titanium	Mid-1940s	Mid-1960s	20 years
Velcro	Early 1950s	Early 1970s	20 years
Polycarbonate	Early 1950s	About 1970	20 years
Gallium arsenide	Mid-1960s	Mid-1980s	20 years
Diamond-like films	Early 1970s	Early 1990s	20 years
Amorphous magnetic materials	Early 1970s	Early 1990s	20 years
Fuel cell electrocatalysts	Early 1990s	Mid-2010s	20 years
Li-ion batteries	Mid-1970s	Mid-1990s	20 years
Carbon fiber composites	Mid-1960s	Mid-2010s	50 years

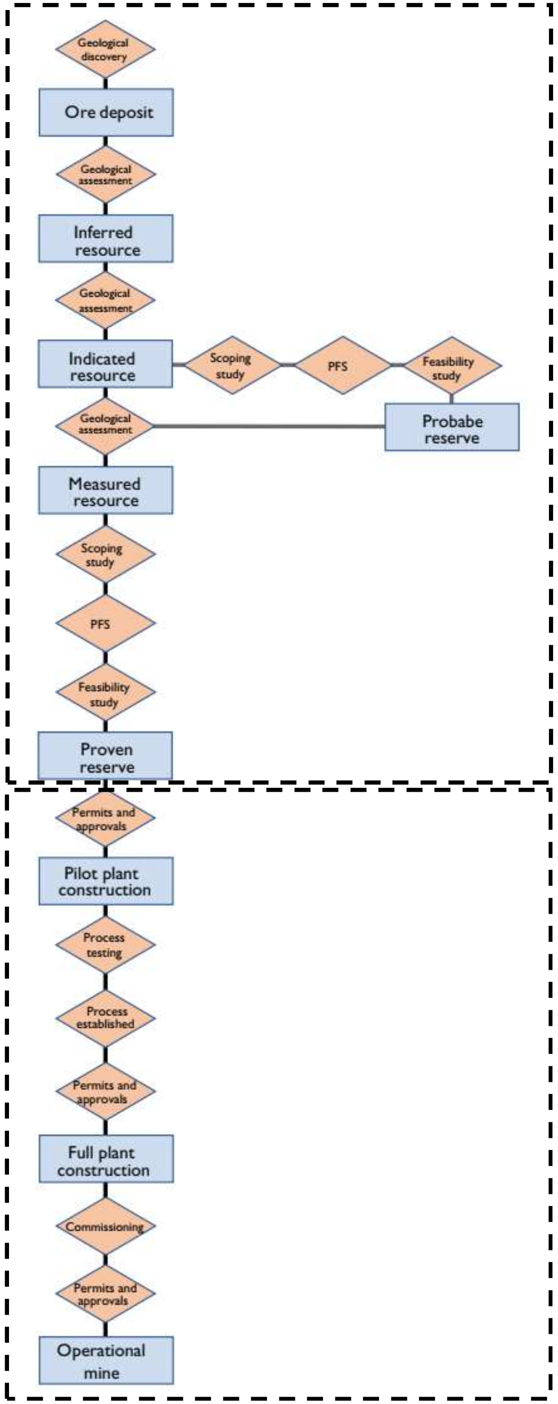
(A. King, Critical Materials, Elsevier 2021)

- *usually too slow to counter criticality*
- *better start as soon as possible*

Source diversification

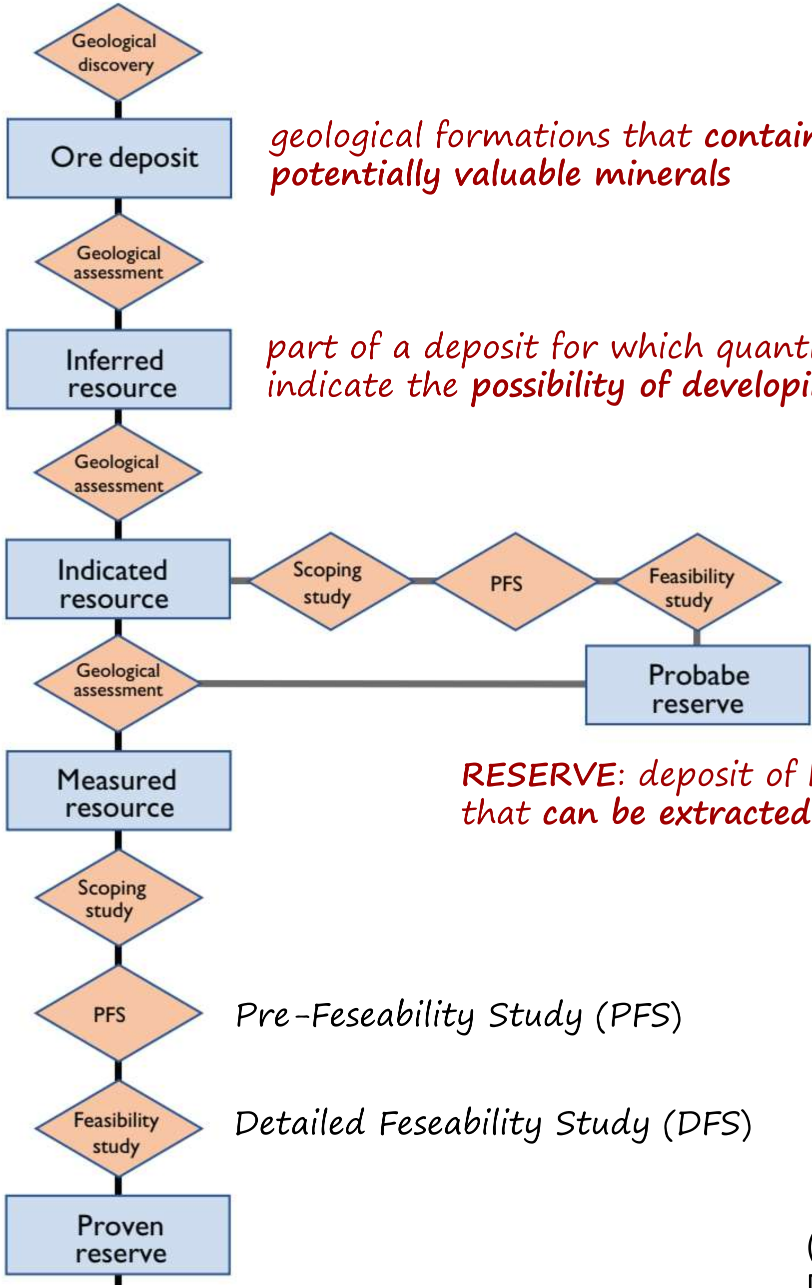
How are mines developed?

10 to 20 years
& 1 billion $ investment
to achieve first production



(A. King, Critical Materials, Elsevier 2021)

Source diversification



geological formations that ***contain potentially valuable minerals***

part of a deposit for which quantity and grade indicate the ***possibility of developing a valuable mine***

quantity, grade, density, shape and other characteristics estimated with sufficient confidence to ***allow for mine planning***

characteristics estimated with sufficient confidence to ***support detailed mine planning and projection of economic viability***

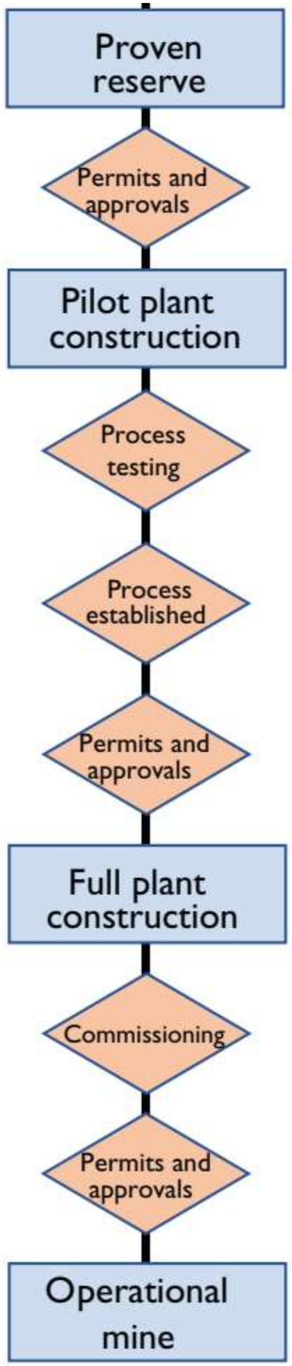
RESERVE*: deposit of* ***known size*** *that* ***can be extracted at a profit***

Pre-Feseability Study (PFS)

Detailed Feseability Study (DFS)

(A. King, Critical Materials, Elsevier 2021)

Source diversification



Political & Social consensus are also needed

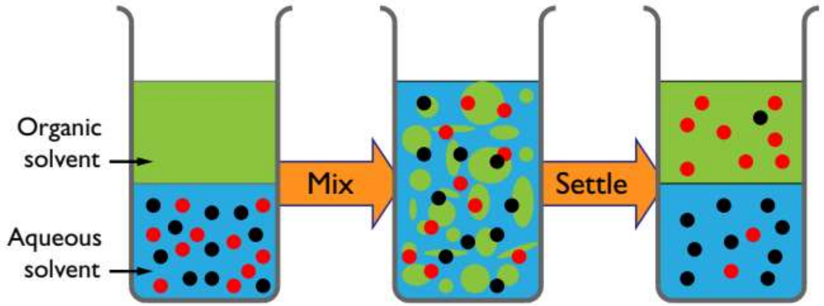
Site-specific procedures *have to be set-up (no general approaches)*

(A. King, Critical Materials, Elsevier 2021)

Source diversification

Separation step *(critical step)*

(e.g. solvent-extraction process **for REEs**)



(400 mixer-settler units might be needed for REEs)

Fig. 6.5 Basic operation of a mixer-settler solvent extraction separation unit. An aqueous solution of mixed elements is mixed with an organic solvent and then allowed to settle. One element migrates preferentially into the organic solvent, but the separation is not perfect.

(A. King, Critical Materials, Elsevier 2021)

- Requires large amounts of water, acids, solvents with associated costs, health and safety risks, environmental challenges
- Mixers consume large amounts of energy
- Settling step can require significant amounts of time
- Largest single capital expenditure for REEs production
- Greatest risk to the production chain

*also performed as a **stand-alone business***

Source diversification

Unconventional sources: extraterrestrial mining

physicsworld

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TELESCOPES AND SPACE MISSIONS | FEATURE

The asteroid trillionaires

11 Jun 2018

Taken from the June 2018 issue of *Physics World*

The race to the riches of asteroids is on, with several p
first space miners. **Andrew Glester** digs into the issues

"I'll make a prediction right now. The first trillionaire will

IndustryWeek

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SUPPLY CHAIN > TRANSPORTATION

Space Mining: The Answer to the Rare Earths Problem?

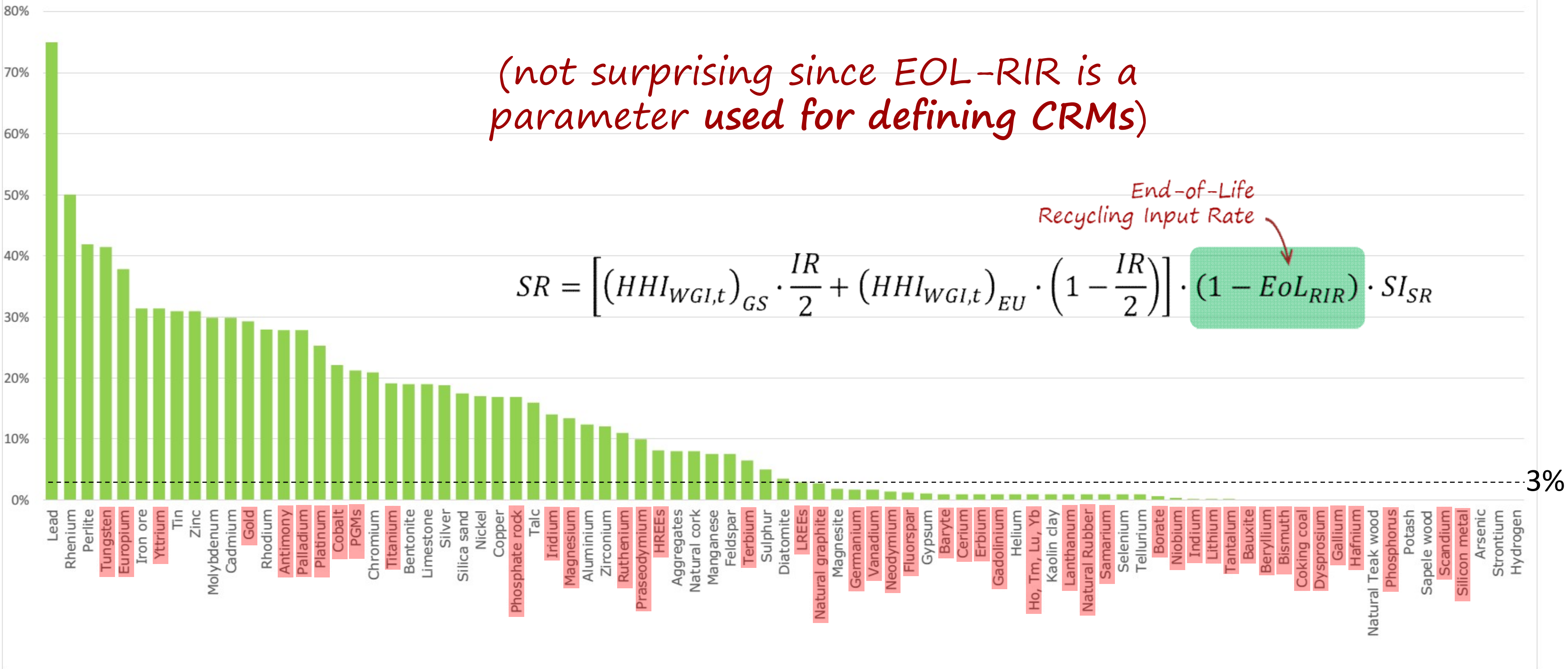
Rare earths are a precious commodity -- so precious scientists are now looking beyond Earth's reaches for new supplies, with moon and asteroid mining becoming a lucrative prospect, according to researchers and tech firms gathered in Sydney for the world's first formal "Off-Earth Mining Forum."

Recycling

(post-consumer)

End-of-life Recycling Input Rate

- majority (65%) of CRMs have a EOL-RIR < 3%
- average EOL-RIR for HREE is 8%, LREE 3%



(EC, Study on the EU's list of CRMs 2020)

CRMs highlighted in red

Recycling

Challenges in End-Of-Life Recycling

(management of products used or stored by society with the aim to recover raw materials)

Conventional Mining	Urban Mining
located within a bounded geographical area	geographically discontinuous
rich in target material	poorer in target material
consistent in composition	inconsistent in composition
energy needed for extraction	energy needed for collection

(target materials are on the surface, but not necessarily easy to collect)

Recycling

Challenges in End-Of-Life Recycling

- Costs and carbon footprint of **collection** and **delivering** to a processing center
- For many high-tech products, **increased complexity** (“high-entropy” objects)
- For growing sectors, recycling can **satisfy only a limited fraction of demand**

(A. King, Critical Materials, Elsevier 2021)

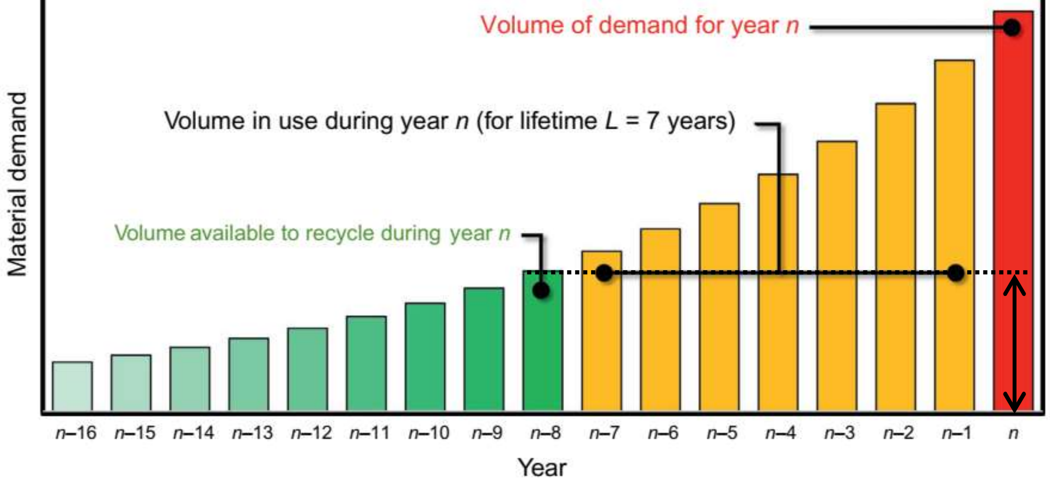


Fig. 7.3 A simplified model to estimate the fraction of current demand for a material that can be met by recycling. Demand grows by a constant fraction per year, and all of the material is assumed to be used in products that have a lifetime of L years, so that L years-worth of production are tied up in current use. Material produced $L + 1$ years ago is available to recycle.

Recycling

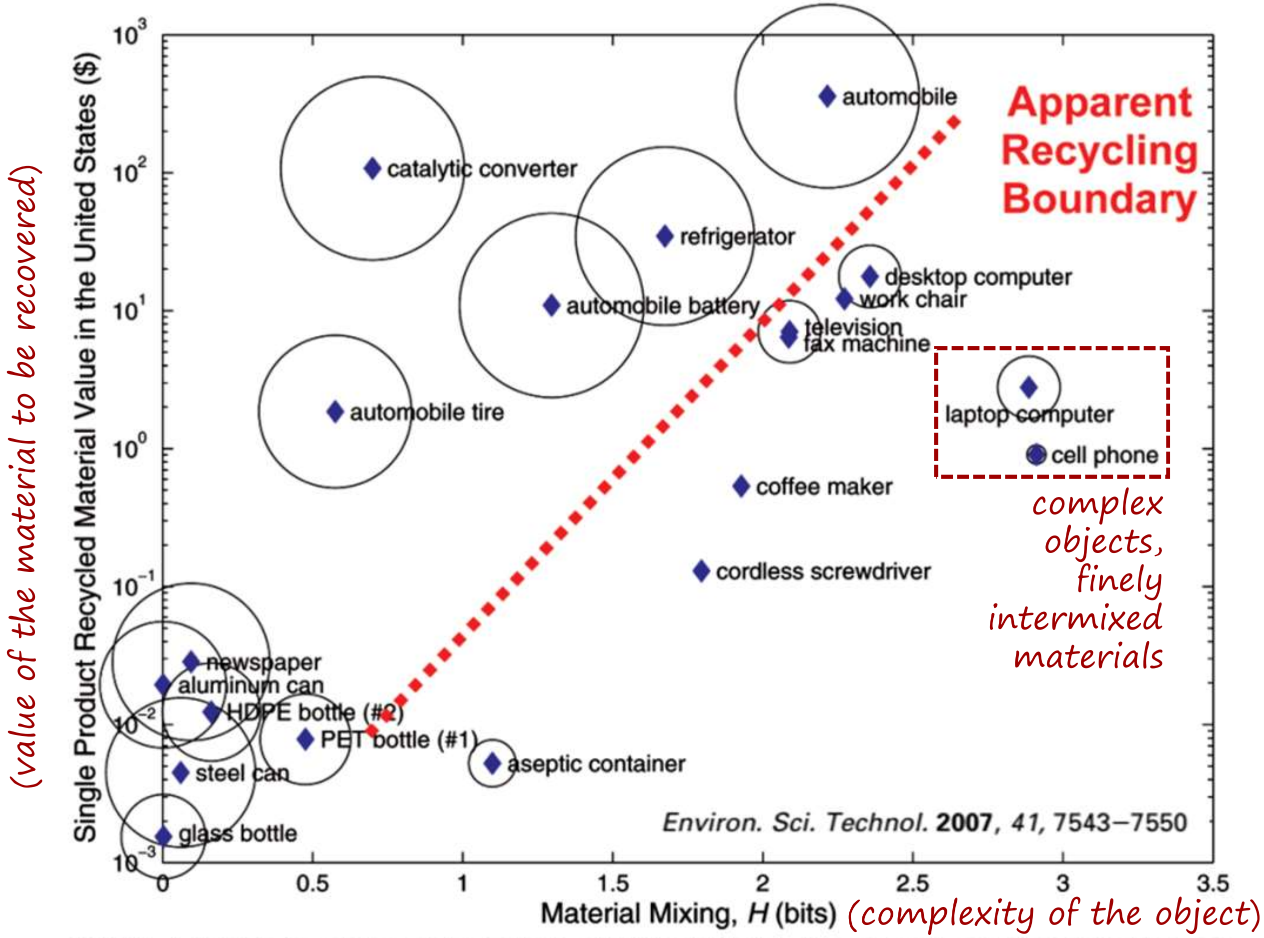


FIGURE 4. A plot of single product recycled material values ($\sum m_i k_i$), material mixing (H), and recycling rates (indicated by the area of the circles) for 20 products in the U.S. The "apparent recycling boundary" is shown.

Lower-complexity *objects and* ***higher-value*** *materials are more likely to be recycled than higher-complexity objects and lower-value materials.*

(Dahmus and Gutowski criterion)

Recycling

"[…] the recycling input rate of CRMs is generally low."

- **sorting** and **recycling technologies** for many CRMs are not available yet at competitive costs
- the supply of many CRMs is currently **locked up in long-life assets**
- **growing demand** for many CRMs in various sectors

note: in some cases (e.g. PGMs) EOL-RIR can be low even if recycle rate is high (because of rapidly growing demand)

Recycling

Benefits of a more circular use of CRMs

Table 2: Energy and water consumption in production of metals from scrap and ores (range given is high to low grade)[19].

Metal	Energy use (MJ per kg of metal extracted)		Water use (m^3 per tonne of metal extracted)	
	Scrap	Ores	Scrap	Ores
Magnesium	10	165-230	2	2-15
Cobalt	20-140	140-2100	30-100	40-2000
PGM	1400-3400	18,860-254,860	3000-6000	100,000-1200,000
Rare Earths	1000-5000	5500-7200	250-1250	1275-1800

(EC, Report on CRMs and the circular economy, 2018)

Recycling

Why are recycling rates of REEs so low?

- REEs are **difficult to separate** *(similar chemistry)*
- REEs are usually present in **small amounts**
- many REE-containing products are **complex** (difficult to disassemble)
- very little or **no recycling incentives** (low prices)
- end-product **collection procedures do not exist**
- **long useful life periods** (e.g. wind turbines, EVs)

Table 177: EOL-RIR of individual REE (1 - UNEP, 2013; 2 - Bio Intelligence Service, 2015; 3 - BRGM, 2015)

REE	LREE					HREE						
	Ce[1]	La[1]	Nd[2]	Pr[3]	Sm[1]	Dy[2]	Er[1]	Eu[2]	Gd[1]	Ho, Tm, Lu, Yb[1]	Tb[2]	Y[2]
End of life recycling input rate (EOL-RIR)	1%	1%	1%	10%	1%	0%	1%	38%	1%	1%	6%	31%

(EC, CRMs factsheets 2020)

Recycling

REEs recycling

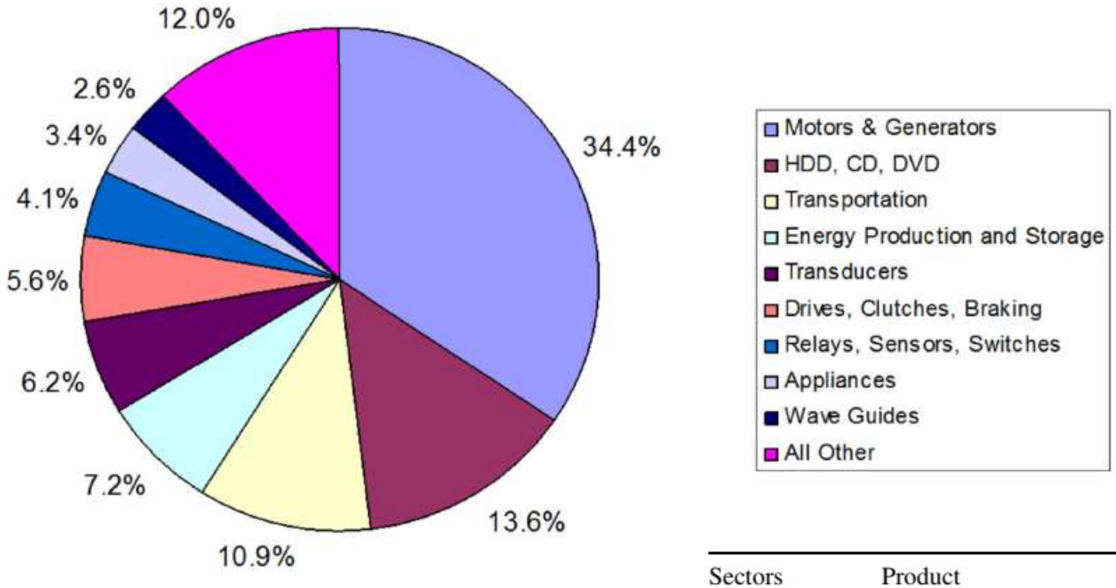


Fig. 5 Shares of the different applications in the global NdFeB market for year 2012 [23] (reprinted with permission)

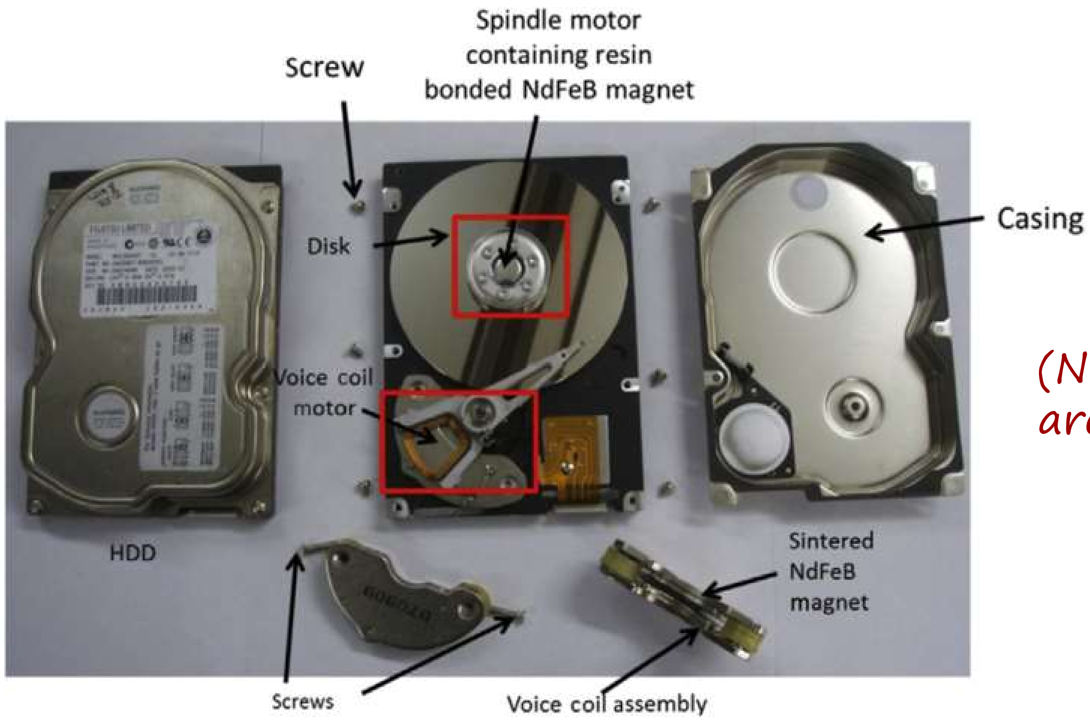
J. Sustain. Metall. (2017) 3:122–149

Sectors	Product	Concrete use	Mass per unit	Total use (ton)
Computers	HDDs (excluding CDs, DVDs)	VCM, SP motors	10–20 g	7500 (2015)
Consumer electronics	Home electronics & electrical appliances*	Small electric motors	Varies greatly	No total statistics
	– Air conditioners	3–4 motors		>4000 (2014)
	– Speakers	From mobile phones to cars		>4500 (2015)
Wind turbines	Generation IV (only)	Generators	400 kg/MW	8500 (2015)
Vehicles	Conventional automobiles	Small motors (40) and sensors (20)	250 g	~22,000 (2015)
	HEVs, PEHVs and EVs (average)	Electric motors	1.25 kg**	>7000 (2015)
	Electric bikes (E-bikes)	Electric motors	300–350 g	6000 (2015)

Recycling

example: rare earths magnets in HDDs

- 13-16% of the market for RE magnets (2012-2014)
- HDDs remain the technology of choice in **large data centers**
- data centers are good targets for urban mining (large amounts of material in a small geographical area)



(A. King, Critical Materials, Elsevier 2021)

(Nd, Pr, Dy, Sm are recovered)

Recycling

Other potential REEs sources for recycling

- Fluorescent lamps (Y, Eu, >20% in weight) — *Solvay developed a recycling unit in France in 2012, but stopped in 2016 because it had become uneconomic*
- Catalysts (La) *(mainly from fluid catalytic cracking)* — *still not economic, see balance problem (if more Nd is needed, La will be in excess)*
- Ni-MH batteries (La, Ce, Pr, Nd) — *long lifespan (7-10 years) makes the lag time quite long, limiting recycling solutions at large scales*

Recycling

Manufacturing waste

(manufacturing scrap)
(in-factory recycling)

- preventing its creation has greater potential economic benefit than recycling it
- target material may be **obtained in a single location**
- it is **consistent in its composition**
- material has already had its **value increased** through several costly and energy-intensive processing steps

Manufacturing waste

Success stories

- **CeO_2 (ceria)** widely used as an **abrasive for polishing silicon wafers and glass**, because it combines a mild chemical attack of the silicon with mechanical abrasion (chemical-mechanical polishing) – **RECYCLED!**
- **Yttria-stabilized zirconia (YSZ)** is *plasma-sprayed* to form a **thermal barrier coating** to protect metal turbine blades in jet engines. In plasma-spraying **80% of YSZ was wasted** – **RECYCLED!**

Why a success?

- *no need for collection and transportation of the material*
- *low-complexity feedstock and high-value output materials*
- *minimal reprocessing (returned to the manufacturing process essentially in their original form)*
- *quantifiable value for their owners*

Recycling

Manufacturing waste

Success stories

- **CeO_2 (ceria)** widely used as an **abrasive for polishing silicon wafers and glass**, because it combines a mild chemical attack of the silicon with mechanical abrasion (chemical-mechanical polishing) – **RECYCLED!**
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BUT…

the overall impact of a successful recycling may be to **increase the criticality of other REEs**

- Ce is a **coproduct** of light REEs: reducing the demand for cerium increases the cost of producing lanthanum, praseodymium, and neodymium
- Y is a **coproduct** of heavy REEs: reducing the demand for yttrium increases the criticality of the heavy REEs