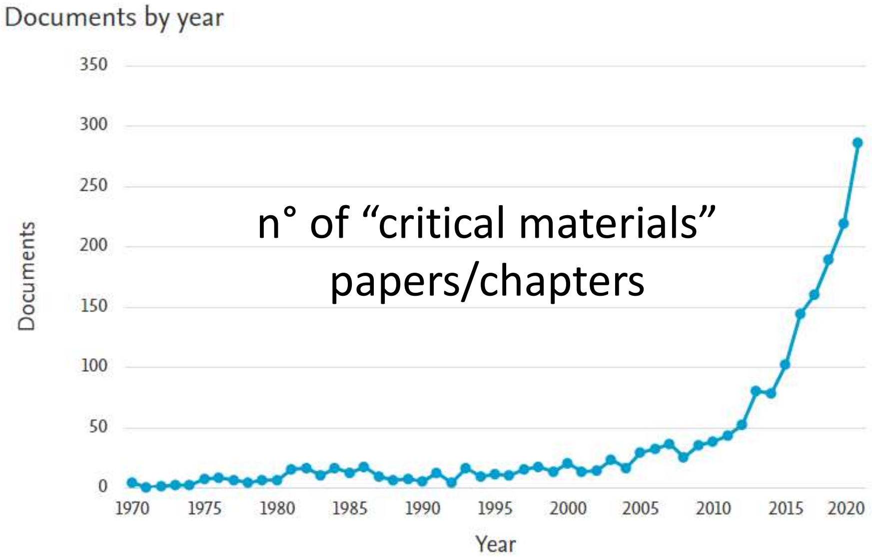
critical and strategic materials

2020-21

(PART 1)

Why this course is different

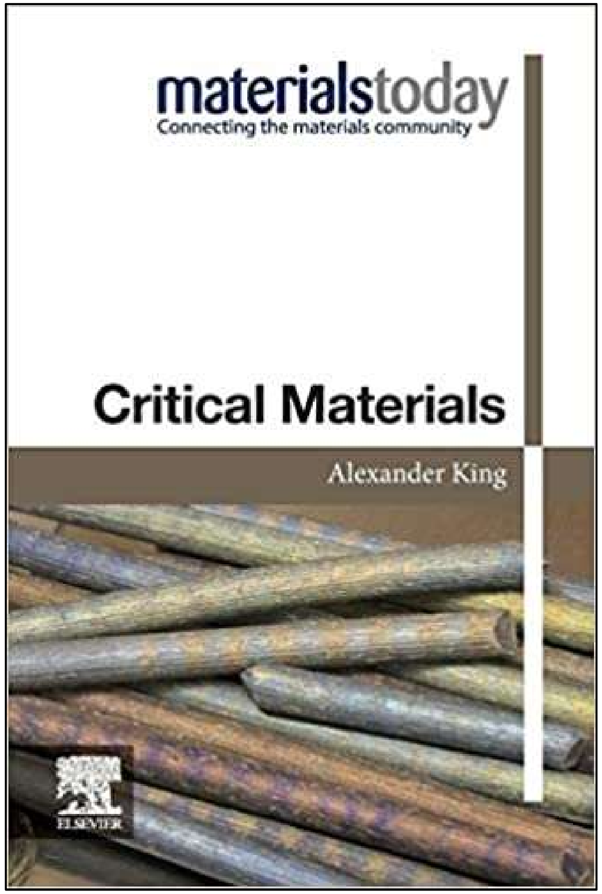
- **new field of study** (from 2008)
- rapidly evolving, constantly changing
- few experts
- just 2 (very recent) books on the subject
- many **unsettled, open aspects**
- **emerging** field (lots of interest!)
- highly **interdisciplinary** (geopolitics, economy, environment, human rights, …)



n° of “critical materials” papers/chapters

(source: SCOPUS, 2021)

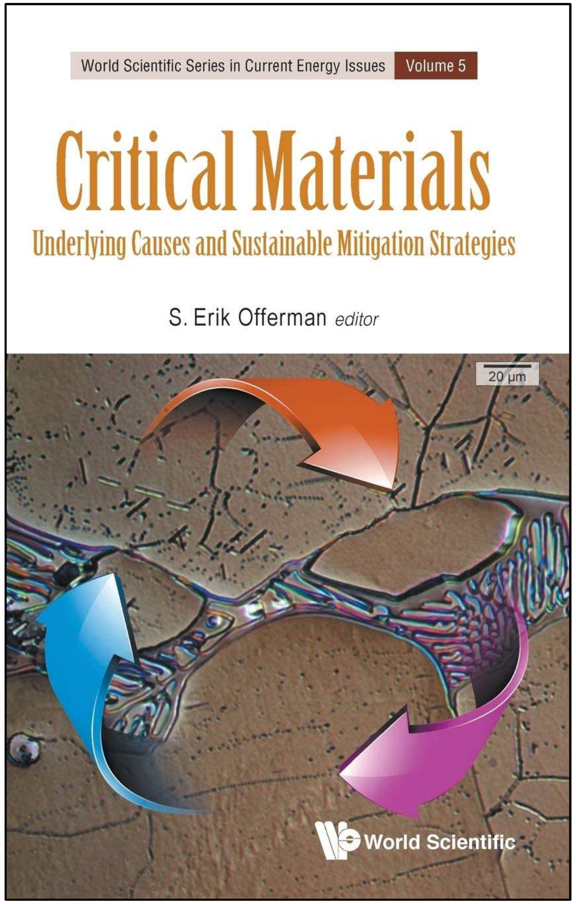
Secondary sources


materialstoday
Connecting the materials community

Critical Materials

Alexander King

ELSEVIER


World Scientific Series in Current Energy Issues Volume 5

Critical Materials

Underlying Causes and Sustainable Mitigation Strategies

S. Erik Offerman *editor*

World Scientific

Primary sources

U.S. DEPARTMENT OF ENERGY

Critical Materials Strategy

December 2011

U.S. DEPARTMENT OF ENERGY

Energy Critical Elements:

Securing Materials for Er

A REPORT BY THE APS PANEL ON PUBLIC AI

APS physics

MRS

European Commission

Study on the EU's list of Critical Raw Materials (2020)

Final Report

Raw Materials

European Commission

JRC SCIENTIFIC AND POLICY REPORTS

Critical Metals in the Path towards the Decarbonisation of the EU Energy Sector

Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies

R.L.Moss[1], E.Tzimas[1], P.Willis[2], J.Arendorf[2], L.Tercero Espinoza[3] et al.

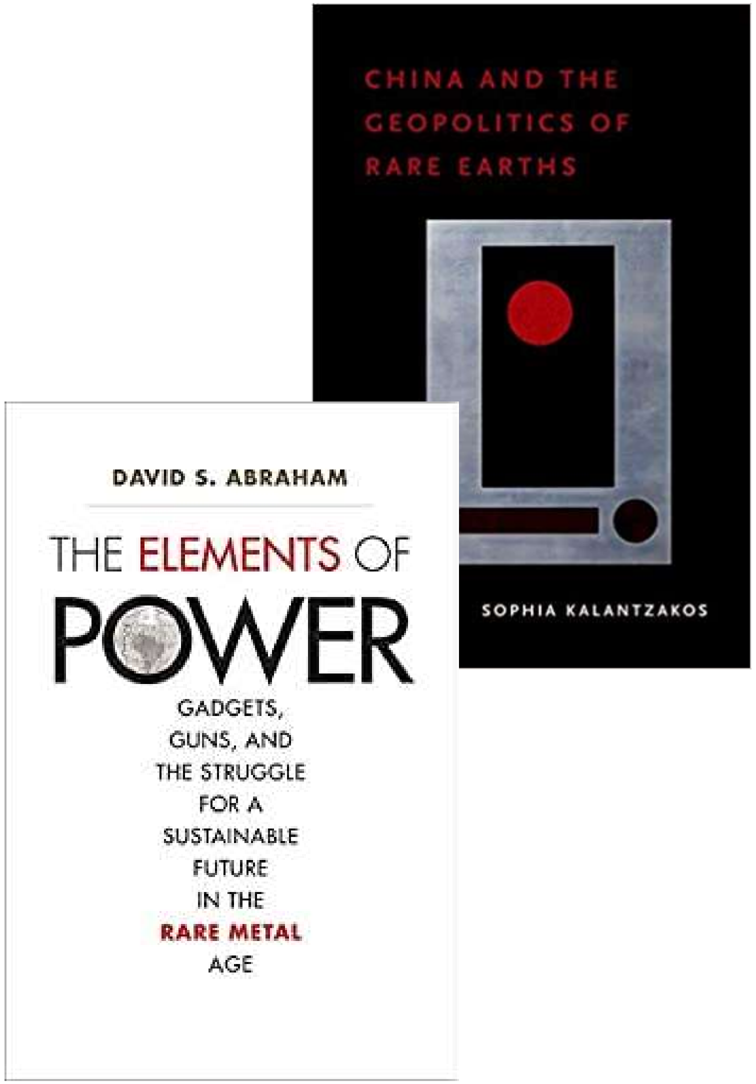
[1]JRC – Institute for Energy and Transport
[2]Oakdene Hollins Ltd
[3]Fraunhofer Institute for Systems and Innovation Research ISI

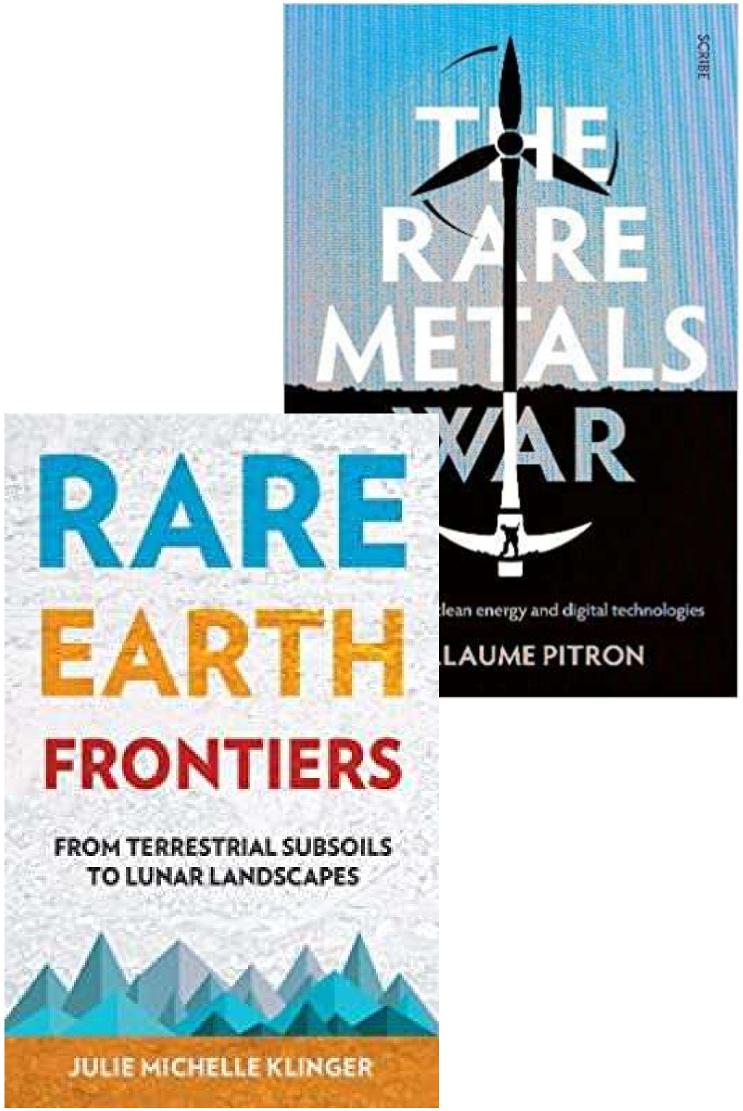
2013

Report EUR 25994 EN

Joint Research Centre

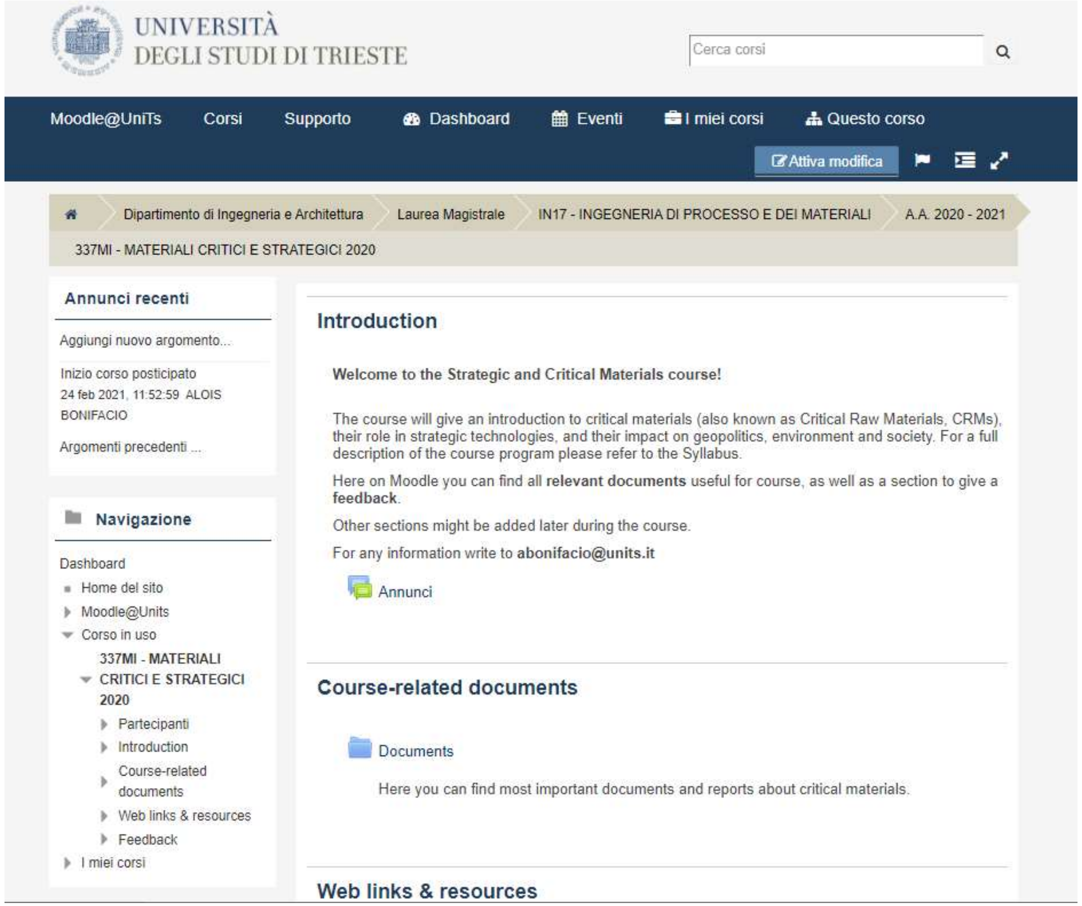
intro/popular books





Moodle

- Documents (primary sources)
- Web links & resources
- Feedback
- **Slides** *(at the end of the course)*



Inizio corso posticipato
24 feb 2021, 11:52:59 ALOIS BONIFACIO

Introduction

Welcome to the Strategic and Critical Materials course!

The course will give an introduction to critical materials (also known as Critical Raw Materials, CRMs), their role in strategic technologies, and their impact on geopolitics, environment and society. For a full description of the course program please refer to the Syllabus.

Here on Moodle you can find all **relevant documents** useful for course, as well as a section to give a **feedback**.

Other sections might be added later during the course.

For any information write to **abonifacio@units.it**

Course-related documents

Here you can find most important documents and reports about critical materials.

Web links & resources

Evaluation (exam)

- 20 min **presentation of a document** (lecture) during the course

  criteria:

  - ✓ clarity of presentation
  - ✓ correctness of concepts
  - ✓ accuracy of language (use of technical terms)
  - ✓ links with course topics
  - ✓ overall understanding of the topic

  (2/3)

- Materials selection **assignment** (check with prof. Lughi)

  (1/3)

Part 1

Troubles

Increased use of resources

“**We are using minerals and metals in greater quantities than ever before**. […] The main reasons for these changes are **increased global population** and the **spread of prosperity** across the world.”

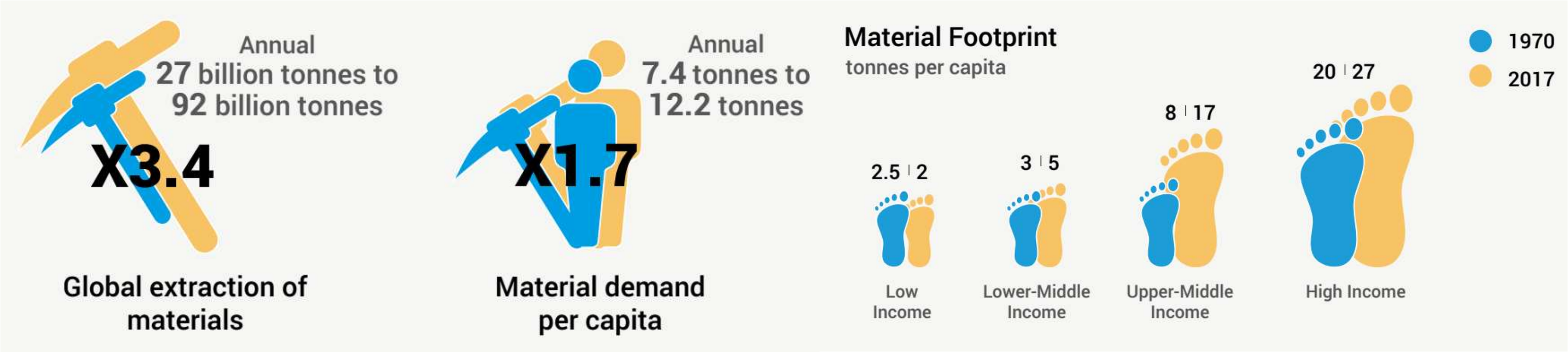
T.E. Graedel, G. Gunn, L. Tercero Espinoza,
Critical Metals Handbook, BGS-Wiley, 2014

“The **use of natural resources** has more than **tripled from 1970** and continues to grow.”

International Resource Panel, Global Resource Outlook 2019

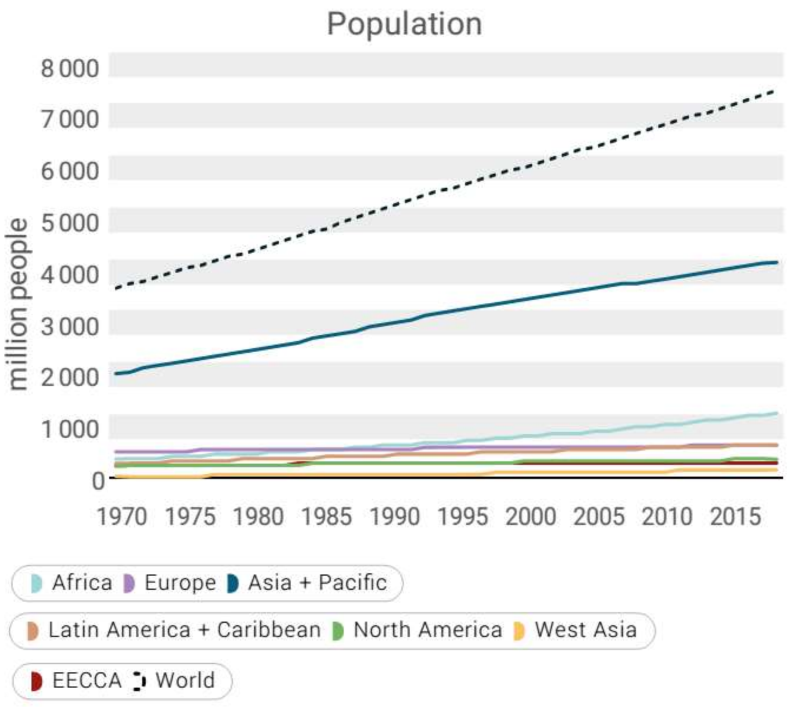
UN environment

International
Resource
Panel



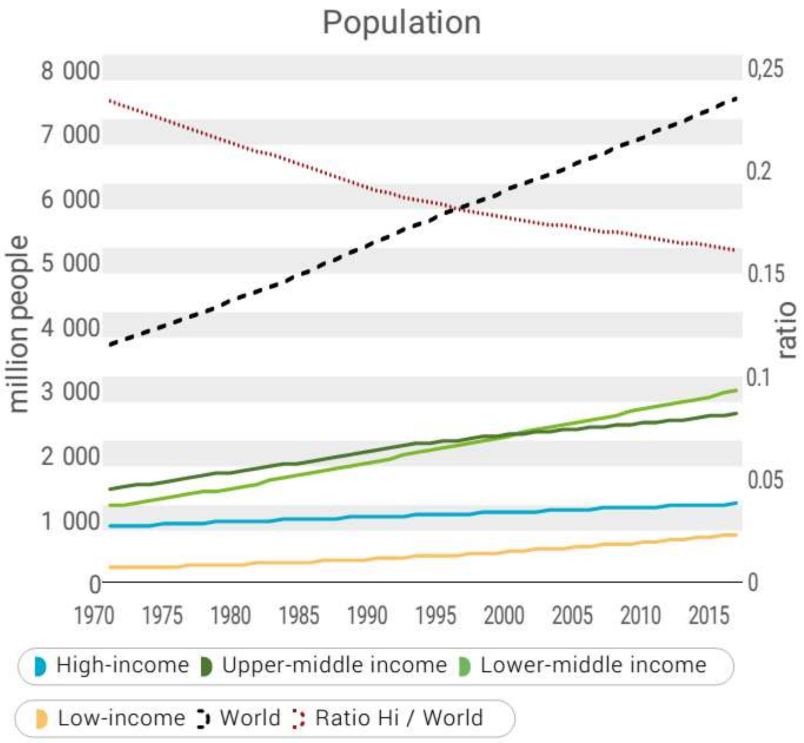
Increased use of resources

FIGURE 2.1 **Distribution of population among seven world regions, 1970 – 2017, million people**



Source: UNDESA, 2017

FIGURE 2.2 **Distribution of global population among four national income bands, with ratio of high-income group to total, 1970 – 2017**



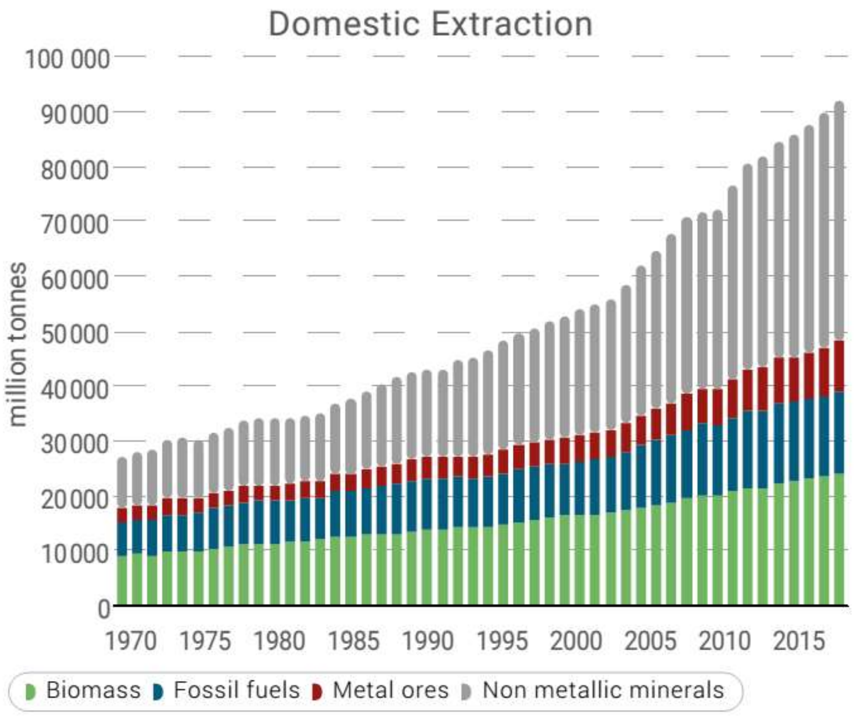
Source: UNDESA, 2017

UN environment

International Resource Panel

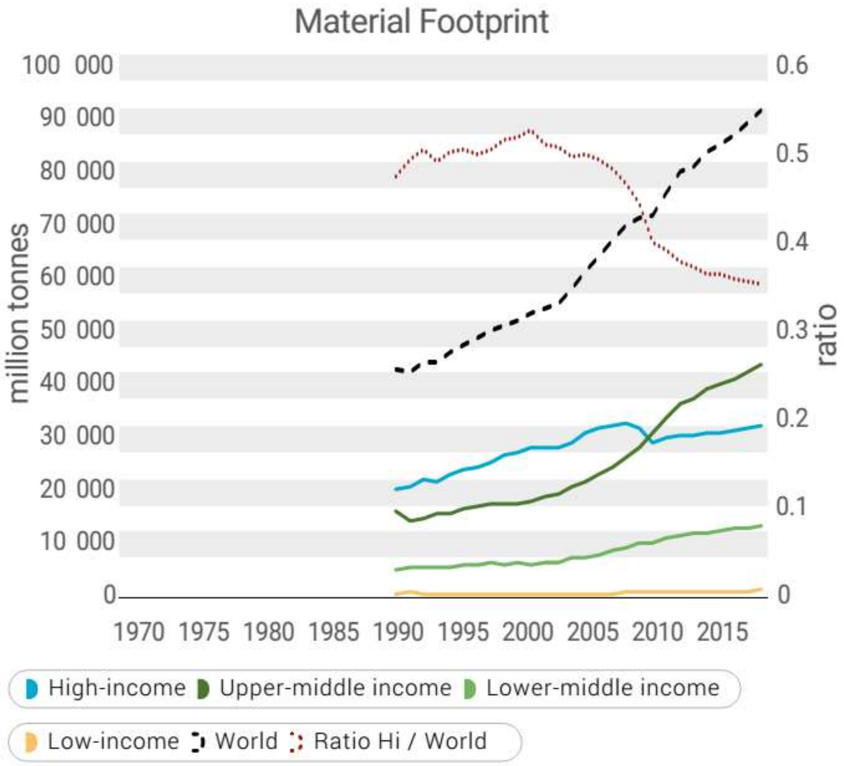
Increased use of resources

FIGURE 2.7 **Global material extraction, four main material categories, 1970 - 2017, million tons. Obtained by totalling domestic material extraction for all individual nations**



Source: UNEP & IRP, 2018

FIGURE 2.24 **Material footprint by four national income bands, with world average, 1970 – 2017, and ratio of high-income group to World total**

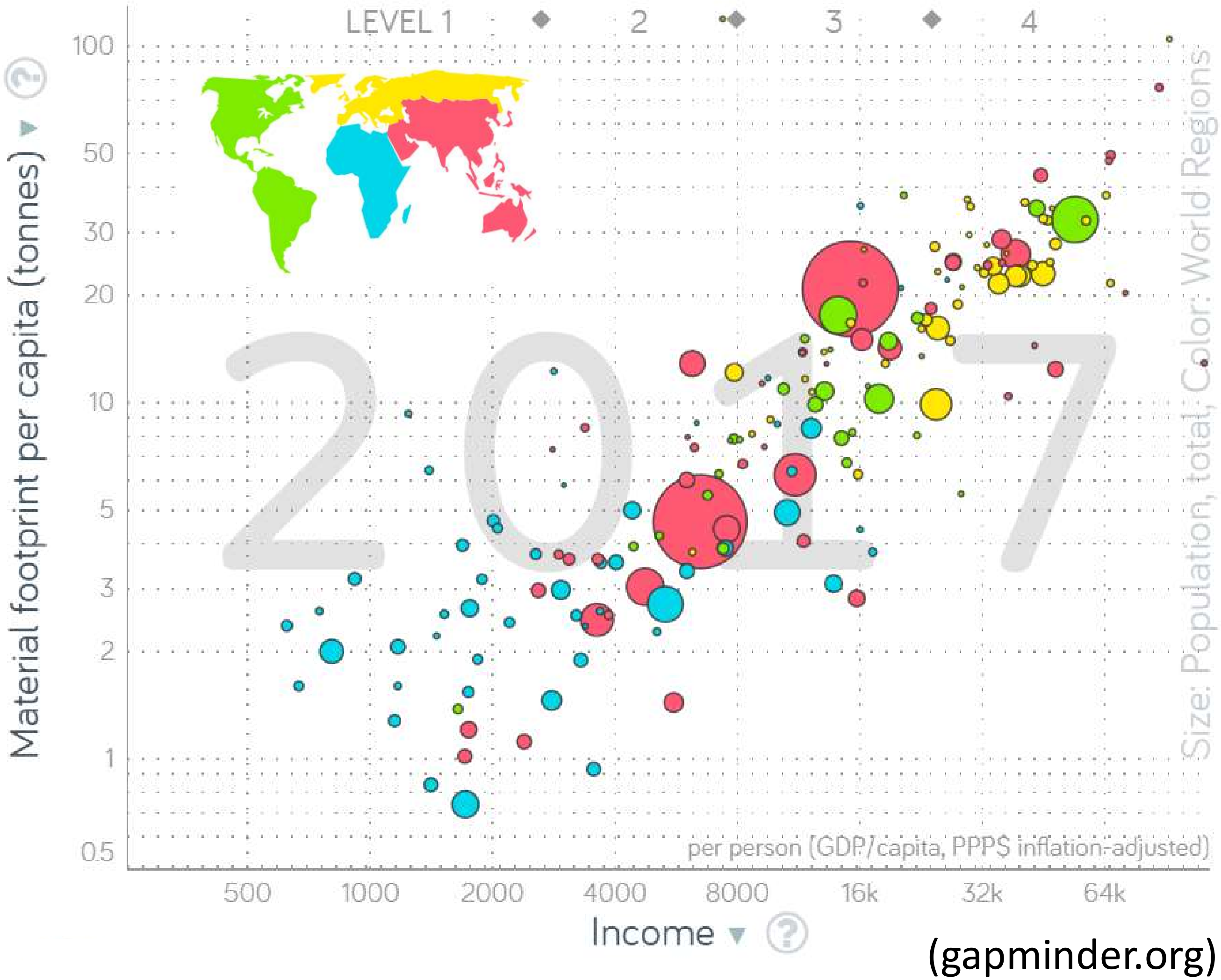


Source: UN, 2017a; UNEP & IRP, 2018

UN environment

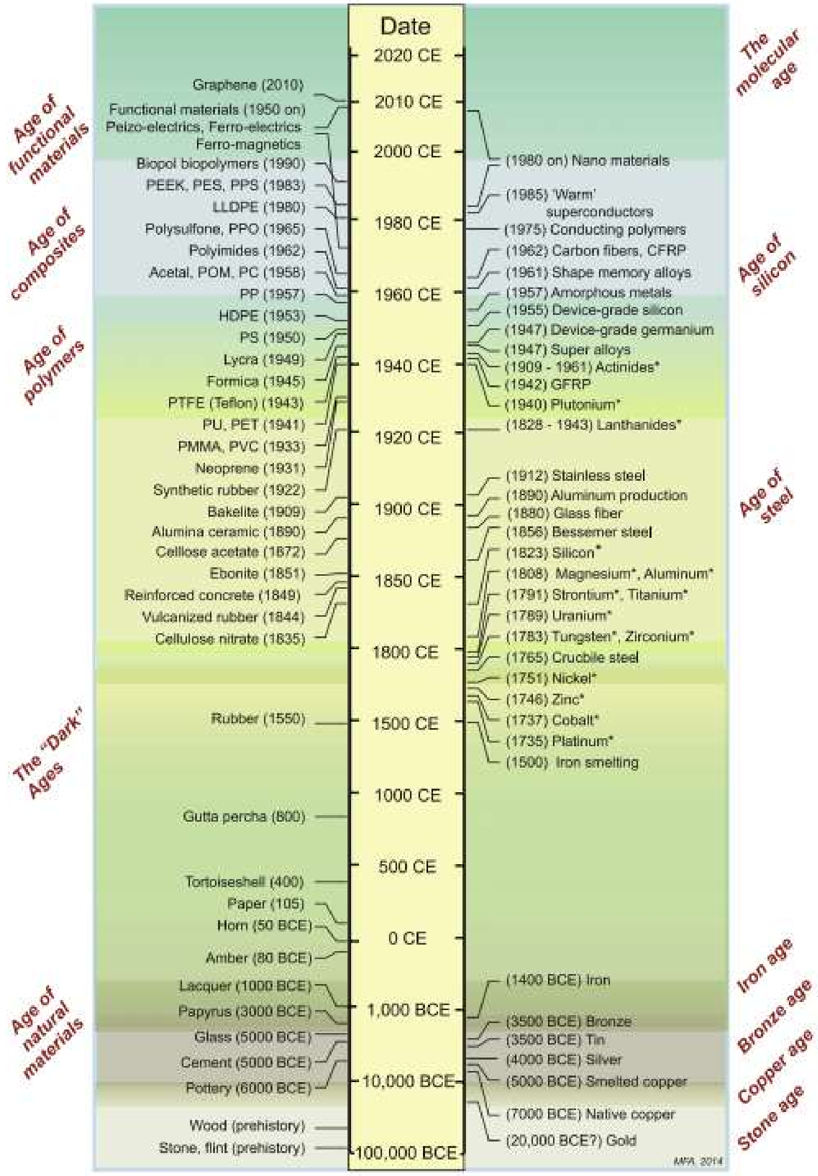
International Resource Panel

Increased use of resources



(gapminder.org)

Increased variety of materials



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

accelerated rate of materials innovation

"In a surprisingly short space of time, we have become dependent on this treasure chest of elements and the materials made from them."

Prof. M. Ashby
Materials and Sustainable development
Elsevier 2016

The omnivorous diet of modern technology

"At no point in human history we have used *more* elements, in *more* combination, and in increasingly refined amounts."

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

"Increasing numbers of elements are being used in nearly all of our technologies. Today's devices rely on a wider array of chemical elements than at any time in history."

A. King, Critical Materials, Elsevier, 2021

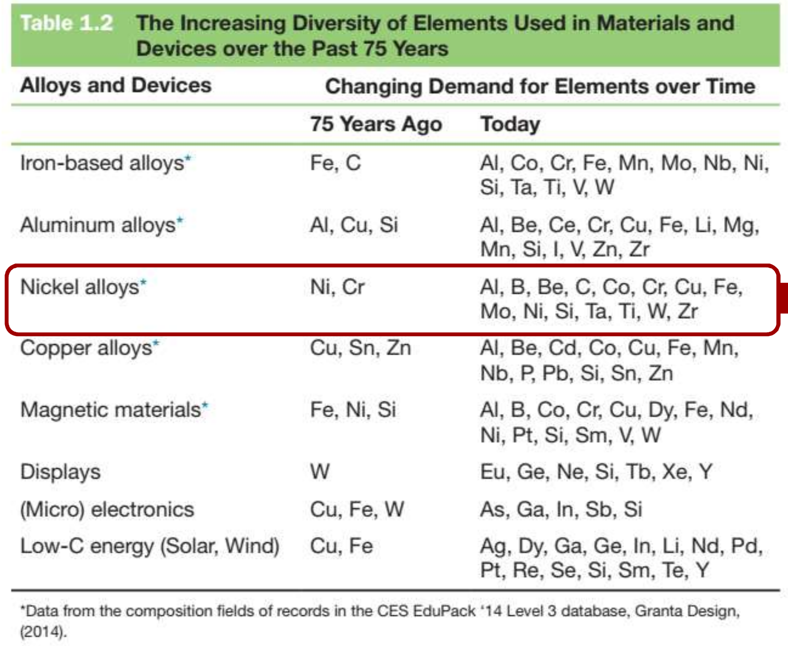
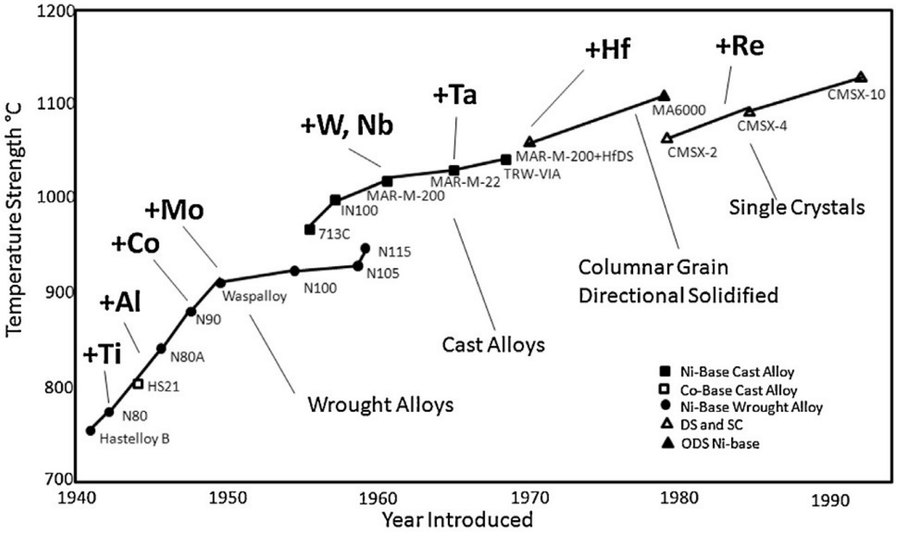


Table 1.2 **The Increasing Diversity of Elements Used in Materials and Devices over the Past 75 Years**

Alloys and Devices	Changing Demand for Elements over Time	
	75 Years Ago	Today
Iron-based alloys*	Fe, C	Al, Co, Cr, Fe, Mn, Mo, Nb, Ni, Si, Ta, Ti, V, W
Aluminum alloys*	Al, Cu, Si	Al, Be, Ce, Cr, Cu, Fe, Li, Mg, Mn, Si, I, V, Zn, Zr
Nickel alloys*	Ni, Cr	Al, B, Be, C, Co, Cr, Cu, Fe, Mo, Ni, Si, Ta, Ti, W, Zr
Copper alloys*	Cu, Sn, Zn	Al, Be, Cd, Co, Cu, Fe, Mn, Nb, P, Pb, Si, Sn, Zn
Magnetic materials*	Fe, Ni, Si	Al, B, Co, Cr, Cu, Dy, Fe, Nd, Ni, Pt, Si, Sm, V, W
Displays	W	Eu, Ge, Ne, Si, Tb, Xe, Y
(Micro) electronics	Cu, Fe, W	As, Ga, In, Sb, Si
Low-C energy (Solar, Wind)	Cu, Fe	Ag, Dy, Ga, Ge, In, Li, Nd, Pd, Pt, Re, Se, Si, Sm, Te, Y

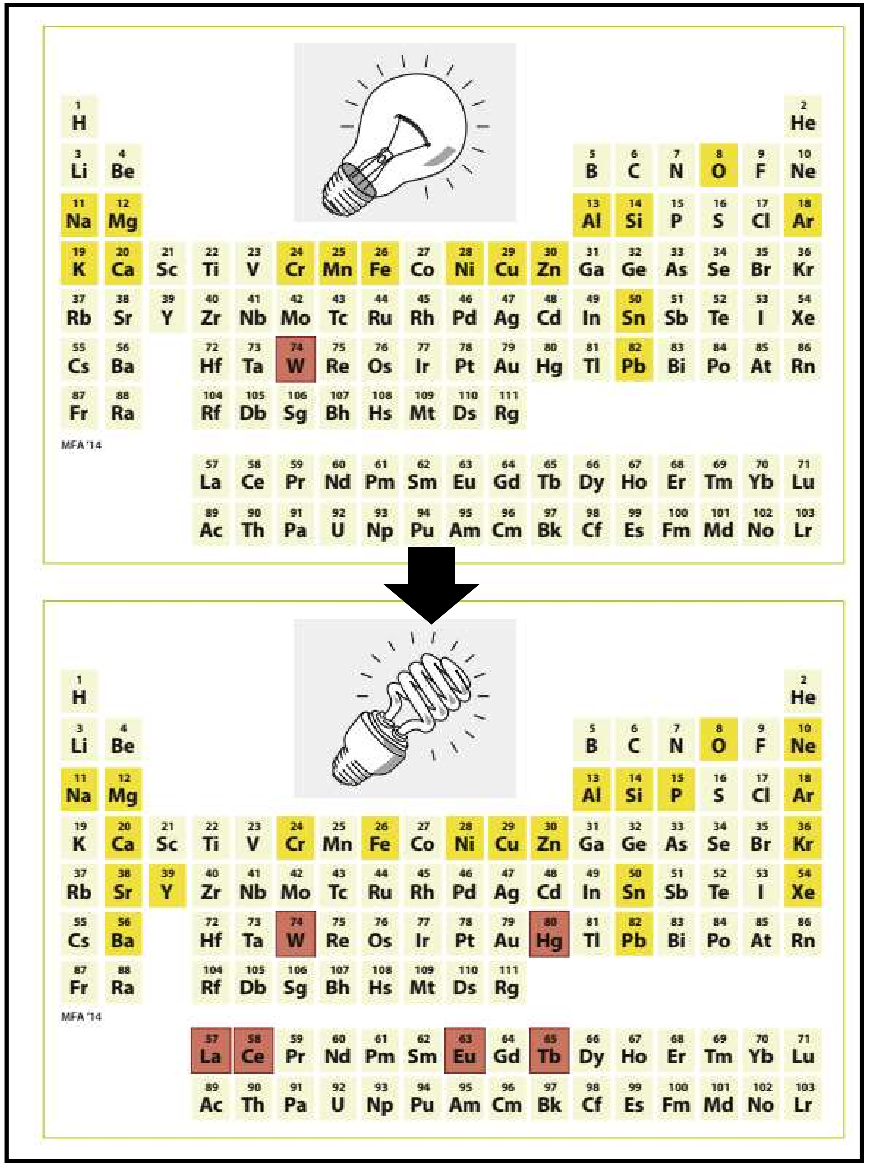
*Data from the composition fields of records in the CES EduPack '14 Level 3 database, Granta Design, (2014).

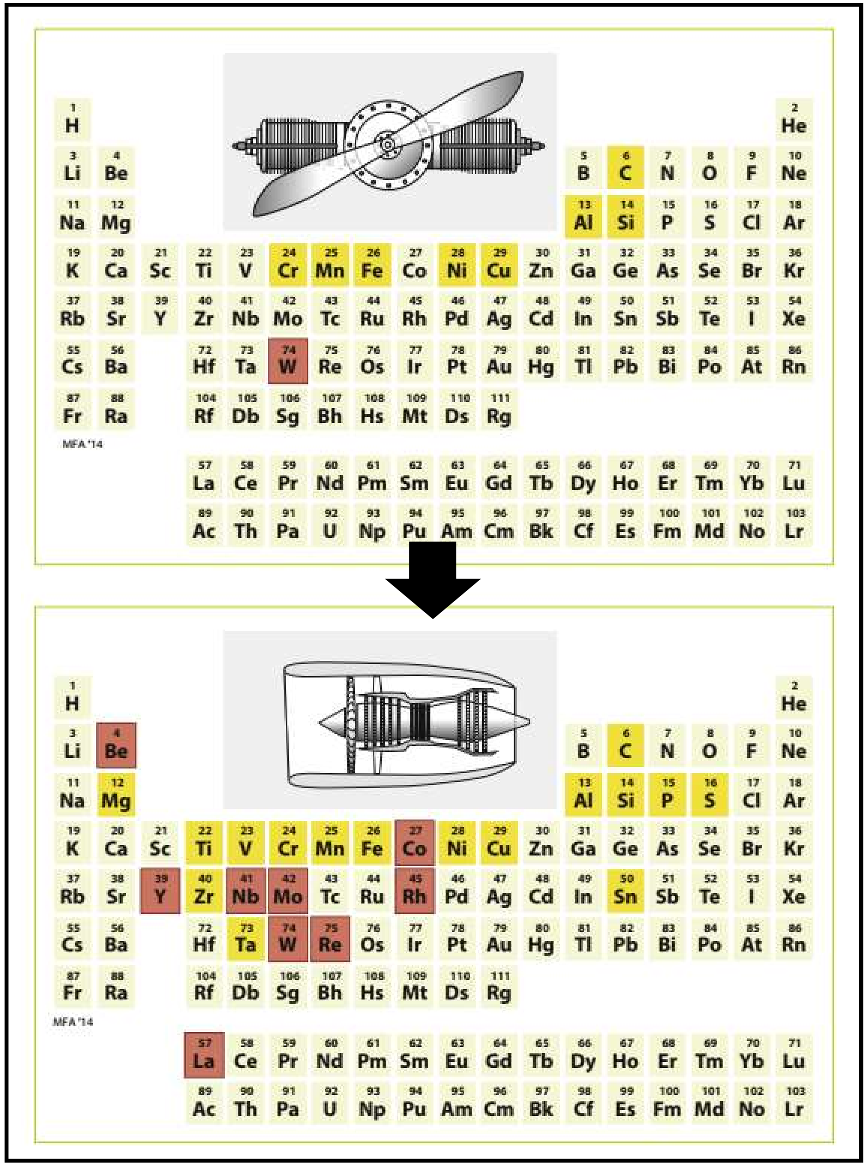
(M. Ashby, "Materials and Sustainable Development", Elsevier 2016)



(A. Greenfield, T.E.Graedel, Resour. Conserv. Recycl. 74, 2013, 1-7)

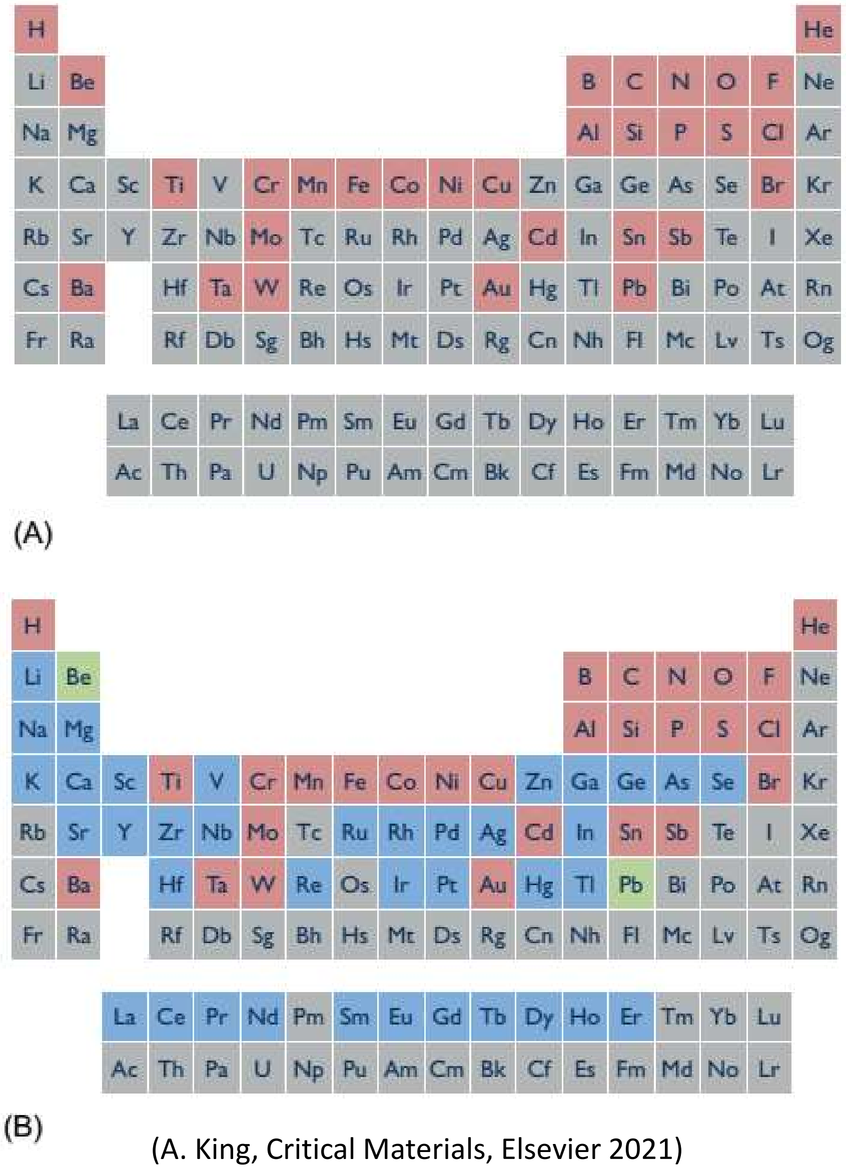
The omnivorous diet of modern technology





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

The omnivorous diet of modern technology



1983

2018

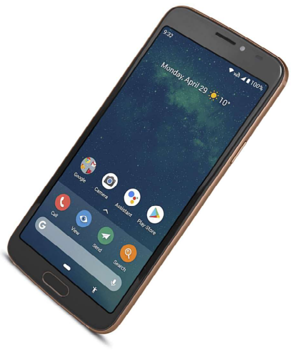
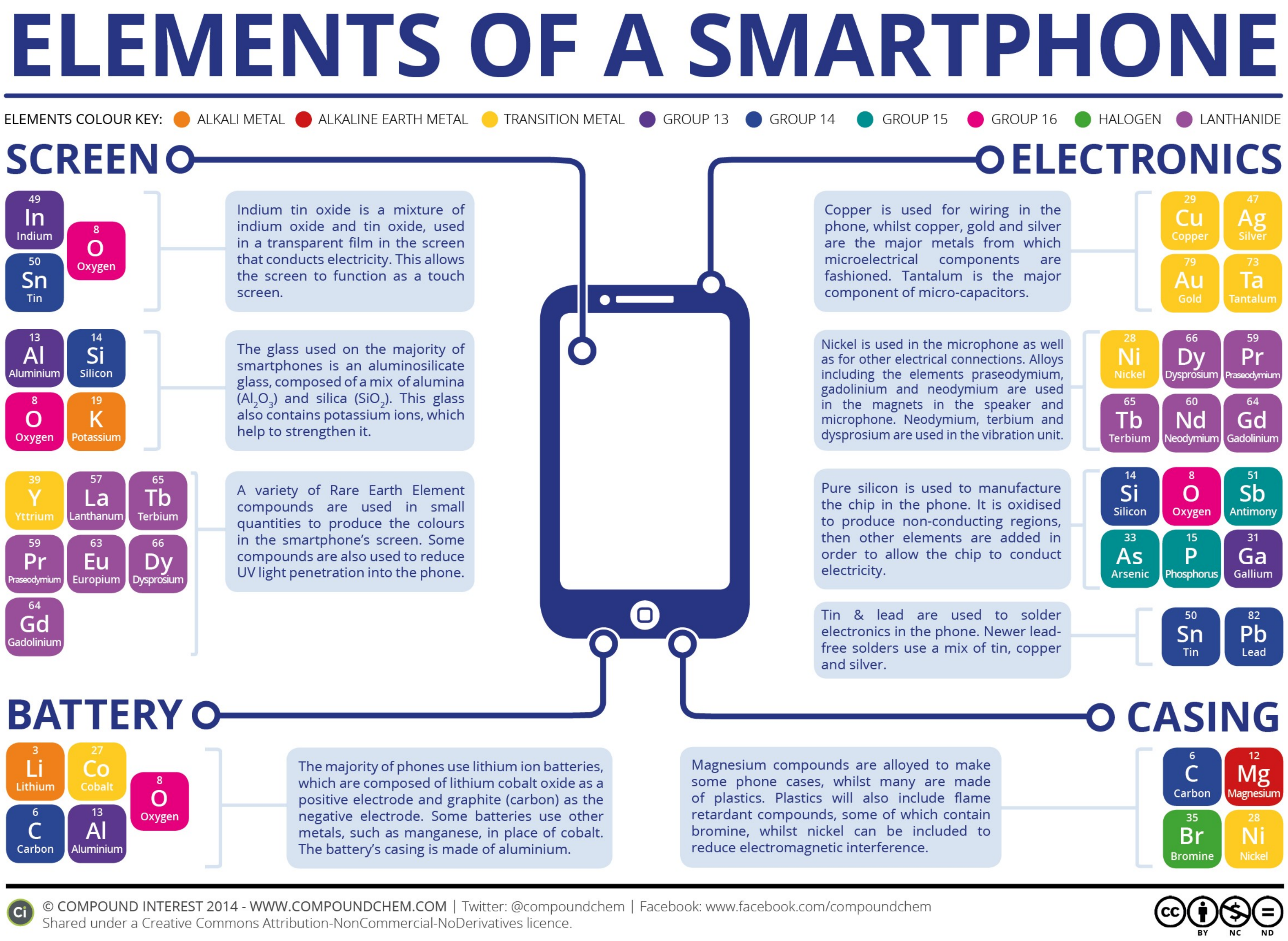


Fig. 3.10 The growing palette of materials in high-tech devices. (A) The elements known or inferred to be required for the manufacture of a 1983 vintage cellular telephone. (B) The elements required to make a 2018 smart phone. The elements used in the 1983 phone are in *blue*, the additional elements are in *red*, and the elements that have been removed are shown in *green*.

(A. King, Critical Materials, Elsevier 2021)

The omnivorous diet of modern technology



ELEMENTS OF A SMARTPHONE

ELEMENTS COLOUR KEY: ● ALKALI METAL ● ALKALINE EARTH METAL ● TRANSITION METAL ● GROUP 13 ● GROUP 14 ● GROUP 15 ● GROUP 16 ● HALOGEN ● LANTHANIDE

SCREEN

49 In Indium
50 Sn Tin
8 O Oxygen

Indium tin oxide is a mixture of indium oxide and tin oxide, used in a transparent film in the screen that conducts electricity. This allows the screen to function as a touch screen.

13 Al Aluminium
14 Si Silicon
8 O Oxygen
19 K Potassium

The glass used on the majority of smartphones is an aluminosilicate glass, composed of a mix of alumina (Al_2O_3) and silica (SiO_2). This glass also contains potassium ions, which help to strengthen it.

39 Y Yttrium
57 La Lanthanum
65 Tb Terbium
59 Pr Praseodymium
63 Eu Europium
66 Dy Dysprosium
64 Gd Gadolinium

A variety of Rare Earth Element compounds are used in small quantities to produce the colours in the smartphone's screen. Some compounds are also used to reduce UV light penetration into the phone.

ELECTRONICS

Copper is used for wiring in the phone, whilst copper, gold and silver are the major metals from which microelectrical components are fashioned. Tantalum is the major component of micro-capacitors.

29 Cu Copper
47 Ag Silver
79 Au Gold
73 Ta Tantalum

Nickel is used in the microphone as well as for other electrical connections. Alloys including the elements praseodymium, gadolinium and neodymium are used in the magnets in the speaker and microphone. Neodymium, terbium and dysprosium are used in the vibration unit.

28 Ni Nickel
66 Dy Dysprosium
59 Pr Praseodymium
65 Tb Terbium
60 Nd Neodymium
64 Gd Gadolinium

Pure silicon is used to manufacture the chip in the phone. It is oxidised to produce non-conducting regions, then other elements are added in order to allow the chip to conduct electricity.

14 Si Silicon
8 O Oxygen
51 Sb Antimony
33 As Arsenic
15 P Phosphorus
31 Ga Gallium

Tin & lead are used to solder electronics in the phone. Newer lead-free solders use a mix of tin, copper and silver.

50 Sn Tin
82 Pb Lead

BATTERY

3 Li Lithium
27 Co Cobalt
6 C Carbon
13 Al Aluminium
8 O Oxygen

The majority of phones use lithium ion batteries, which are composed of lithium cobalt oxide as a positive electrode and graphite (carbon) as the negative electrode. Some batteries use other metals, such as manganese, in place of cobalt. The battery's casing is made of aluminium.

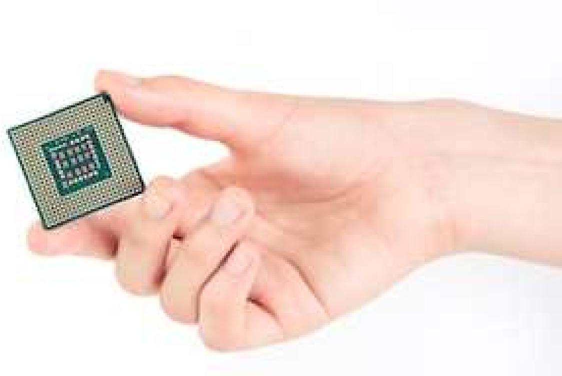
CASING

Magnesium compounds are alloyed to make some phone cases, whilst many are made of plastics. Plastics will also include flame retardant compounds, some of which contain bromine, whilst nickel can be included to reduce electromagnetic interference.

6 C Carbon
12 Mg Magnesium
35 Br Bromine
28 Ni Nickel

(www.compoundchem.com)

The omnivorous diet of modern technology



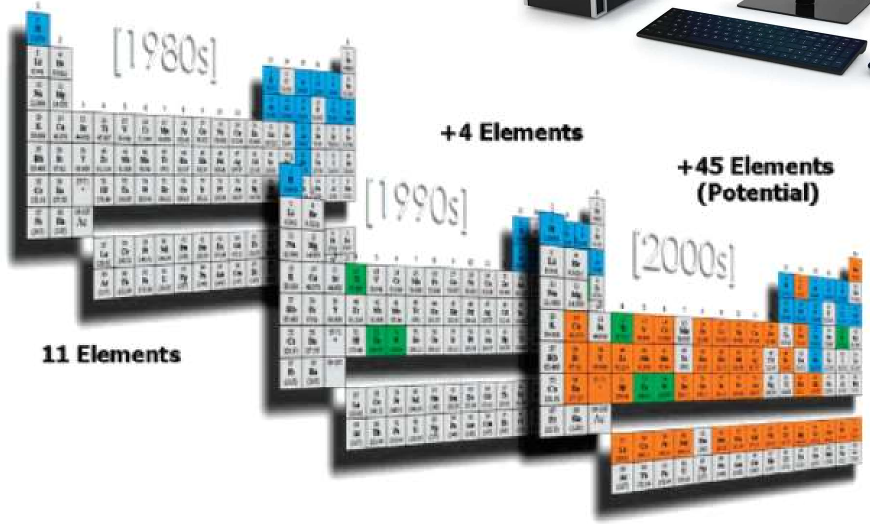
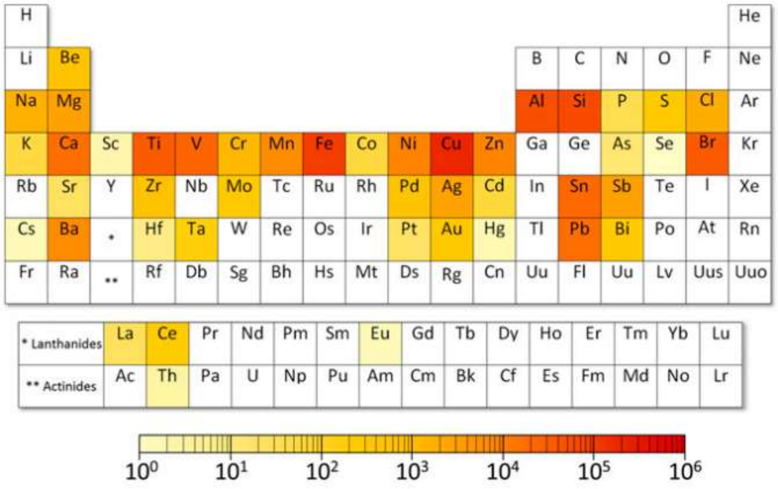


FIGURE 2. Use of elements in a circuit board (from T. McManus, Intel Corporation, private communication, 2006).

Environ. Sci. Technol. **2007**, *41*, 1759−1765



H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	*	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	**	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Uu	Fl	Uu	Lv	Uus	Uuo

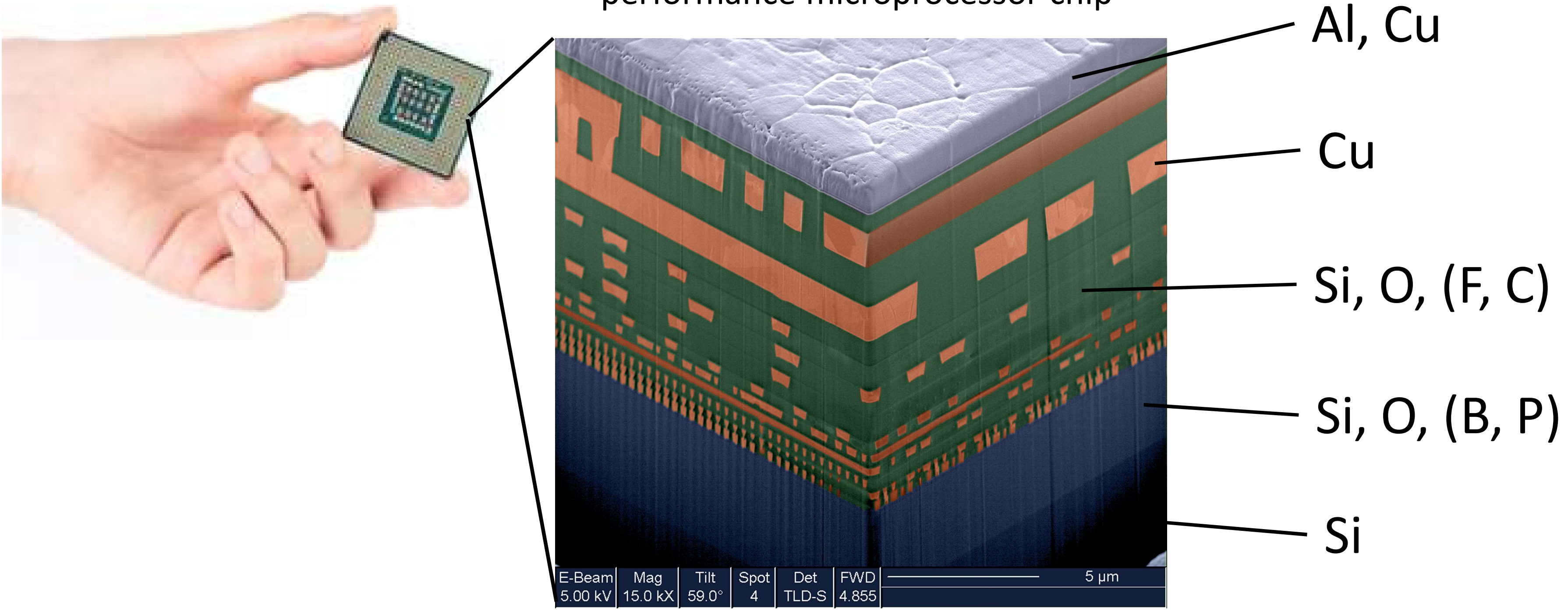
* Lanthanides	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
** Actinides	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Fig. 1. The concentrations (parts per million) of 44 elements found on printed circuit boards (33).

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

Mixed together at smaller and smaller scales

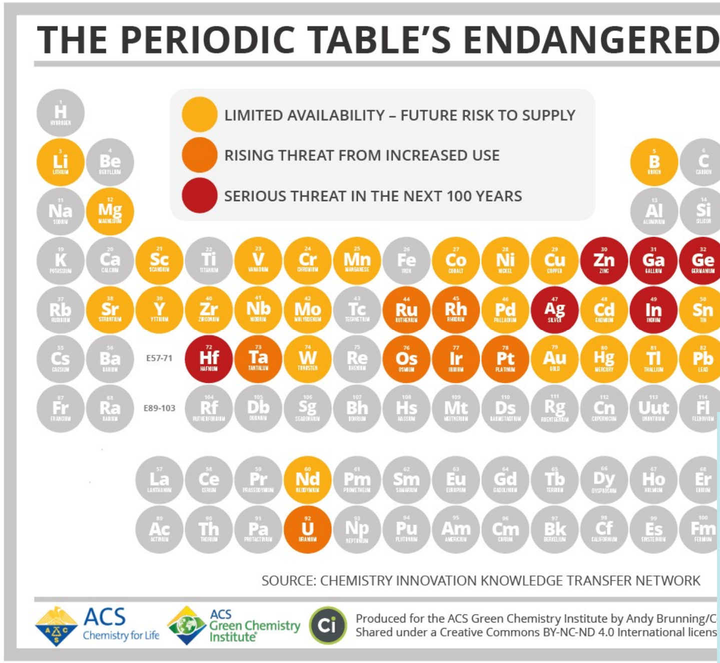
(SEM) Cross-section of 64-bit high-performance microprocessor chip



(https://www-03.ibm.com/press/us/en/photo/19014.wss)

not easy to recycle…

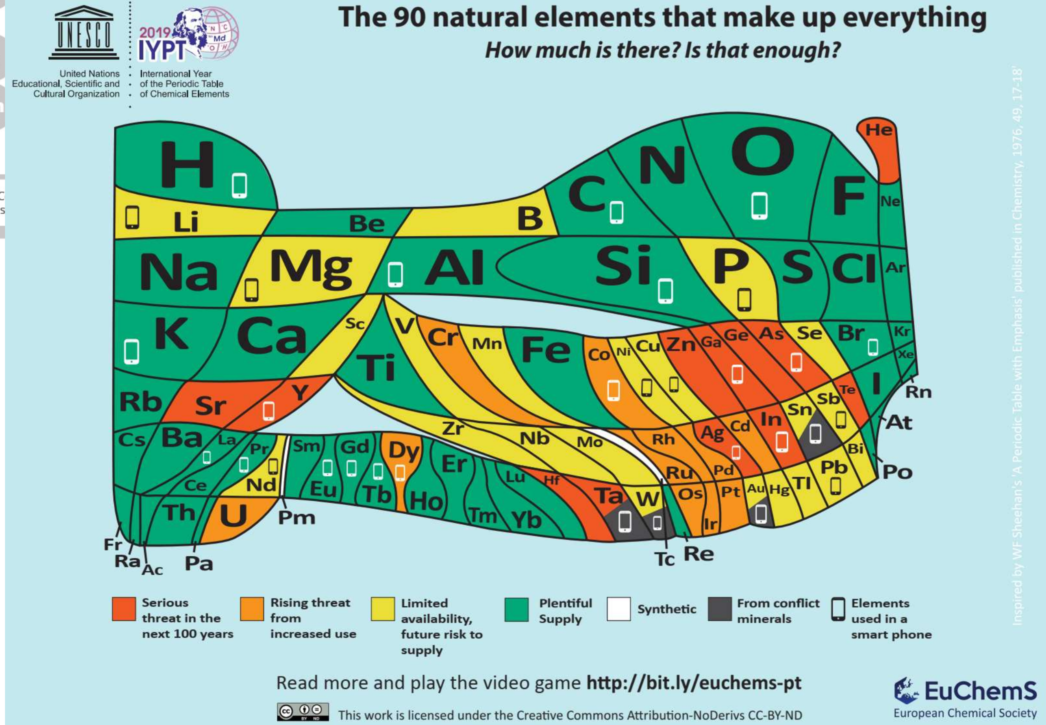
Endangered elements?



(https://www.acs.org/content/acs/en/greenchemistry/research-innovation/endangered-elements.html)

"Of the 118 elements that make up everything […] 44 will face supply limitations in the coming years."

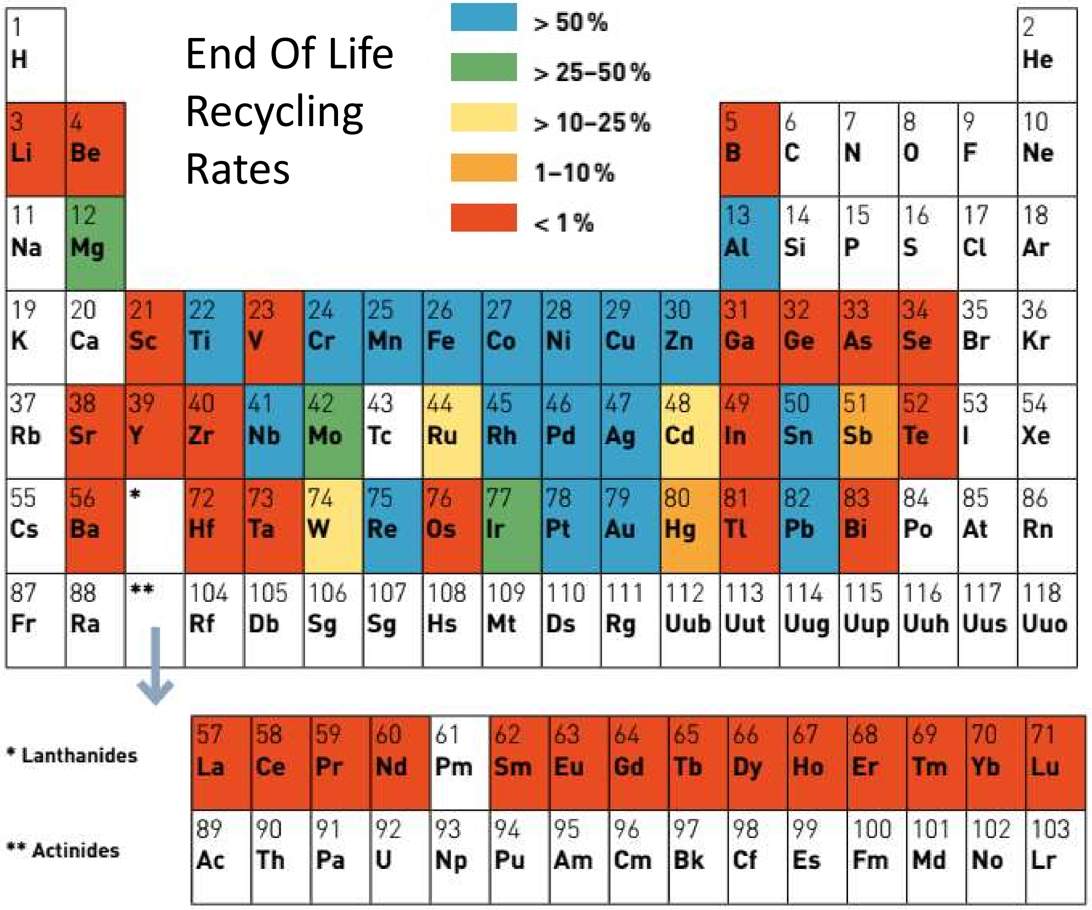
American Chemical Society
Green Chemistry Institute, 2015



"The issue of element scarcity cannot be stressed enough."

European Chemical Society, 2019

Endangered elements?



End Of Life Recycling Rates

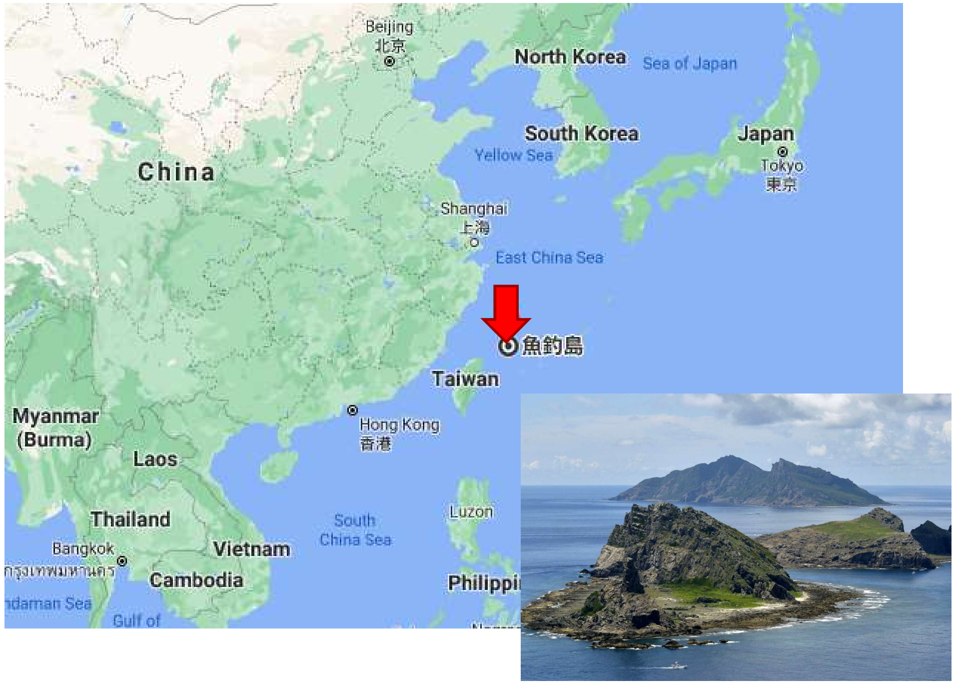
🟦 > 50 %
🟩 > 25–50 %
🟨 > 10–25 %
🟧 1–10 %
🟥 < 1 %

1 H																	2 He
3 Li 🟥	4 Be 🟥											5 B 🟥	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg 🟩											13 Al 🟦	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc 🟥	22 Ti 🟦	23 V 🟥	24 Cr 🟦	25 Mn 🟦	26 Fe 🟦	27 Co 🟦	28 Ni 🟦	29 Cu 🟦	30 Zn 🟦	31 Ga 🟥	32 Ge 🟥	33 As 🟥	34 Se 🟥	35 Br	36 Kr
37 Rb	38 Sr 🟥	39 Y 🟥	40 Zr 🟥	41 Nb 🟦	42 Mo 🟩	43 Tc	44 Ru 🟨	45 Rh 🟦	46 Pd 🟦	47 Ag 🟦	48 Cd 🟨	49 In 🟥	50 Sn 🟦	51 Sb 🟧	52 Te 🟥	53 I	54 Xe
55 Cs	56 Ba 🟥	*	72 Hf 🟥	73 Ta 🟥	74 W 🟨	75 Re 🟦	76 Os 🟥	77 Ir 🟩	78 Pt 🟦	79 Au 🟦	80 Hg 🟧	81 Tl 🟥	82 Pb 🟦	83 Bi 🟥	84 Po	85 At	86 Rn
87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Sg	108 Hs	109 Mt	110 Ds	111 Rg	112 Uub	113 Uut	114 Uug	115 Uup	116 Uuh	117 Uus	118 Uuo

* Lanthanides	57 La 🟥	58 Ce 🟥	59 Pr 🟥	60 Nd 🟥	61 Pm	62 Sm 🟥	63 Eu 🟥	64 Gd 🟥	65 Tb 🟥	66 Dy 🟥	67 Ho 🟥	68 Er 🟥	69 Tm 🟥	70 Yb 🟥	71 Lu 🟥
** Actinides	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

(source: UNEP, International Resource Panel, Metal Recycling Report 2019)

The 2010 Senkaku crisis



● Senkaku Islands (尖閣諸島)

🟥 Diaoyu Islands (釣魚臺列嶼)

- disputed territory
- **economic** value
  (fishing ground, oil/gas deposits)
- **geostrategic** value
  (control of E. China Sea)

Timeline of key events

2010

7 September
Chinese fishing boat rams two Japan Coast Guard (JCG) vessels. The captain and 14 crew members are detained by the JCG.

7-14 September
Japanese ambassador is summoned six times to meet high level Chinese officials.

8-18 September
Anti-Japanese protests across China (Beijing, Shanghai, Hong Kong).

11 September
China suspends talks with Japan on joint exploration of the gas and oil resources in the East China Sea.

19 September
China suspends ministerial and provincial-level contacts with Japan.

20 September
Four Japanese nationals are arrested in China for allegedly entering a military zone without authorisation and photographing military targets.

21 September
China unofficially restricts shipments of unprocessed (e.g. salts, oxides, metals) REE exports to Japan.

embargo

24 September
Japan releases Captain Zhan Qixiong.

2 October
Large-scale protests across Japan against PM Kan's handling of the crisis and China's behaviour.

16-26 October
Second, more intense, wave of anti-Japan protests in China.

18-28 October
Chinese customs officials suspend REE shipments to the EU and US for ten days.

1 November
Closed-door screening of the video recording of the Senkaku collision for a limited group of parliament representatives.[2]

4 November
Video showing the September collision incident between Chinese trawler and JCG vessels is leaked to YouTube.

29 November
REE shipments to Japan are fully restored.

(NATO www.stratcomcoe.org)

The 2010 Senkaku crisis

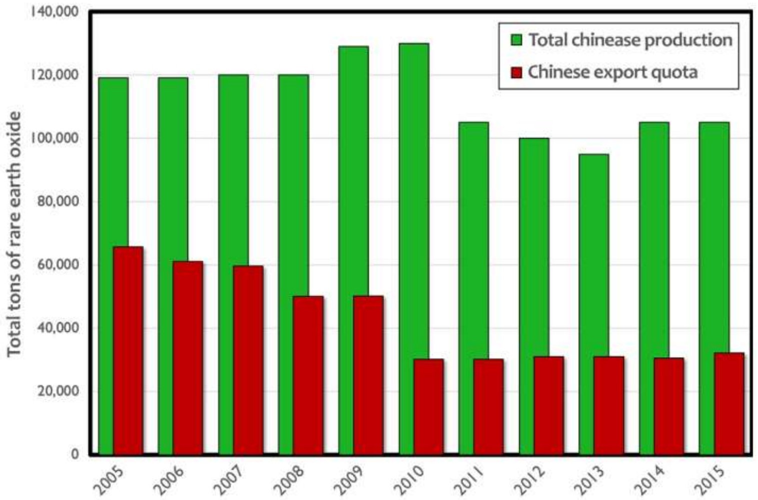


Fig. 1.5 Chinese rare earth oxide production *(in green)* and export quotas *(in red)* from 2005 to 2015. The export quotas ended in 2016.

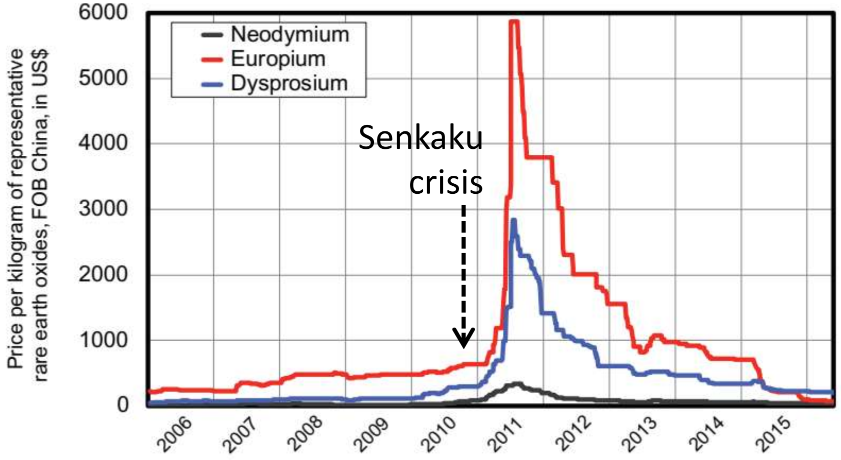


Fig. 1.6 The prices of three representative rare earths from 2006 to 2016. Source of raw price data: Argus Media Inc. (direct.argusmedia.com).

(A. King, Critical Materials, Elsevier 2021)

The New York Times

Amid Tension, China Blocks Vital Exports to Japan

By Keith Bradsher

Sept. 22, 2010

HONG KONG — Sharply raisin
Japan's detention of a Chinese f
government has blocked export
minerals used in products like h
guided missiles.

Critical raw materials for the EU

Report of the Ad-hoc Working Group on defining critical raw materials

The ad-hoc Working Group is a sub-group of the Raw Materials Supply Group and is chaired by the European Commission

European Commission
Enterprise and Industry

We Mean Business

U.S. DEPARTMENT OF ENERGY

December 2010

U.S. DEPARTMENT OF ENERGY

Critical Materials Strategy

2010
reports

- ✓ governments report REE as critical
- ✓ perception of 2010 Japan embargo
- ✓ stringent export quotas

→ *price spike*
(market panic)

A sudden awareness

Forbes

Oct 4, 2010, 01:16am EDT

The Politics of Rare Earth

NATIONAL GEOGRAPHIC

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Replacing Oil Addiction With Metals Dependence?

China's rare-earth minerals monopoly gives it key clean energy supply role

THE WALL STREET JOURNAL.

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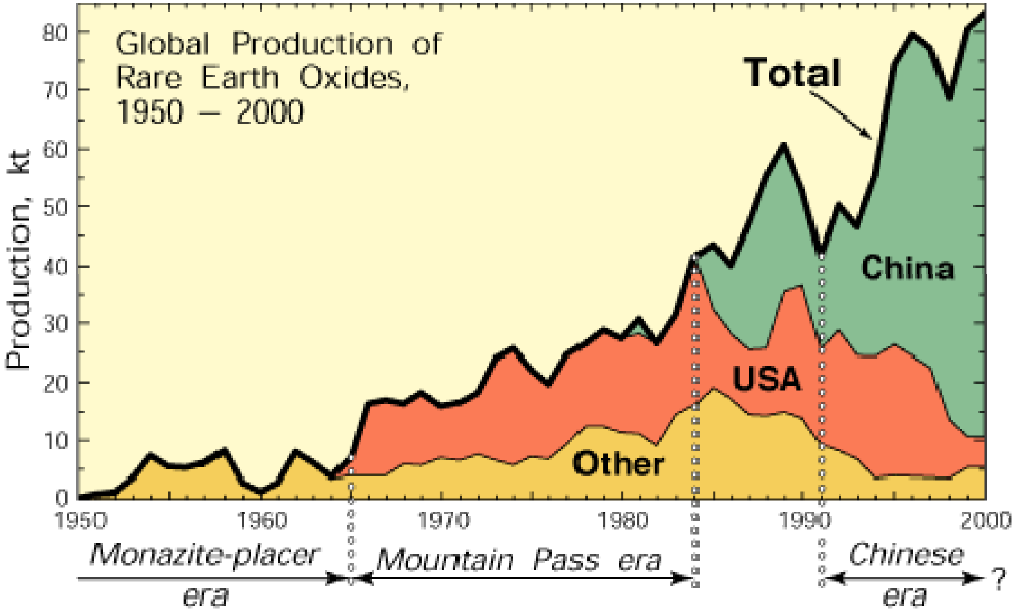
China Moves to Strengthen Grip Over Supply of Rare-Earth Metals

"The Middle East has oil; we have rare earths"

Deng Xiaoping, 1992



(USGS: Mineral Commodity Summaries)

politicization of rare earths

fears that China might use them as a ***economic weapon*** *for geopolitical purposes*

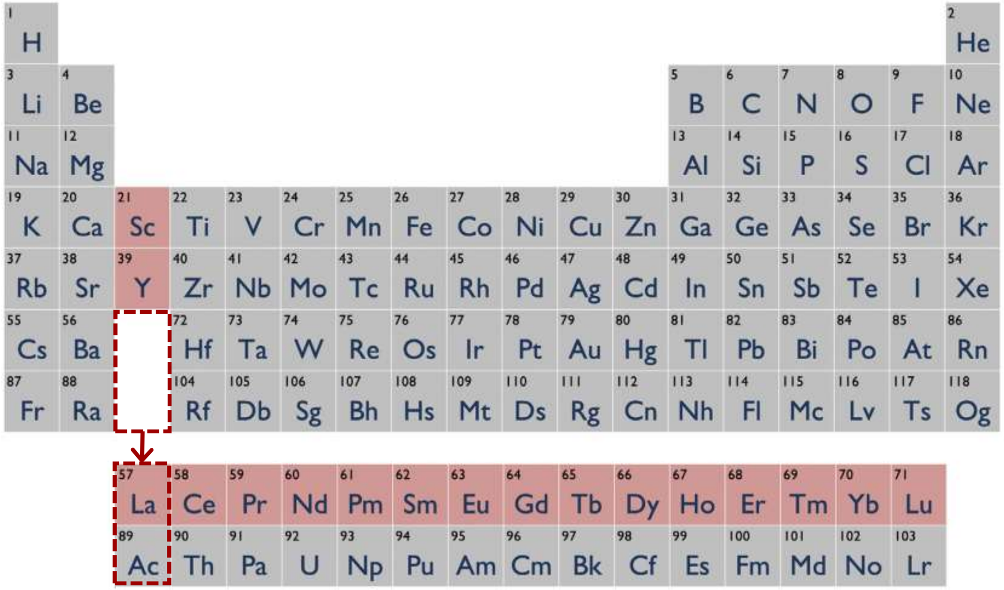
What are rare earths?

RE: *rare earths*
REE: *rare earts elements*
REY: *rare elements +Y*
REO: *rare earths oxides*
REM: *rare earth metals*

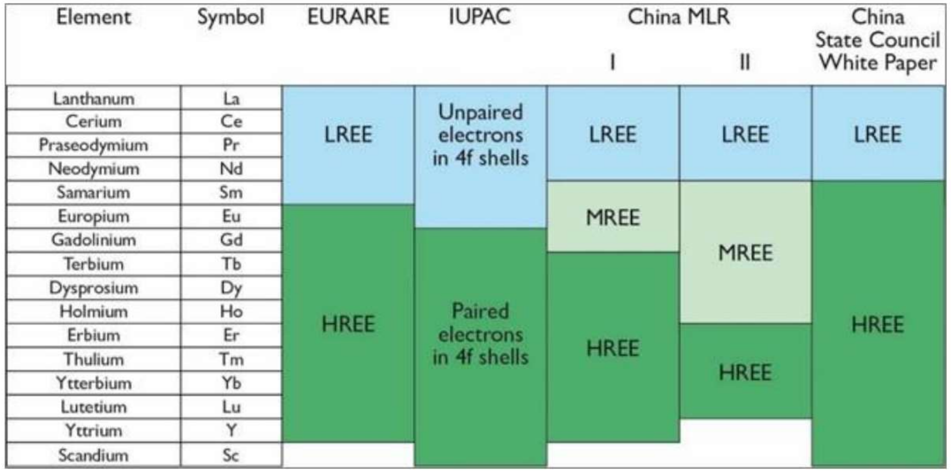
17 elements

15 lanthanides (from La to Lu) ← from Gr. Λανθάνειν (hidden)

+ Scandium (Sc) and Yttrium (Y) ← ***often considered RE:*** *also in Group 3 and closely related to Lanthanides in terms of chemical behaviour*



HREE and LREE



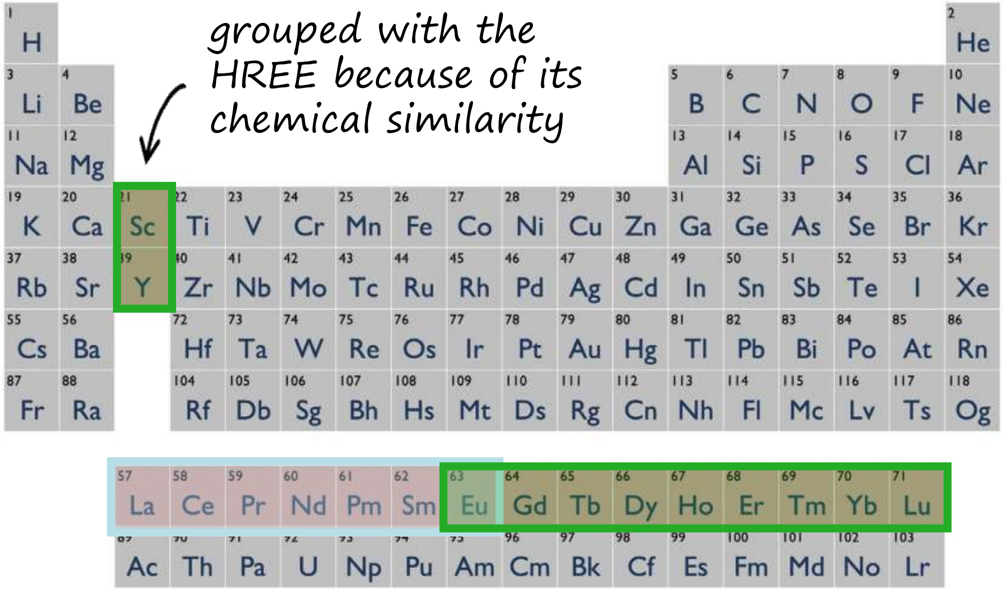
Element	Symbol	EURARE	IUPAC	China MLR		China State Council White Paper
				I	II	
Lanthanum	La	LREE	Unpaired electrons in 4f shells	LREE	LREE	LREE
Cerium	Ce					
Praseodymium	Pr					
Neodymium	Nd					
Samarium	Sm			MREE	MREE	HREE
Europium	Eu	HREE				
Gadolinium	Gd		Paired electrons in 4f shells			
Terbium	Tb			HREE		
Dysprosium	Dy					
Holmium	Ho					
Erbium	Er				HREE	
Thulium	Tm					
Ytterbium	Yb					
Lutetium	Lu					
Yttrium	Y					
Scandium	Sc					

(Machacek and Kalvig, 2017: EURARE)

Light REE (LREE)

Heavy REE (HREE)

inconsistent classification

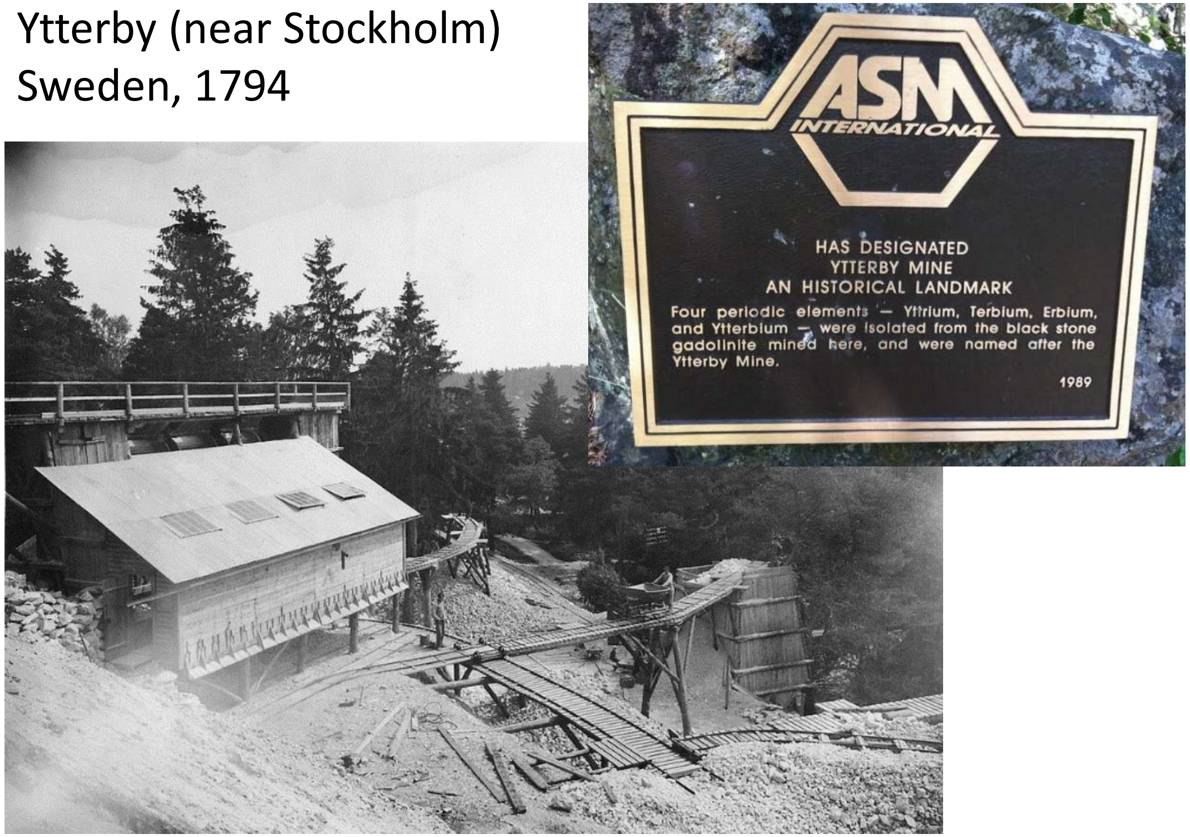


grouped with the HREE because of its chemical similarity

Where it all started

J. Gadolin (1760-1852)

Ytterby (near Stockholm)
Sweden, 1794



HAS DESIGNATED
YTTERBY MINE
AN HISTORICAL LANDMARK

Four periodic elements — Yttrium, Terbium, Erbium, and Ytterbium — were isolated from the black stone gadolinite mined here, and were named after the Ytterby Mine.

1989

Ytterby

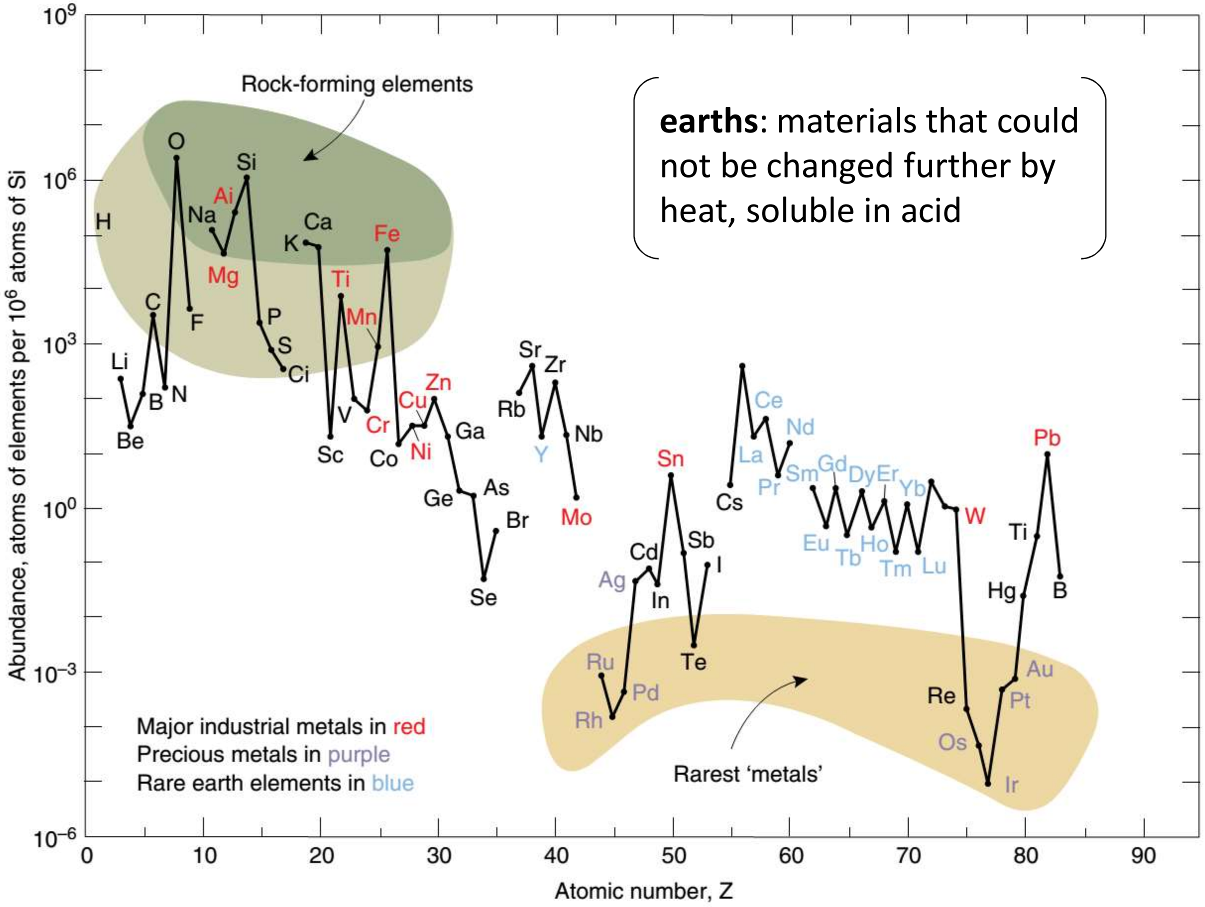
Yttrium	**Y**
Terbium	**Tb**
Erbium	**Er**
Ytterbium	**Yb**

A new element *(Y) is isolated from a black mineral (**gadolinite**)*

Rare earths: neither rare nor earths

"The first thing you need to know is they are neither rare nor earths“

A. Sella, Professor of Inorganic Chemistry at UCL, BBC interview



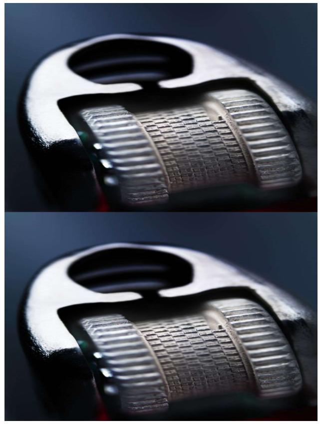
earths: materials that could not be changed further by heat, soluble in acid

(G.Gunn, ed. «Critical metals handbook», Wiley 2014: from USGS 2002 data)

Early uses of REEs

ceramics
pigment (Pr)

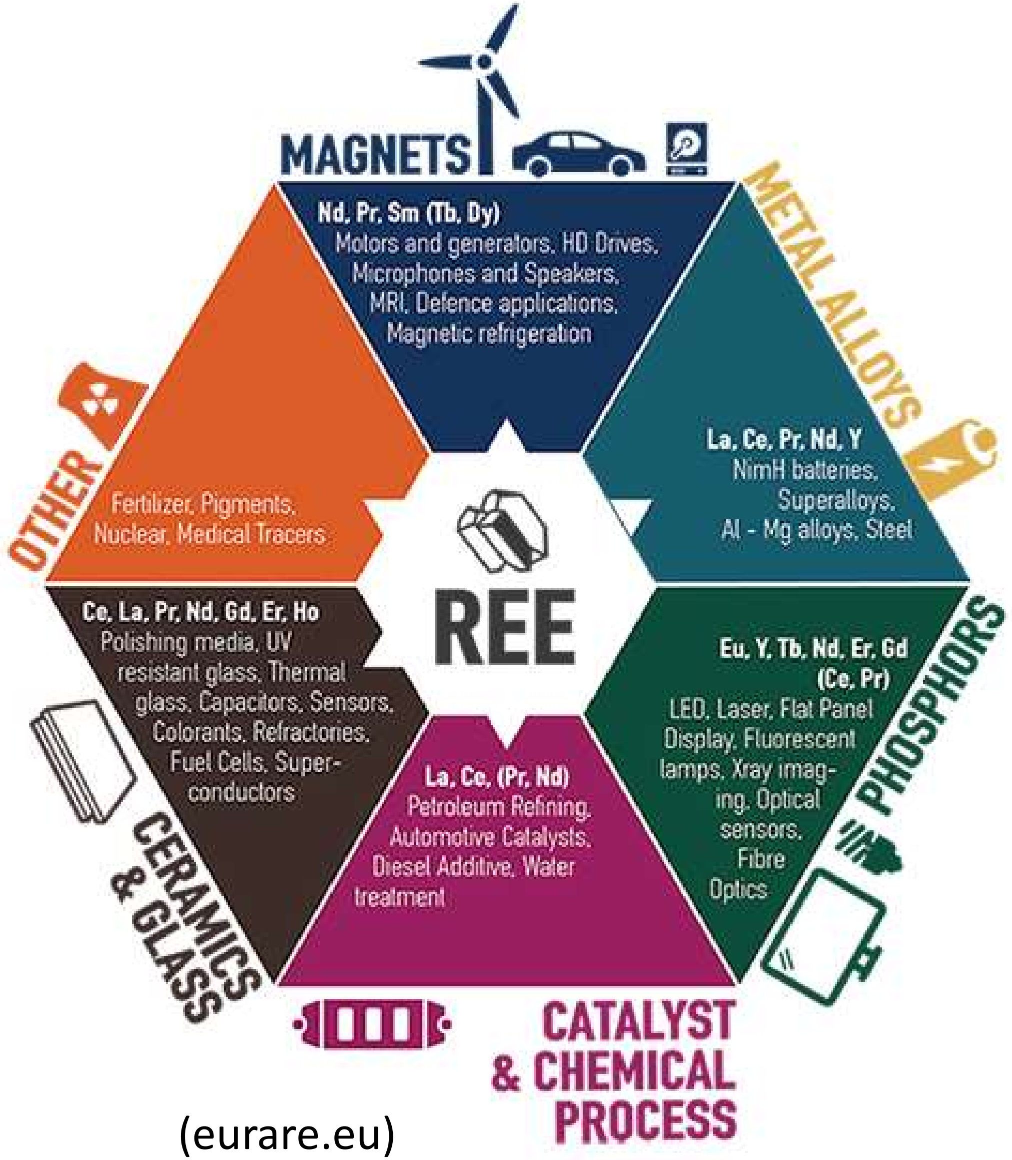
gas mantles (Th, Ce)



lighters
(mischmetal:
Ce, La, Nd, Fe)

Carl Auer von Welsbach
(1858-1929)

Current uses of REEs



MAGNETS

Nd, Pr, Sm (Tb, Dy)
Motors and generators, HD Drives, Microphones and Speakers, MRI, Defence applications, Magnetic refrigeration

METAL ALLOYS

La, Ce, Pr, Nd, Y
NimH batteries, Superalloys, Al - Mg alloys, Steel

PHOSPHORS

Eu, Y, Tb, Nd, Er, Gd (Ce, Pr)
LED, Laser, Flat Panel Display, Fluorescent lamps, Xray imaging, Optical sensors, Fibre Optics

CATALYST & CHEMICAL PROCESS

La, Ce, (Pr, Nd)
Petroleum Refining, Automotive Catalysts, Diesel Additive, Water treatment

CERAMICS & GLASS

Ce, La, Pr, Nd, Gd, Er, Ho
Polishing media, UV resistant glass, Thermal glass, Capacitors, Sensors, Colorants, Refractories, Fuel Cells, Superconductors

OTHER

Fertilizer, Pigments, Nuclear, Medical Tracers

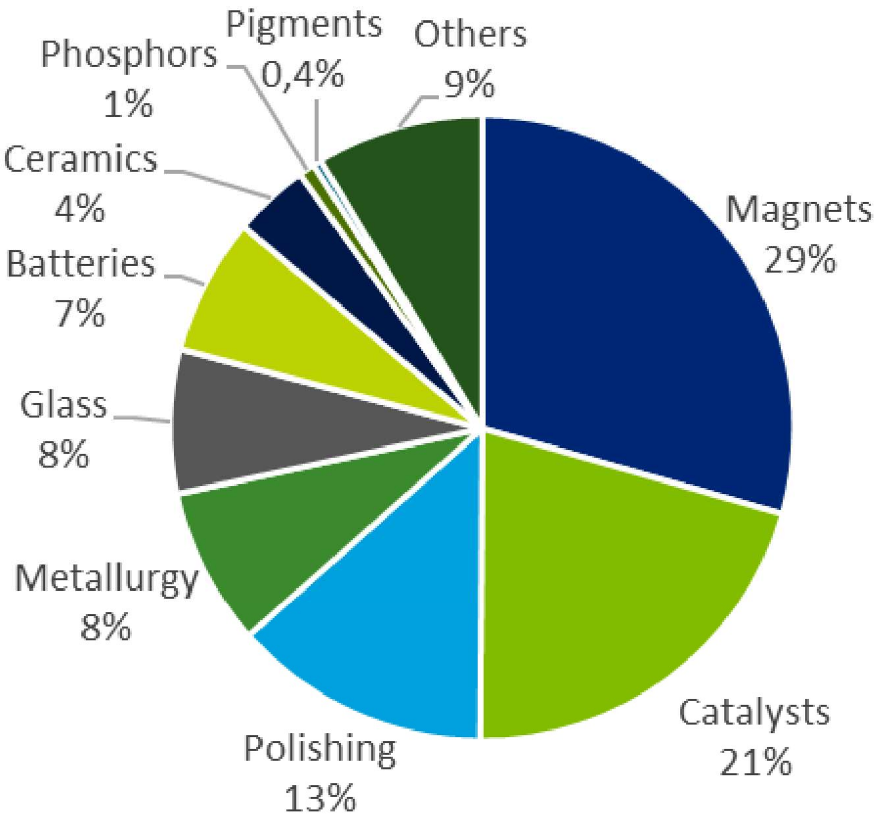
(eurare.eu)

metallic state

---

oxidized state

Current uses of REEs



Global consumption of REO in 2019: 139 551 t

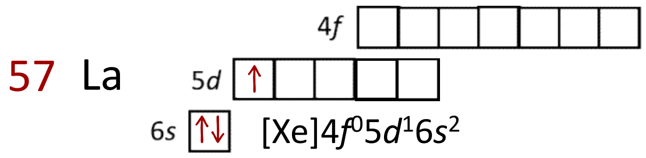
(EC, CRMs Factsheets, 2020, citing
EUROSTAT, EURARE, Roskill)

"The REE are **critical** for the success of the EU ambitions to become climate-neutral by 2050. They are essential in the production of high-tech, low-carbon goods […]. They are also indispensable in the defence sector […]."

EC CRMs Factsheets, 2020

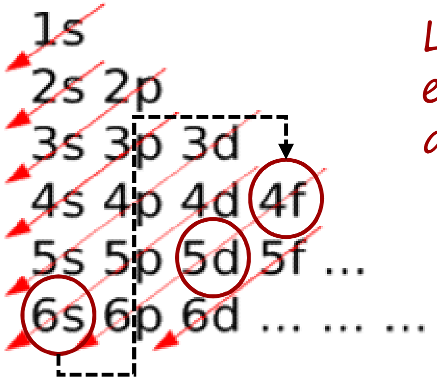
European
Commission

Electronic configuration of REEs

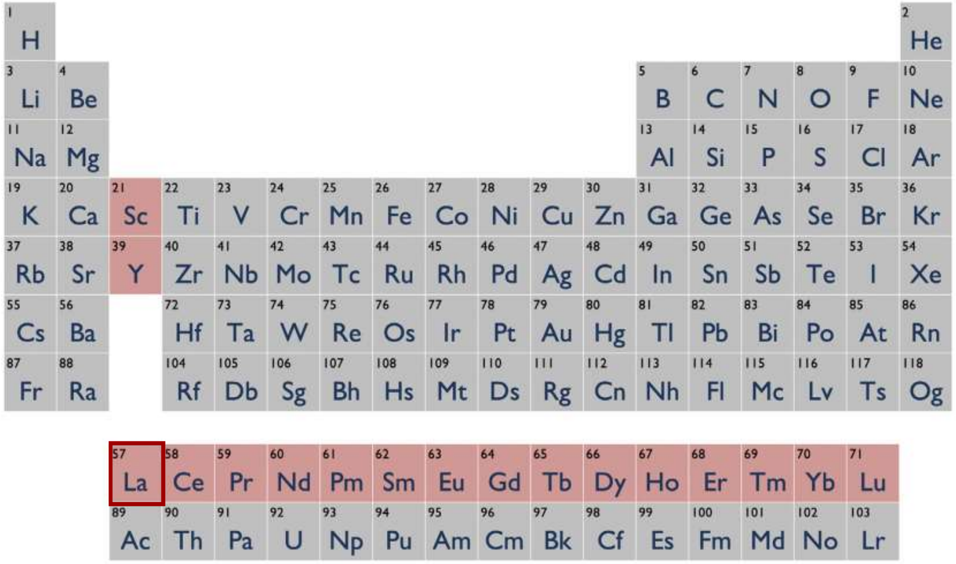


$[Xe]4f^0 5d^1 6s^2$

(Madelung's rule)

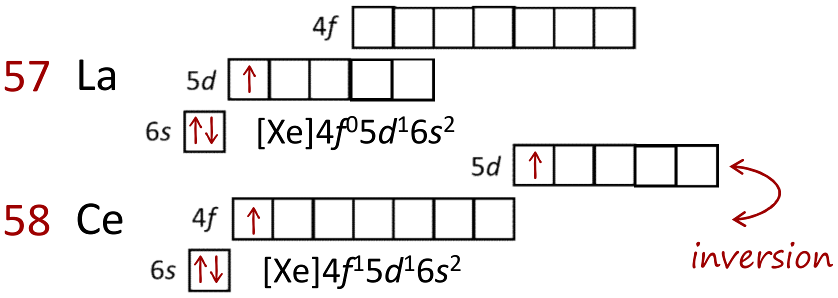


Lanthanium exception to aufbau rules



1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
		89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

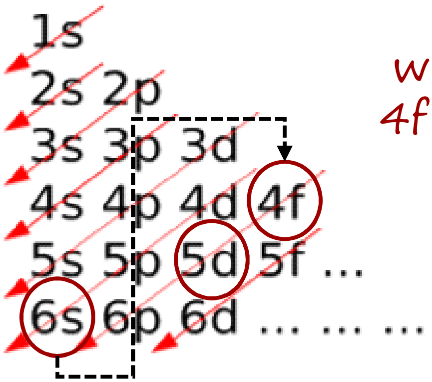
Electronic configuration of REEs



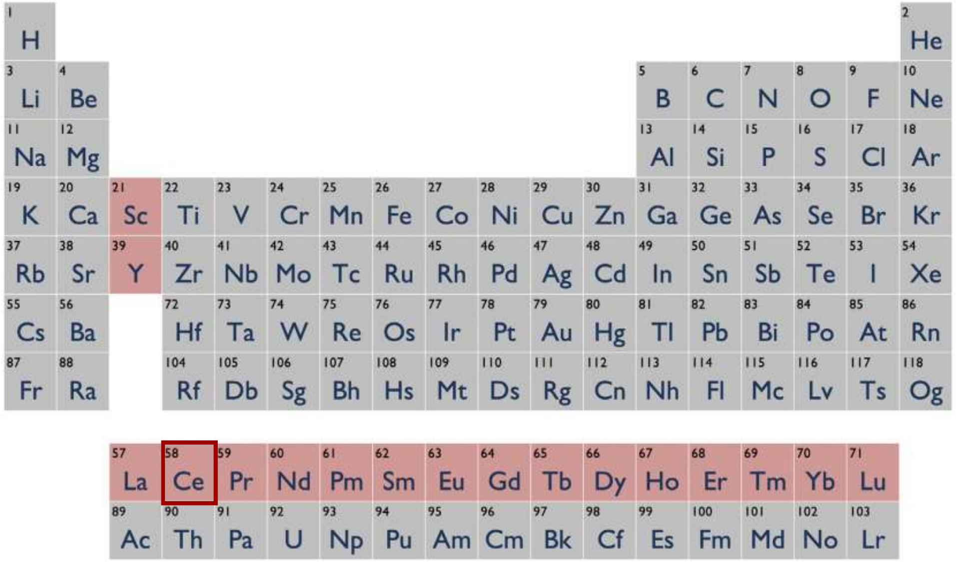
$[Xe]4f^05d^16s^2$

$[Xe]4f^15d^16s^2$

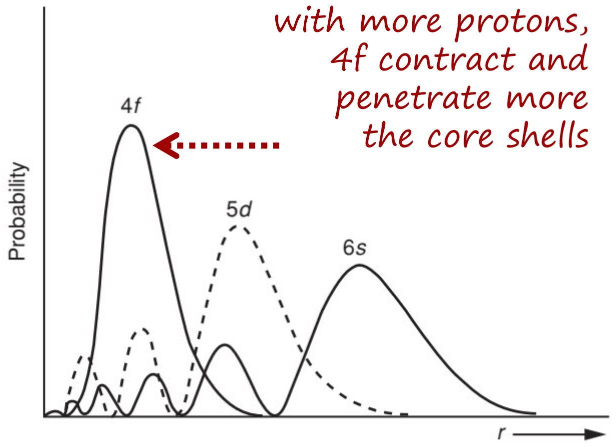
(Madelung's rule)



with Cerium 4f start to be filled



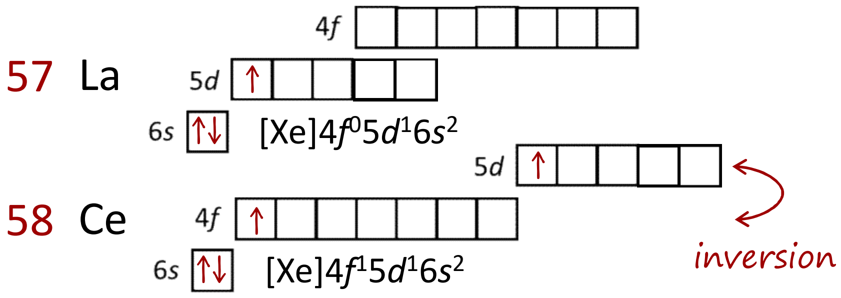
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
		89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	



with more protons, 4f contract and penetrate more the core shells

The radial probability function for 4f, 5d and 6s for Ce.
(H.G. Friedman et al. J. Chem. Educ. 1964, 41, 357)

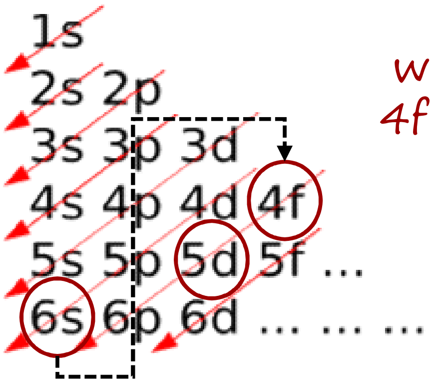
Electronic configuration of REEs



La: $[Xe]4f^0 5d^1 6s^2$

Ce: $[Xe]4f^1 5d^1 6s^2$

(Madelung's rule)



with Cerium
4f start to be
filled

all REE have
similar chemistry!

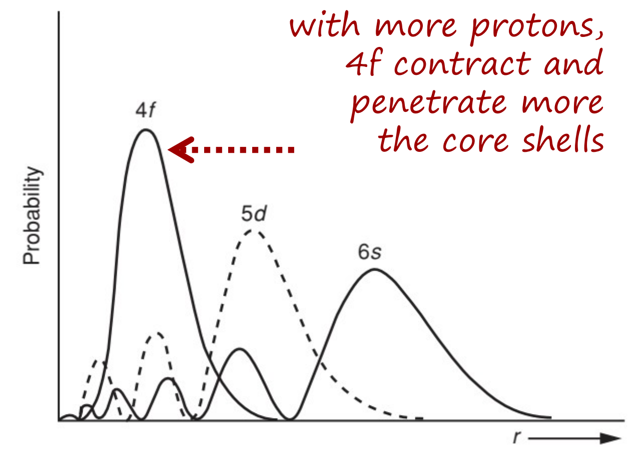
chemical behavior
dictated by outer **6s**
5d valence electrons

"**inner**" *f* electrons:

- do not participate in bonding
- magnetic properties
  unaffected by environment

behaves like
a free atom

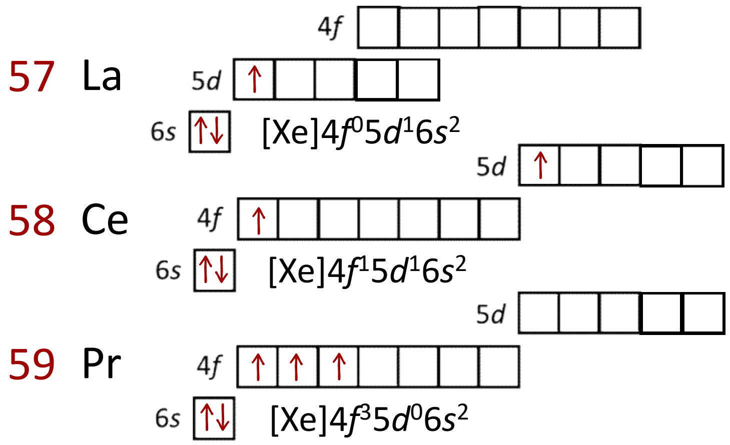
("core-like" behavior)



with more protons,
4f contract and
penetrate more
the core shells

The radial part for 4f, 5d and 6s for Ce.
(H.G. Friedman et al. J. Chem. Educ. 1964, 41, 357)

Electronic configuration of REEs

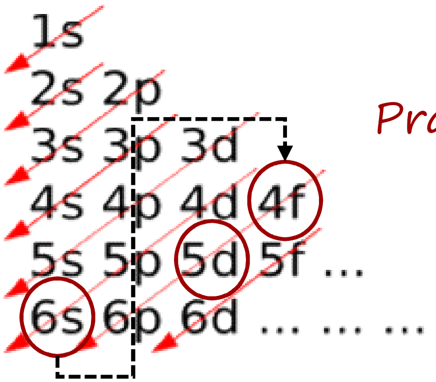


$[\mathrm{Xe}]4f^{0}5d^{1}6s^{2}$

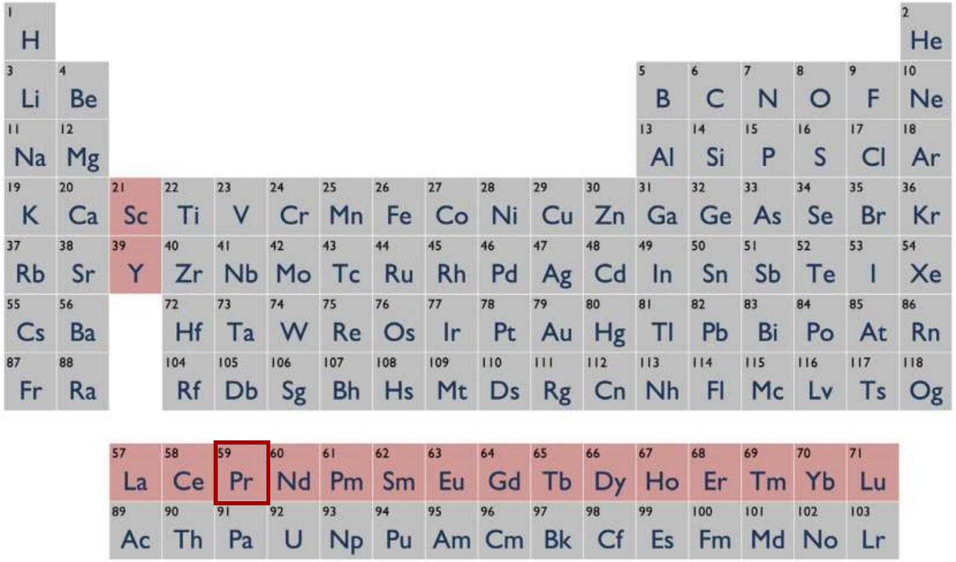
$[\mathrm{Xe}]4f^{1}5d^{1}6s^{2}$

$[\mathrm{Xe}]4f^{3}5d^{0}6s^{2}$

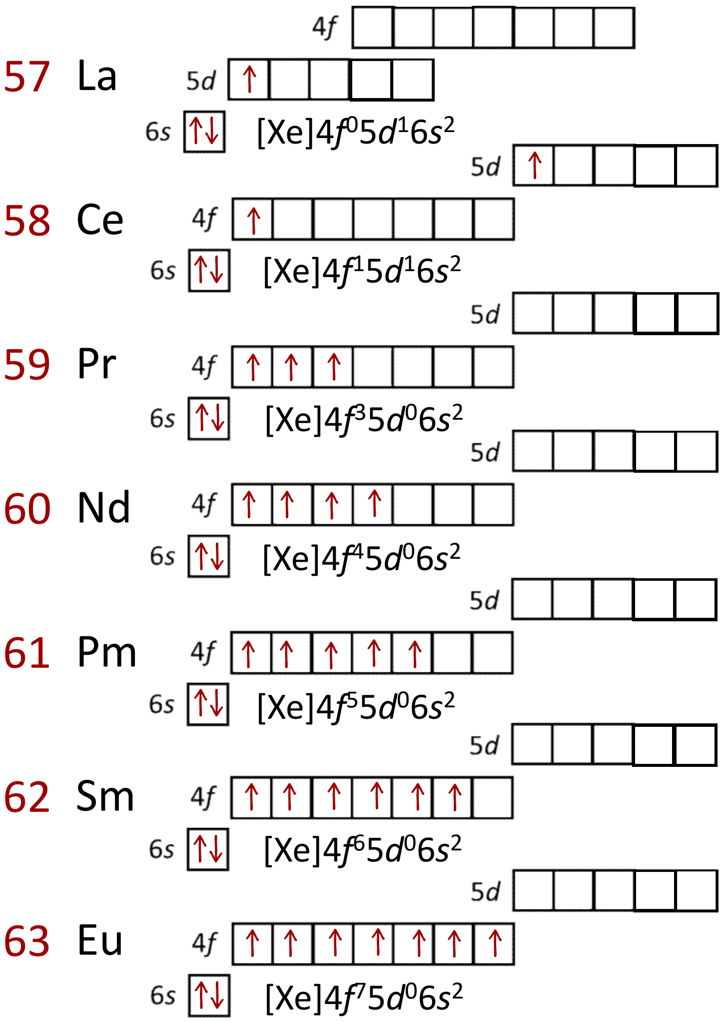
(Madelung’s rule)



with Praseodimium aufbau restored



Electronic configuration of REEs



57 La [Xe]$4f^0 5d^1 6s^2$

58 Ce [Xe]$4f^1 5d^1 6s^2$

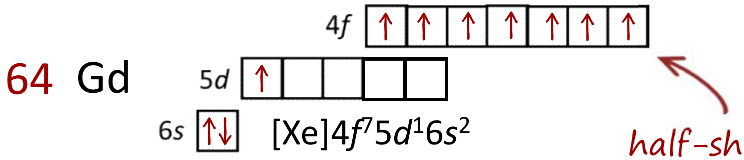
59 Pr [Xe]$4f^3 5d^0 6s^2$

60 Nd [Xe]$4f^4 5d^0 6s^2$

61 Pm [Xe]$4f^5 5d^0 6s^2$

62 Sm [Xe]$4f^6 5d^0 6s^2$

63 Eu [Xe]$4f^7 5d^0 6s^2$

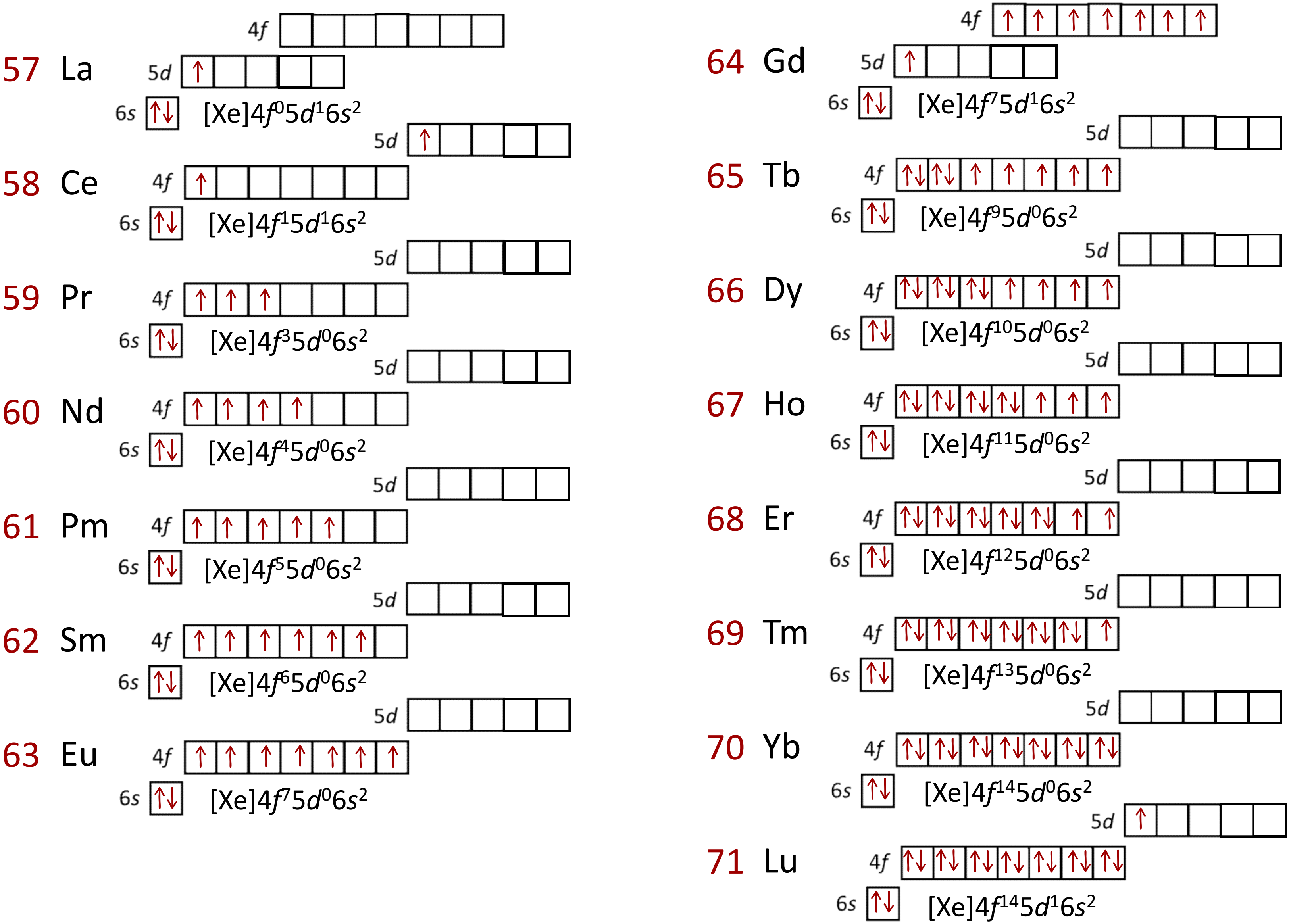


64 Gd [Xe]$4f^7 5d^1 6s^2$

half-shell
very stable

it costs more E to couple
a 2nd electron into a 4f
orbital than to put it in
a 5d state

Electronic configuration of REEs



57 La [Xe]$4f^{0}5d^{1}6s^{2}$

58 Ce [Xe]$4f^{1}5d^{1}6s^{2}$

59 Pr [Xe]$4f^{3}5d^{0}6s^{2}$

60 Nd [Xe]$4f^{4}5d^{0}6s^{2}$

61 Pm [Xe]$4f^{5}5d^{0}6s^{2}$

62 Sm [Xe]$4f^{6}5d^{0}6s^{2}$

63 Eu [Xe]$4f^{7}5d^{0}6s^{2}$

64 Gd [Xe]$4f^{7}5d^{1}6s^{2}$

65 Tb [Xe]$4f^{9}5d^{0}6s^{2}$

66 Dy [Xe]$4f^{10}5d^{0}6s^{2}$

67 Ho [Xe]$4f^{11}5d^{0}6s^{2}$

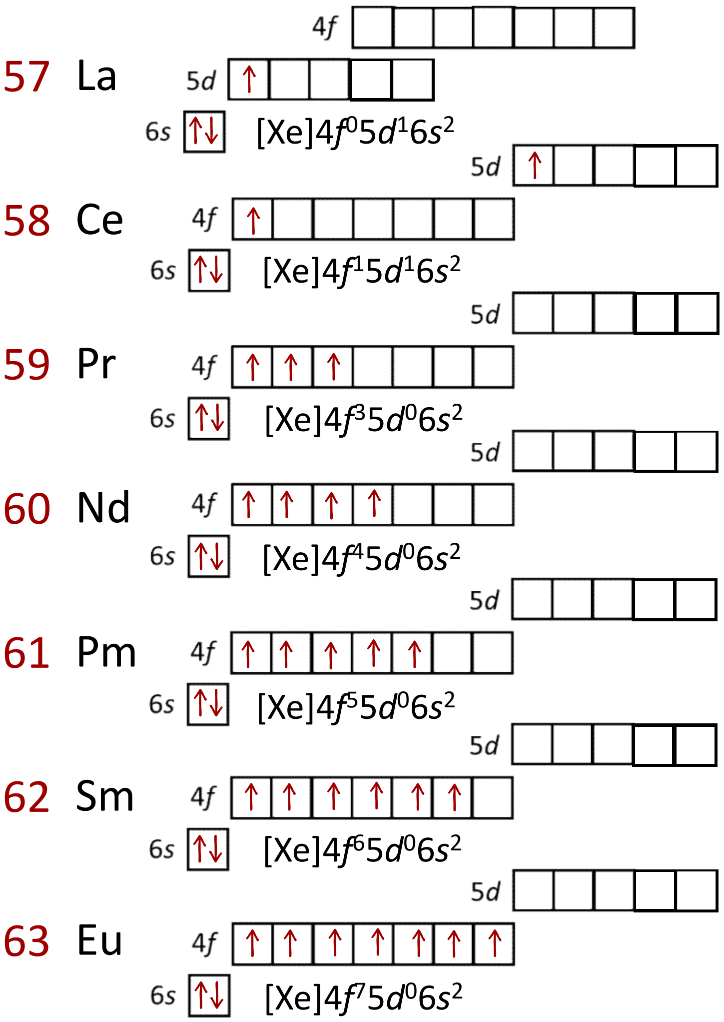
68 Er [Xe]$4f^{12}5d^{0}6s^{2}$

69 Tm [Xe]$4f^{13}5d^{0}6s^{2}$

70 Yb [Xe]$4f^{14}5d^{0}6s^{2}$

71 Lu [Xe]$4f^{14}5d^{1}6s^{2}$

Electronic configuration of REEs



57 La $[\mathrm{Xe}]4f^{0}5d^{1}6s^{2}$

58 Ce $[\mathrm{Xe}]4f^{1}5d^{1}6s^{2}$

59 Pr $[\mathrm{Xe}]4f^{3}5d^{0}6s^{2}$

60 Nd $[\mathrm{Xe}]4f^{4}5d^{0}6s^{2}$

61 Pm $[\mathrm{Xe}]4f^{5}5d^{0}6s^{2}$

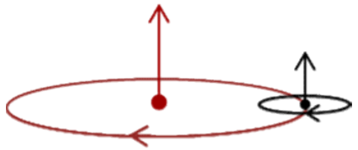
62 Sm $[\mathrm{Xe}]4f^{6}5d^{0}6s^{2}$

63 Eu $[\mathrm{Xe}]4f^{7}5d^{0}6s^{2}$

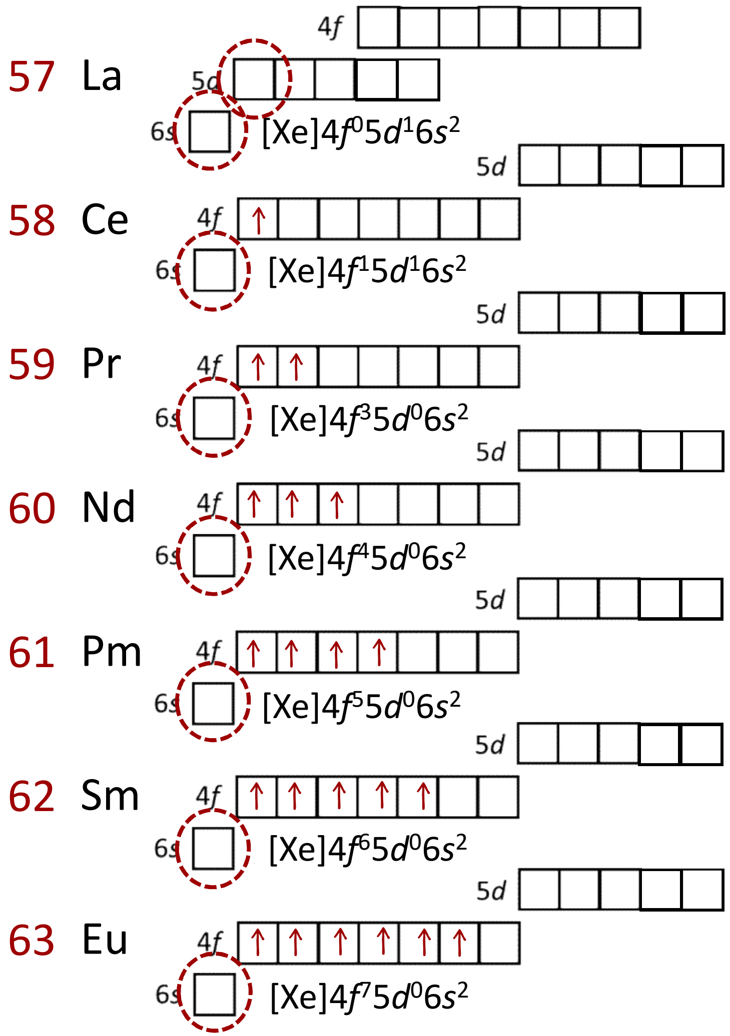
many **unpaired** *f* electrons (↑↑↑↑...)

- high *total spin S*
- high *orbital angular momentum L*
- high *total atomic angular momentum J*

  (spin-orbit coupling $J = S + L$)
- **high overall magnetic moment**



Electronic configuration of REEs *ions*



57 La $[Xe]4f^05d^16s^2$

58 Ce $[Xe]4f^15d^16s^2$

59 Pr $[Xe]4f^35d^06s^2$

60 Nd $[Xe]4f^45d^06s^2$

61 Pm $[Xe]4f^55d^06s^2$

62 Sm $[Xe]4f^65d^06s^2$

63 Eu $[Xe]4f^75d^06s^2$

Ln^{3+}

Ln (III)

most common oxidation state

6s and 5d electrons are lost first

REEs demand

trend of rapidly increasing REEs demand

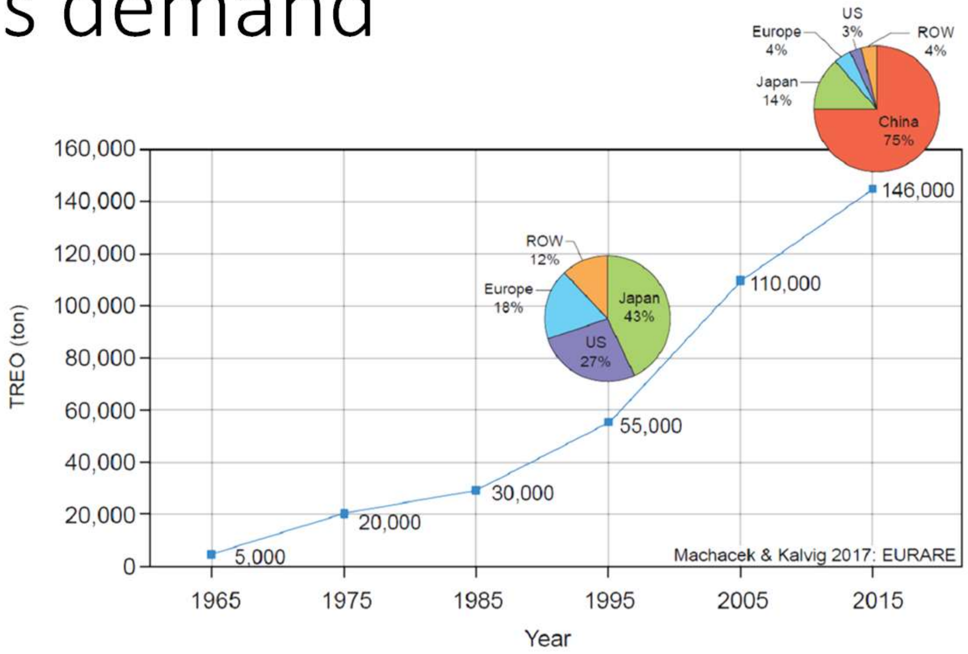
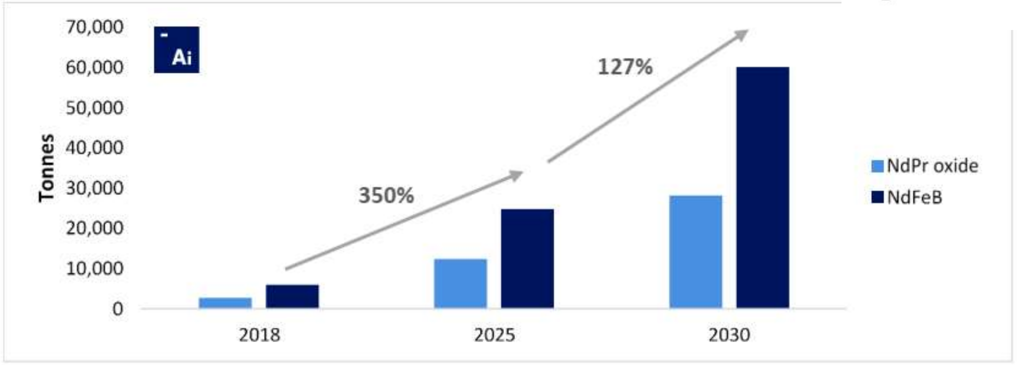
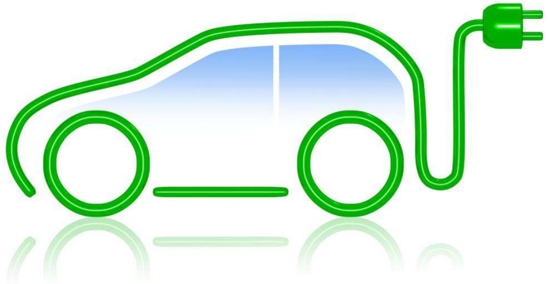


Figure 344: Changes in total rare earth demand during 1965-2015 (t REO). (Machacek and Kalvig 2017: EURARE)



Source: Adamas Intelligence

Figure 327: Changes in rare earths (Nd, Pr) and NdFeB magnets demand for EV traction motors to increase by 350% between 2018 and 2025 (Adamas Intelligence, 2019)



(EC, CRMs Factsheets, 2020)

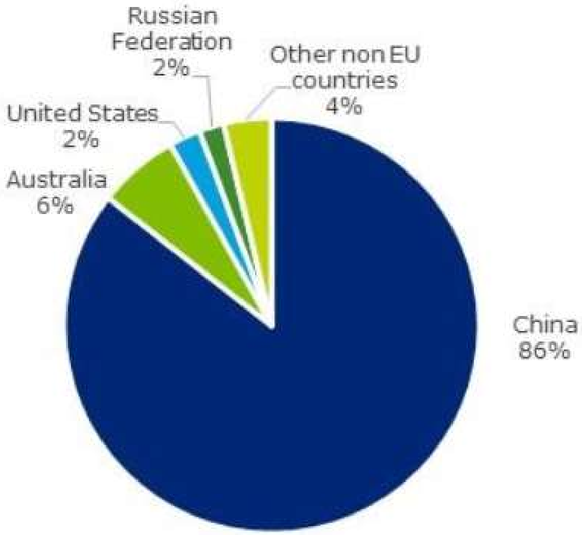
REEs sourcing & substitutes

"China provides around 80-90% of the world production of the whole range and purity of REE and their compounds"

EC, CRMs Factsheets 2020

"In most of their applications, REE are not substitutable without losses of performance."

EC, CRMs Factsheets 2020



Global production of Dy oxide: 1,018 t

(EC, CRMs Factsheets, 2020)

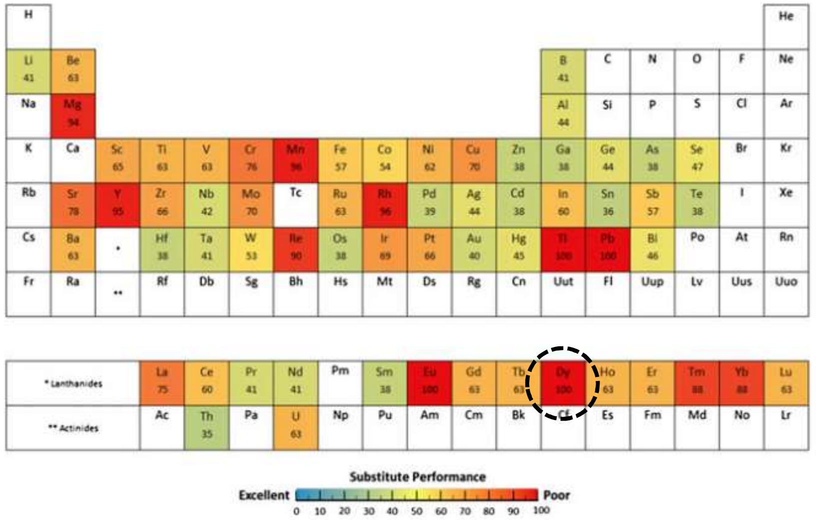


Fig. 5. The periodic table of substitute performance. The results are scaled from 0 to 100, with 0 indicating that exemplary substitutes exist for all major uses and 100 indicating that no substitute with even adequate performance exists for any of the major uses.

Recycling of REEs

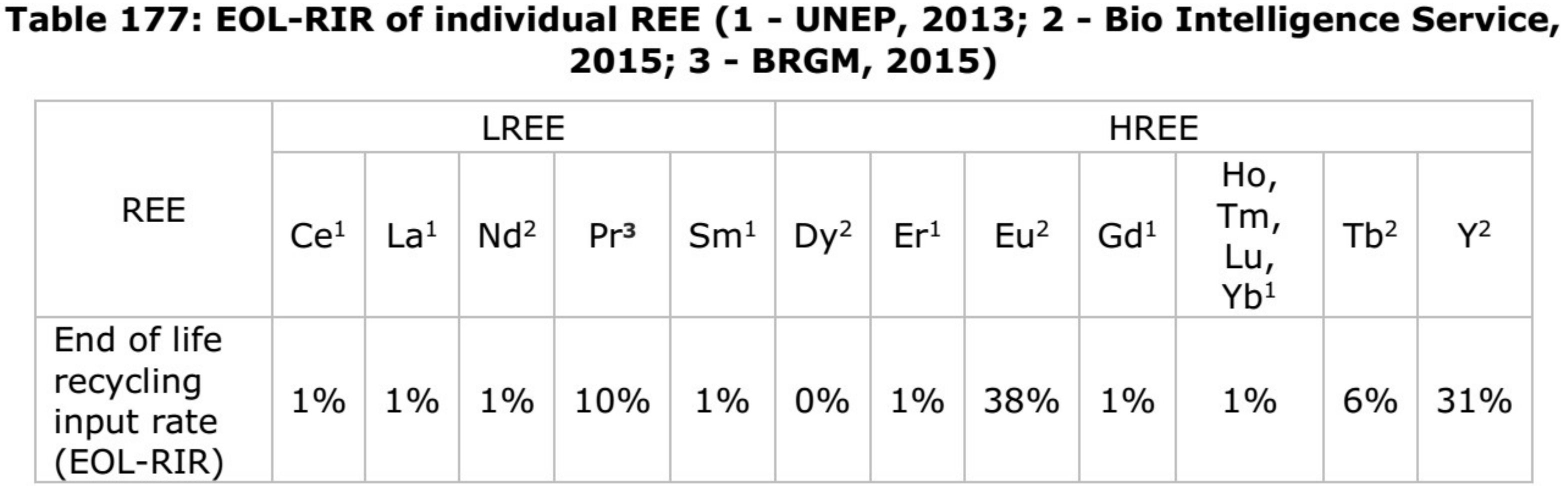


Table 177: EOL-RIR of individual REE (1 - UNEP, 2013; 2 - Bio Intelligence Service, 2015; 3 - BRGM, 2015)

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%

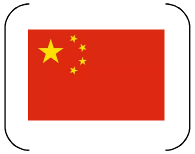
(EC, CRMs Factsheets, 2020, citing various sources)

REEs recycling rate is very low

Are we in trouble?

FACTS

- REEs are **essential** for digital & green technologies, industry and defence
- REEs are sourced mainly from a **single producer**



- REEs **demand is increasing**
- REEs are **not recycled**

Part 2

Criticality:
an historical perspective

Copper and the Bronze Age (~1200 BCE)

(= Cu + Sn)

Cyprus dominated Cu production

(Cu chemical symbol from Latin cuprum, derived from Cyprium)

PROBLEM: single supply source

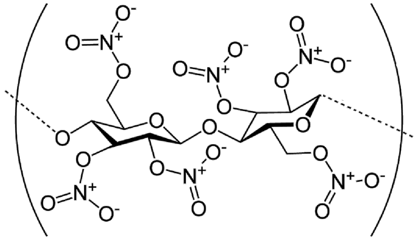
around 1200 BCE, widespread breakdown of civilization (Bronze Age Collapse)

collapse of Cyprus society (invasions?) might have an important factor in the Bronze Age Collapse ***(copper supply shortage)***

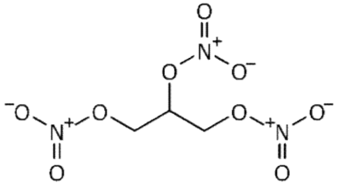
Cordite (WWI, 1914-18)

- made mainly from *guncotton* and *nitroglycerine*

(nitrocellulose)



(1,2,3-trinitroxypropane)



- used as smokeless propellant instead of gunpowder for **bullets and shells**
- production needs lots of **acetone**
- **acetone** produced by distillation of **dry wood**
- UK imported acetone, but not enough

(UK not a timber-producer)

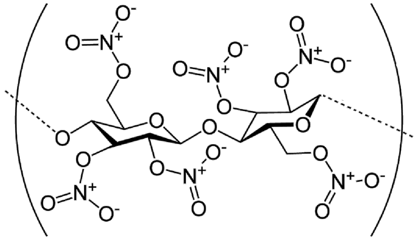
PROBLEM:
lack of supply

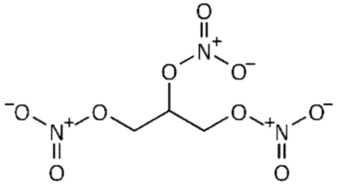
Cordite (WWI, 1914-18)

made mainly from

guncotton and *nitroglycerine*

(nitrocellulose) (1,2,3-trinitroxypropane)





- *solution*: new acetone production methods found using starch *(e.g. horse-chestnut)*

(agricultural products substituted timber)

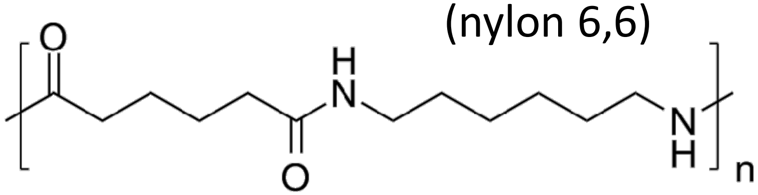
Silk (WWII, 1941-1945)

- silk used for parachutes, ropes, mosquito nets, …
- US imported 90% of silk from Japan

PROBLEM:
single supply source

- *solution*: silk *substituted* with nylon (*invented in 1937*)

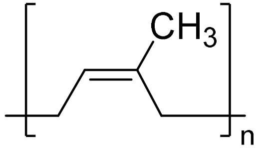
(nylon 6,6)



«The fiber that won the war»

(used for *parachutes, tire cords, ropes, aircraft fuel tanks, shoe laces, mosquito netting* and *hammocks*)

Rubber (WWII, 1941-1945)



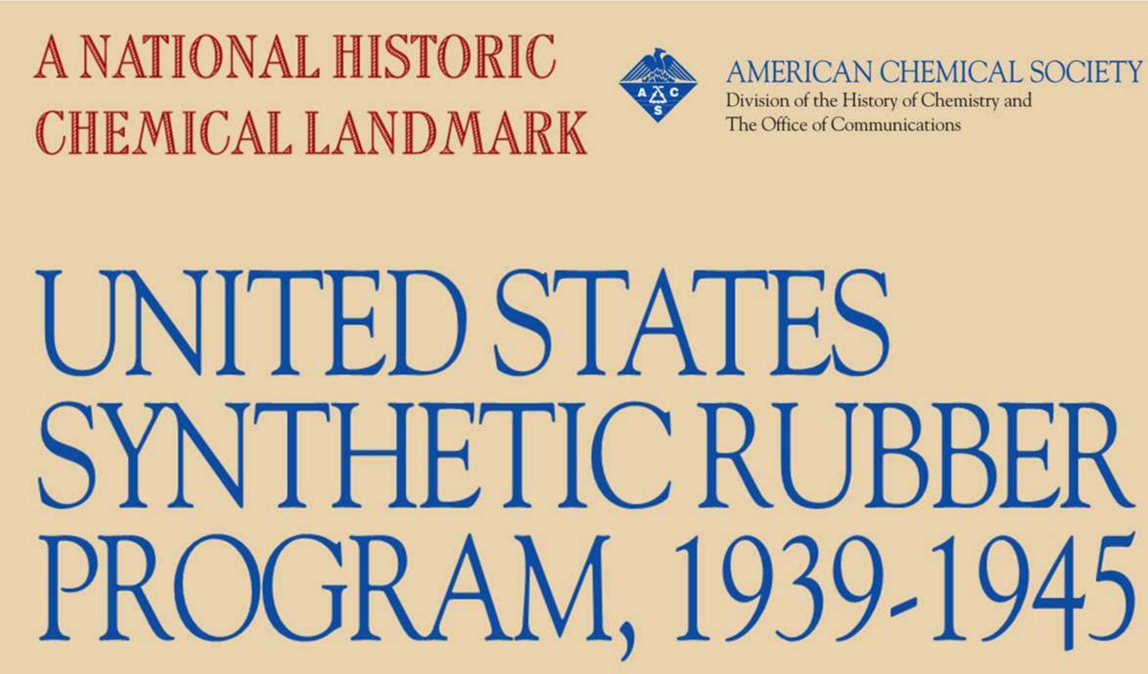
- natural rubber (*cis-polyisoprene*) used for many military applications
- produced from a tree, mainly in southeast asia (controlled by Japan)

PROBLEM:
single supply source

- *solution*: development of a *substitute* (syntethic polymers)

  (Government Rubber-Styrene)

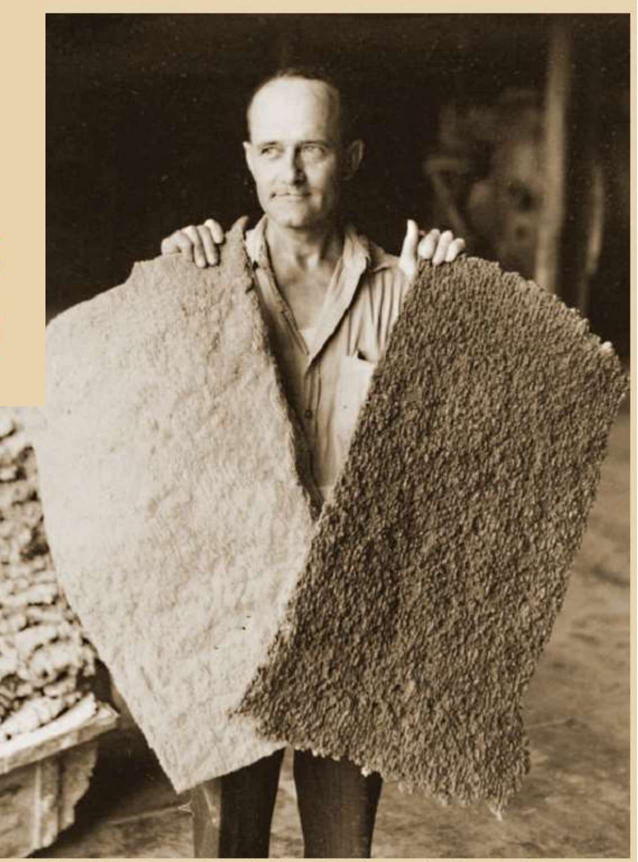
Rubber (WWII, 1941-1945)



A NATIONAL HISTORIC
CHEMICAL LANDMARK

AMERICAN CHEMICAL SOCIETY
Division of the History of Chemistry and
The Office of Communications

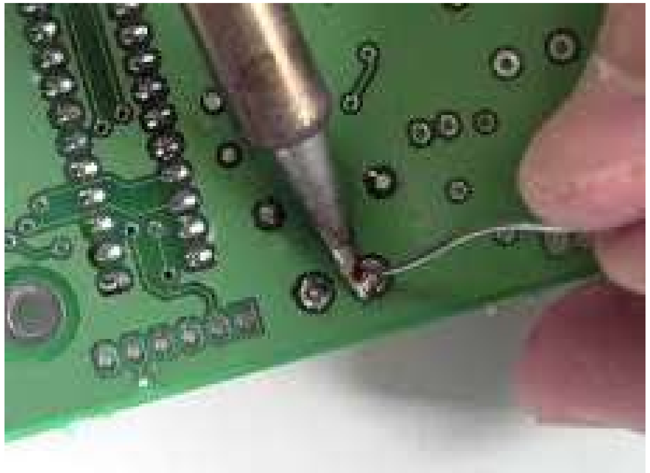
UNITED STATES
SYNTHETIC RUBBER
PROGRAM, 1939-1945



Sheets of dried synthetic rubber (left) and dried natural rubber (right).

enormous (secret)
cooperative effort

Old lead (1978-2006)



- Pb used as solder in electronics
- 4 stable isotopes ^{204}Pb, ^{206}Pb, ^{207}Pb, ^{208}Pb
- ^{204}Pb primordial, while others end-products of decay series (U, Ac, Th)
- α-emission from radioactive impurities in ^{206}Pb, ^{207}Pb, ^{208}Pb cause *soft-errors* in RAM
- only low-α Pb can be used *(difficult to find)*

SCIENTIFIC AMERICAN

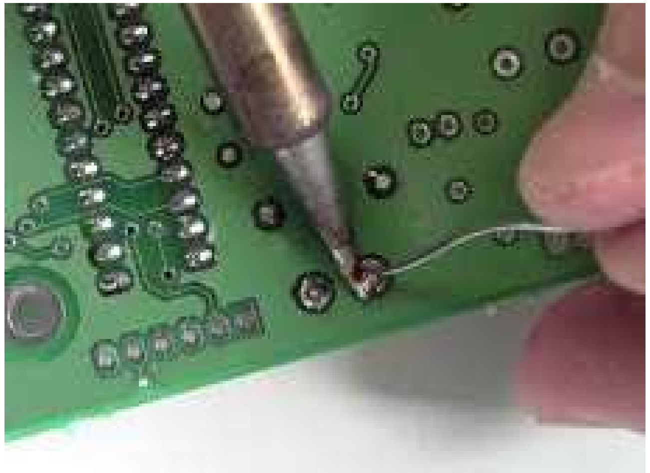
Ancient Roman Metal Used for Physics Experiments Ignites Science Feud

Physicists prefer Roman-era lead ingots to recently mined metal for shielding particle experiments, but archaeologists want them preserved

By Clara Moskowitz on December 18, 2013

PROBLEM:
lack of supply

Old lead (1978-2006)



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- α-emission from radioactive impurities in ^{206}Pb, ^{207}Pb, ^{208}Pb cause *soft-errors* in RAM
- only low-α Pb can be used *(difficult to find)*

- *solution*: development of a *substitute* (lead-free solder alloys: SnAgCu, SnCu)

Cobalt (1978)

- Co used in superalloys for jet engines, chemical plants, magnets Sm-Co
- major productor Zaire (now DRC), under Mobutu's dictatorship
- in 1978, rebellions in Co mines region

PROBLEMS:
single supplier, supply risk

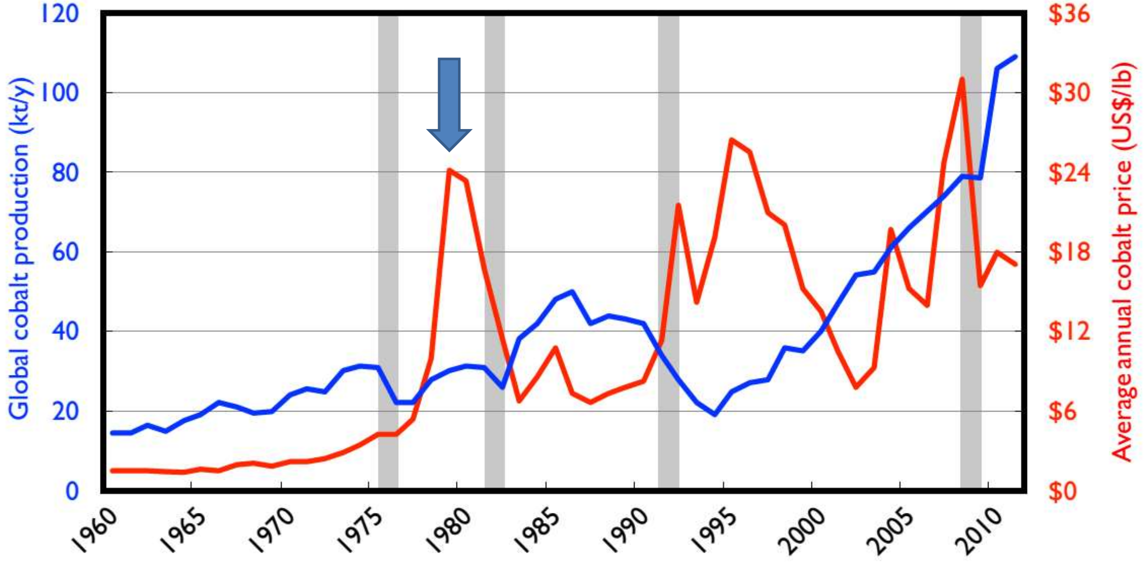


Fig. 2.3 Global cobalt production levels (left ordinate axis) and annual average cobalt prices (right ordinate axis) between 1980 and 2012. *Gray bands* represent the approximate dates of global recessions. Price and production rise and fall in-phase or out of phase at different times. Original data from the USGS Mineral Commodity Summaries for the relevant years.

(A. King, Critical Materials, Elsevier 2021)

Cobalt (1978)

- Co used in superalloys for jet engines, chemical plants, magnets Sm-Co
- major productor Zaire (now DRC), under Mobutu's dictatorship
- in 1978, rebellions in Co mines region

PROBLEMS:
single supplier, supply risk

- solution: development of *substitutes* (Ni superalloys, NdFeB magnets)

include Nb as well:
induced sudden
increase of
demand & price
spike for Nb!

a critical material
was substituted
with another (Nd)

Photovoltaic Si (mid-2000s)

- PV silicon requires extreme purity (99.999%)
- large PV growth (1999-2005) outstripped global production
- PV silicon facilities need 3y and billions of investment (investors reclutant)

PROBLEM: lack of supply

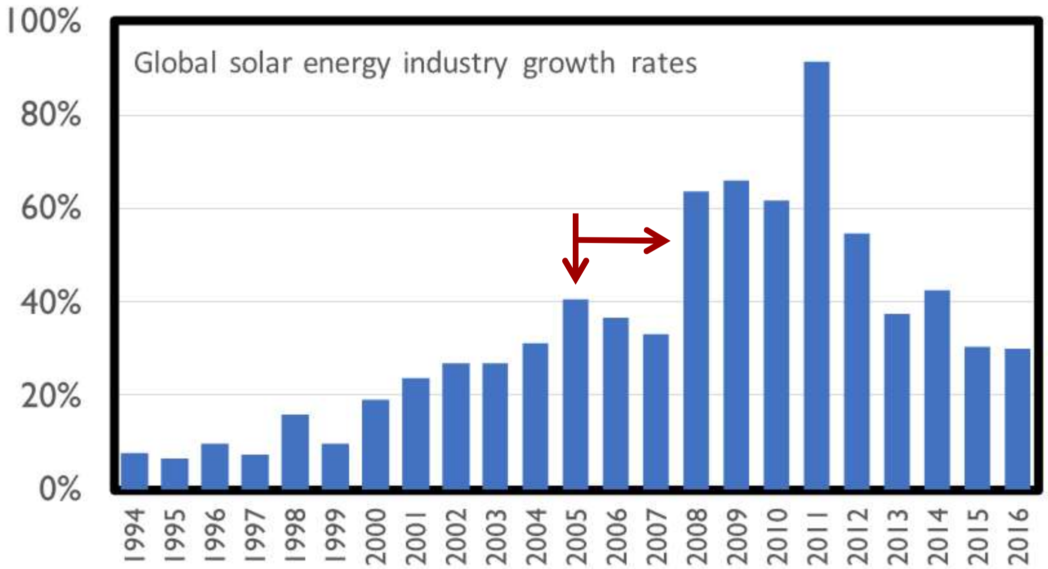


Fig. 2.5 Annual growth rates of the global installed solar-PV capacity, between 1994 and 2016. The industry's growth outstripped the global production capacity for solar-grade polycrystalline silicon in the mid-2000s, despite the high crustal abundance of silicon.

(3y needed to **expand production** to keep up with demand)

(A. King, Critical Materials, Elsevier 2021)

Lessons learned from history

- excessive reliance on single sources / highly localized prodution is a *supply risk*
- sudden changes in demand induce *criticality*
- technologies with purity/grade requirements (e.g. low-α lead, PV silicon) induce *criticality*

- possible *solutions* are:
  - expand production
  - diversify sources
  - find substitutes or change technology
  - recycle *(if possible)*
  - any combination of the above work best

Part 3

Criticality assessments

Defining critical materials

critical

Merriam-Webster

1. *of, relating to, or being a **turning point** or specially important juncture*
2. ***indispensable, vital***
3. *being in or approaching a state of **crisis***
4. ***crucial**, decisive*

Cambridge Dictionary

1. ***very important** for the way things will happen in the **future***
2. *very serious or **dangerous***

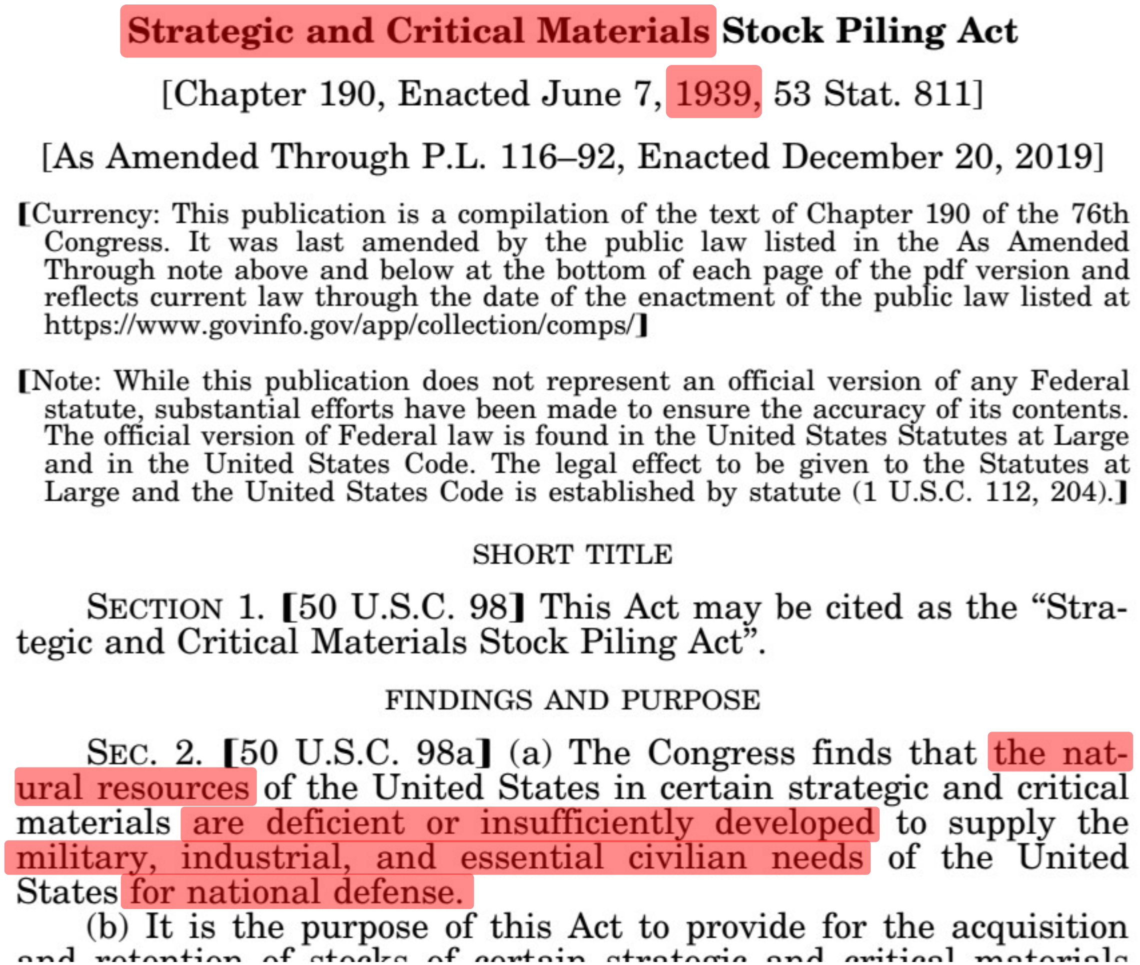
OED Oxford English Dictionary
The definitive record of the English language

1. *of **decisive importance** in relation to the issue*
2. *tending to determine or decide; decisive, crucial*

Defining critical materials

“The background of **critical material thinking** has been defined through **war**.”

(D. Peck, in “Critical Materials”, E. Offerman ed., World Scientific 2019)



Strategic and Critical Materials Stock Piling Act

[Chapter 190, Enacted June 7, 1939, 53 Stat. 811]

[As Amended Through P.L. 116–92, Enacted December 20, 2019]

[Currency: This publication is a compilation of the text of Chapter 190 of the 76th Congress. It was last amended by the public law listed in the As Amended Through note above and below at the bottom of each page of the pdf version and reflects current law through the date of the enactment of the public law listed at https://www.govinfo.gov/app/collection/comps/]

[Note: While this publication does not represent an official version of any Federal statute, substantial efforts have been made to ensure the accuracy of its contents. The official version of Federal law is found in the United States Statutes at Large and in the United States Code. The legal effect to be given to the Statutes at Large and the United States Code is established by statute (1 U.S.C. 112, 204).]

SHORT TITLE

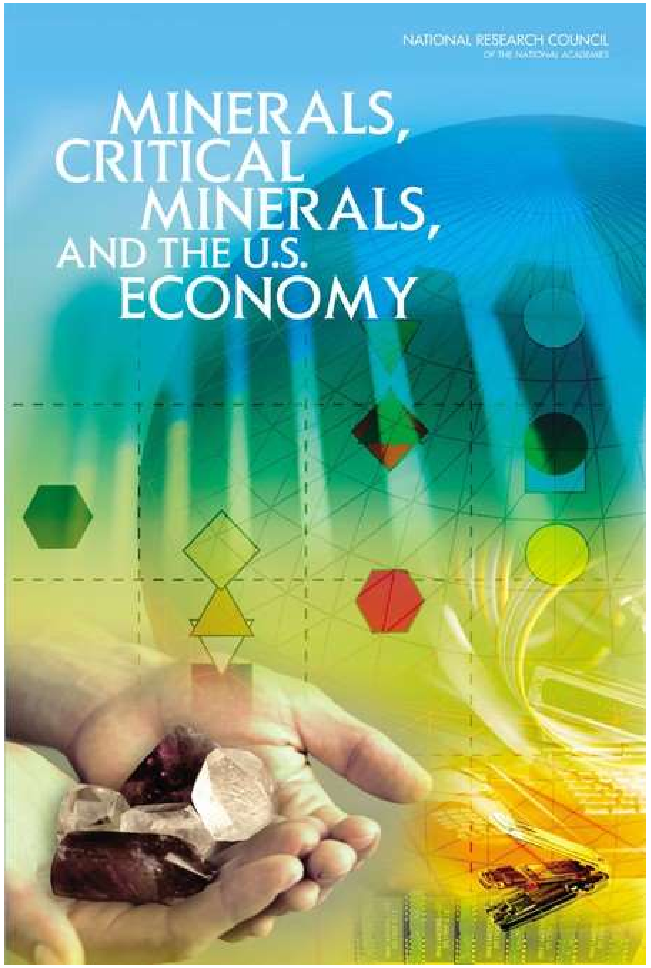
SECTION 1. [50 U.S.C. 98] This Act may be cited as the “Strategic and Critical Materials Stock Piling Act”.

FINDINGS AND PURPOSE

SEC. 2. [50 U.S.C. 98a] (a) The Congress finds that the natural resources of the United States in certain strategic and critical materials are deficient or insufficiently developed to supply the military, industrial, and essential civilian needs of the United States for national defense.

(b) It is the purpose of this Act to provide for the acquisition and retention of stocks of certain strategic and critical materials

Defining critical materials



National Research Council, **2006**

> “[…] a critical mineral is one that is *both* **essential** in use and subject to the **risk of supply restriction**.”

2 defining concepts

- importance
- supply risk

Defining critical materials

2019 **critical material**: an element […] or […] material which […] enables a product to deliver value-added functionality, wherein the ability to substitute that functionality using an alternative material is limited […] and for which one or more of its constituents or precursors is at **risk of** experiencing a **supply disruption**.

(J. Goddin, in "Critical Materials",
E. Offerman ed., World Scientific 2019)

2020 **critical raw material (CRMs)**: raw materials of a **high importance to the economy** of the EU and whose **supply is associated with a high risk**.

(European Commission, Study on the EU's list
of Critical Raw Materials – Final Report 2020)

Assessments of materials criticality

what?

the applicaton of a **method**
to determine materials criticality

*with respect to a **country**, a specific **industrial sector**, a **company** or a **product***

why?

decision tools for industry
and policymakers

(e.g. materials selection, product and process design, investment decisions, trade agreements, research strategies, policy agendas, …)

Assessments of materials criticality

important documents

National Research Council NRC

Critical Minerals (2008) 11

U.S. DEPARTMENT OF ENERGY

14 Critical Materials Strategy (2010)

16 (2011)

European Commission

Critical Raw Materials for the EU

41 (2010)

32 Critical metals and decarbonization (2013)

54 (2014)

78 (2017)

83 (2020)

APS physics

Energy Critical Elements (2011) 29

Assessment of critical minerals

50 (2016)

77 (2018)

number of materials considered

LISTS

British Geological Survey BGS

Risk List (2011)

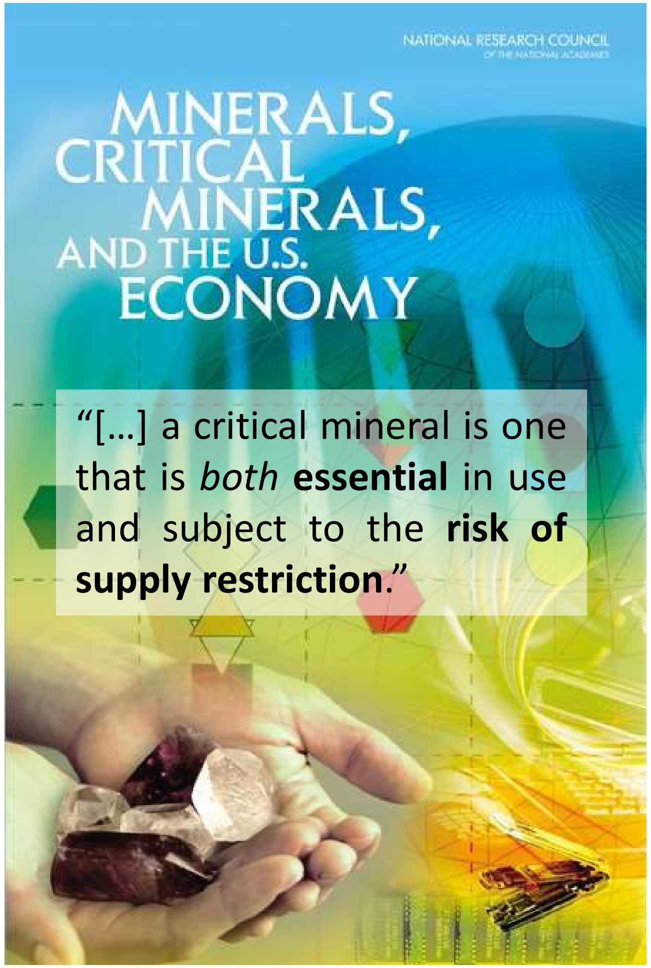
Risk List (2015)

USGS science for a changing world

Draft Critical Minerals List (2018)

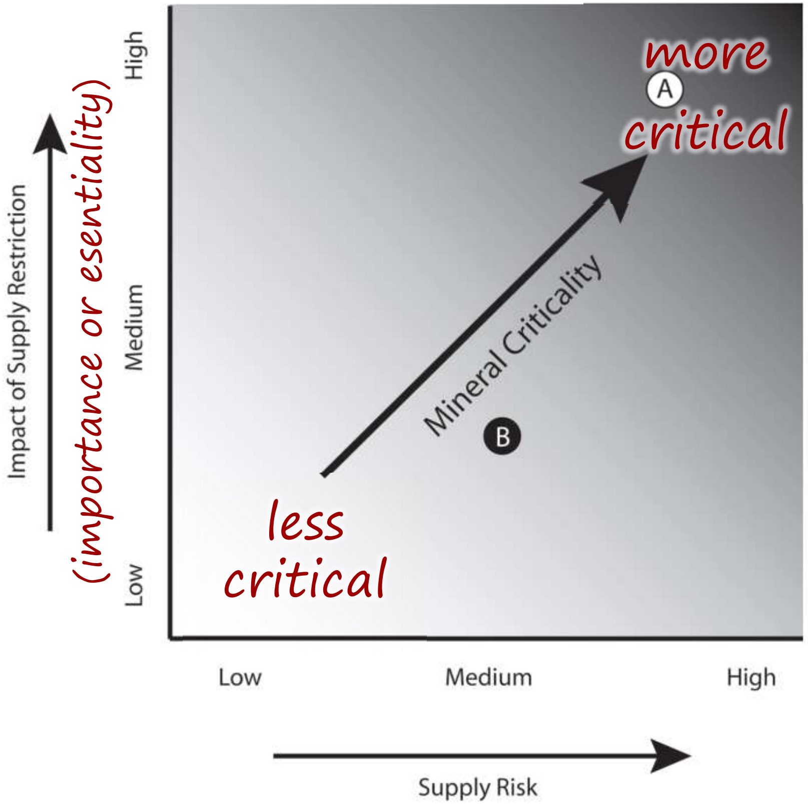
Assessments of materials criticality

NRC, **2008**



"[…] a critical mineral is one that is *both* **essential** in use and subject to the **risk of supply restriction**."

criticality matrix



(importance or esentiality)

more critical

less critical

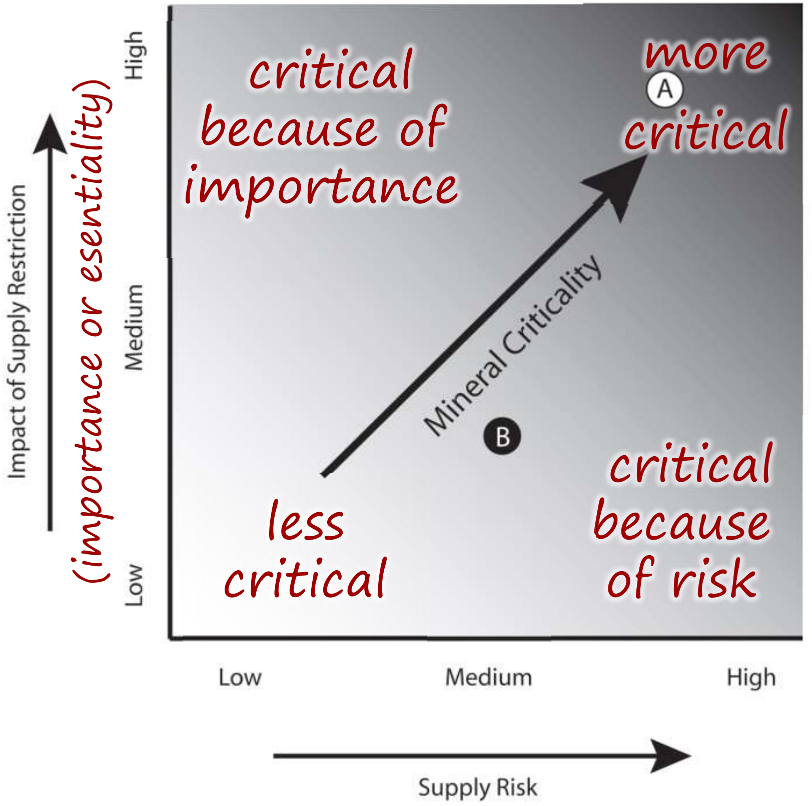
at the basis of all subsequent methodologies

Assessments of materials criticality

NOTE: criticality is a matter of **degree**, not of state (i.e. y/n), although thresholds can be set

different methods differ in the way **importance** and **supply risk** are evaluated

criticality matrix

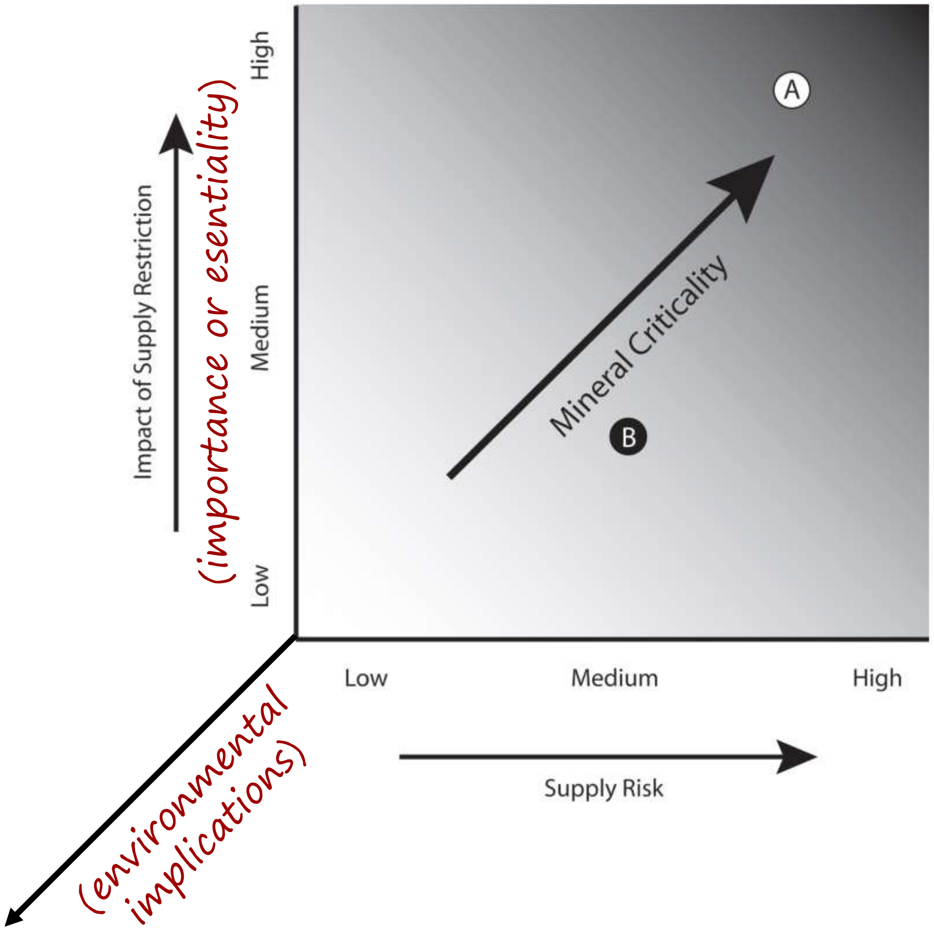


at the basis of all subsequent methodologies

Assessments of materials criticality

criticality matrix

in some
methodologies, a
third dimension is
added to the
criticality matrix



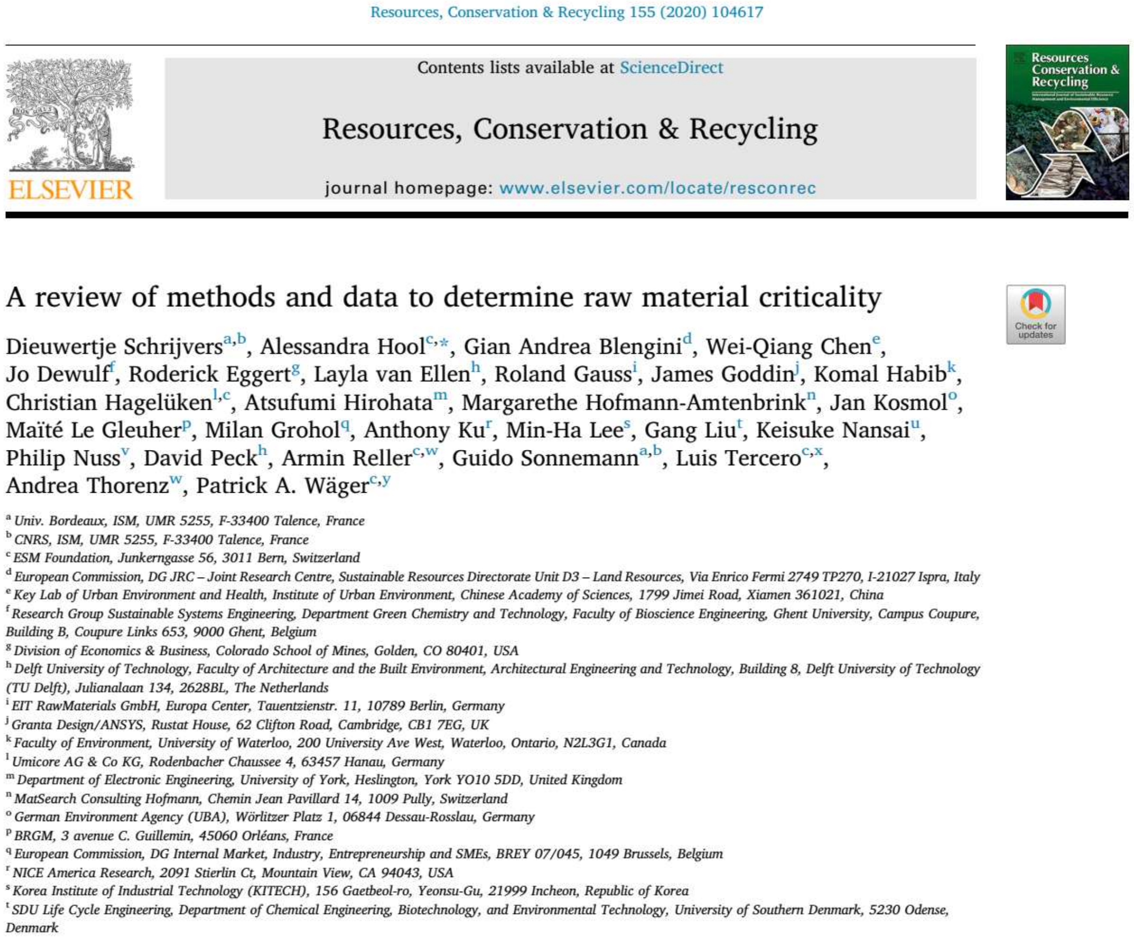
Assessments of materials criticality

irtc business

International Round Table on Materials Criticality in Business Practice

comparison among different methodologies

"criticality is in the eye of the beholder, […] there is no generic standard approach to conduct a criticality assessment"



Resources, Conservation & Recycling 155 (2020) 104617

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

A review of methods and data to determine raw material criticality

Dieuwertje Schrijvers[a,b], Alessandra Hool[c,*], Gian Andrea Blengini[d], Wei-Qiang Chen[e], Jo Dewulf[f], Roderick Eggert[g], Layla van Ellen[h], Roland Gauss[i], James Goddin[j], Komal Habib[k], Christian Hagelüken[l,c], Atsufumi Hirohata[m], Margarethe Hofmann-Amtenbrink[n], Jan Kosmol[o], Maïté Le Gleuher[p], Milan Grohol[q], Anthony Ku[r], Min-Ha Lee[s], Gang Liu[t], Keisuke Nansai[u], Philip Nuss[v], David Peck[h], Armin Reller[c,w], Guido Sonnemann[a,b], Luis Tercero[c,x], Andrea Thorenz[w], Patrick A. Wäger[c,y]

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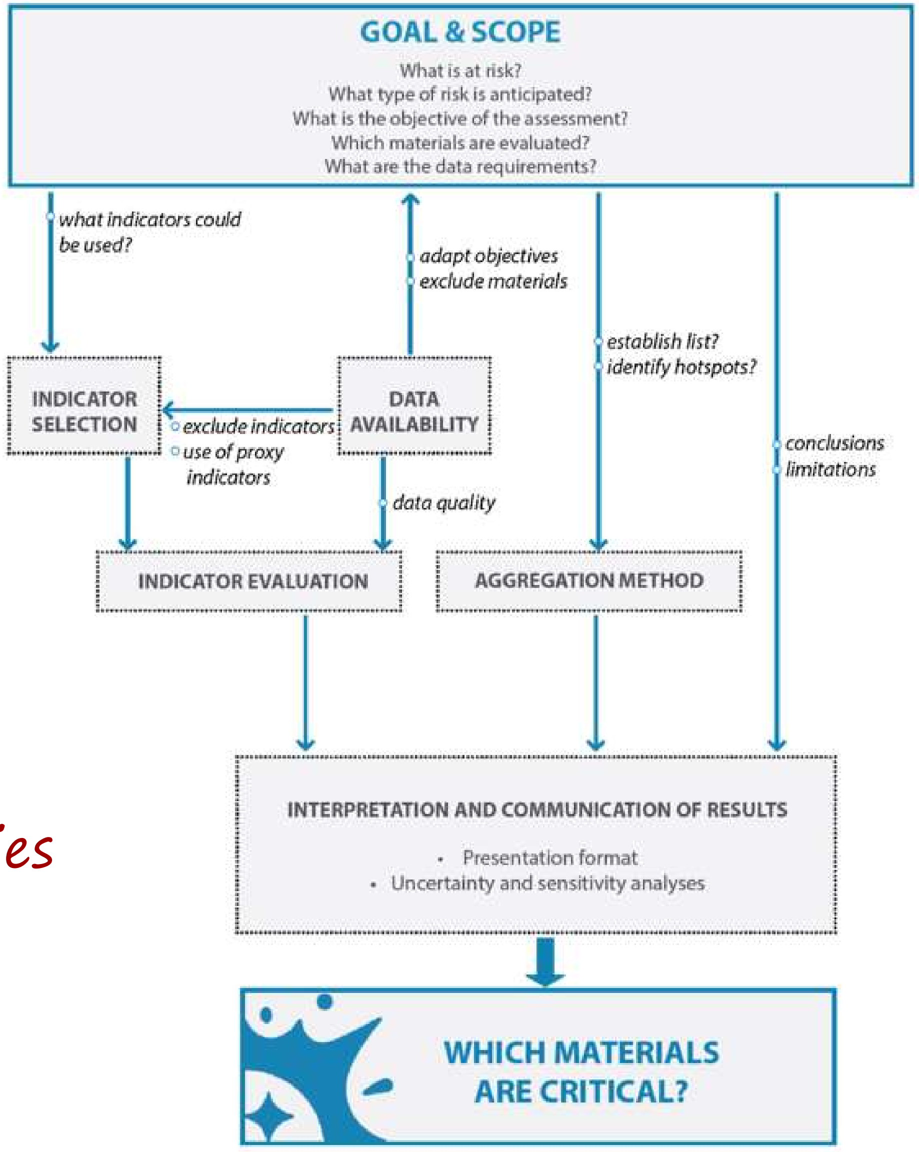
Assessments of materials criticality



GOAL & SCOPE

What is at risk?
What type of risk is anticipated?
What is the objective of the assessment?
Which materials are evaluated?
What are the data requirements?

what indicators could be used?

adapt objectives
exclude materials

establish list?
identify hotspots?

conclusions
limitations

INDICATOR SELECTION

DATA AVAILABILITY

- *exclude indicators*
- *use of proxy indicators*

data quality

INDICATOR EVALUATION

AGGREGATION METHOD

INTERPRETATION AND COMMUNICATION OF RESULTS

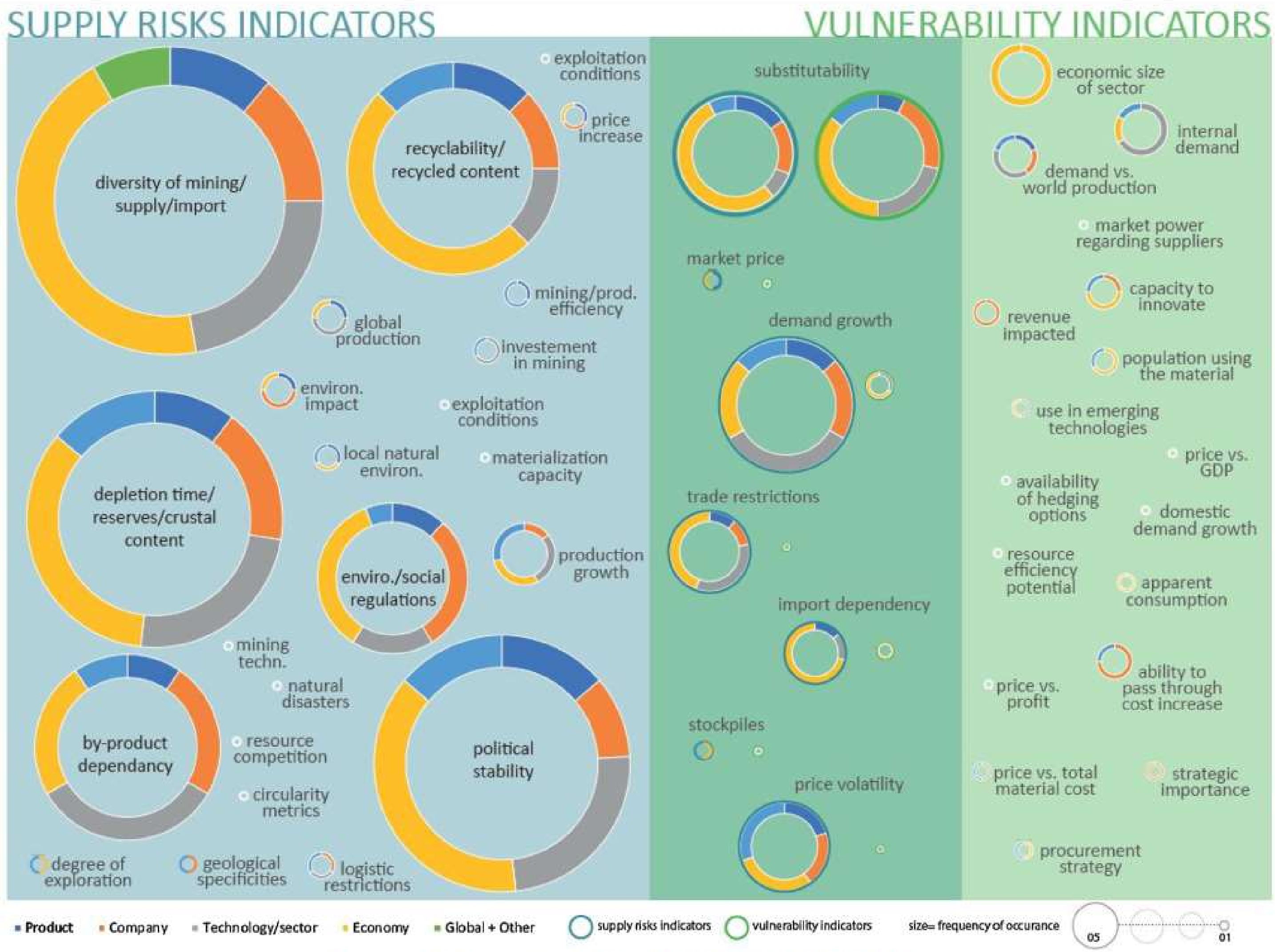
- Presentation format
- Uncertainty and sensitivity analyses

WHICH MATERIALS ARE CRITICAL?

common aspects of different methodologies

Assessments of materials criticality

Indicators used



Resources, Conservation & Recycling 155 (2020) 104617

Assessments of materials criticality

Data sources used

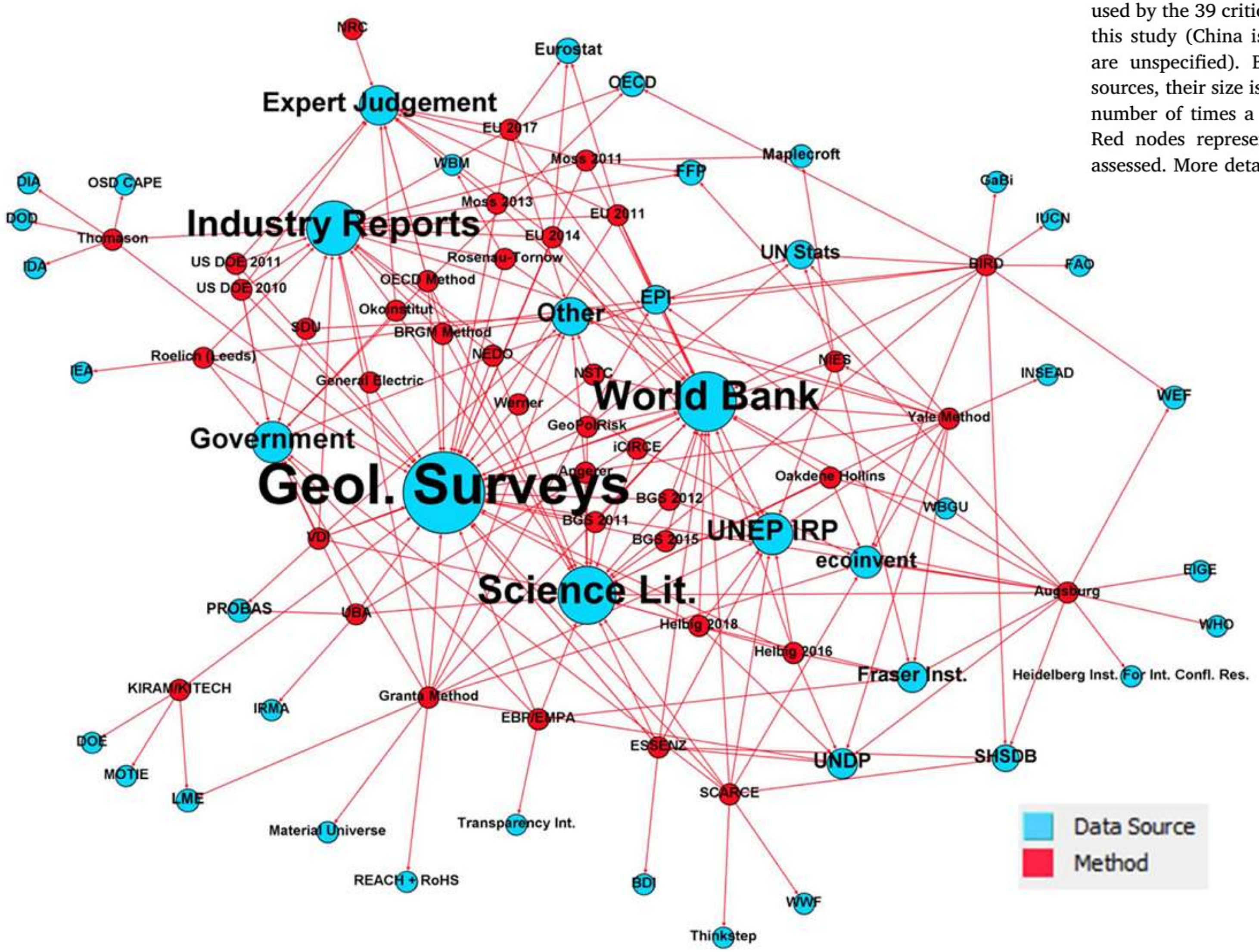


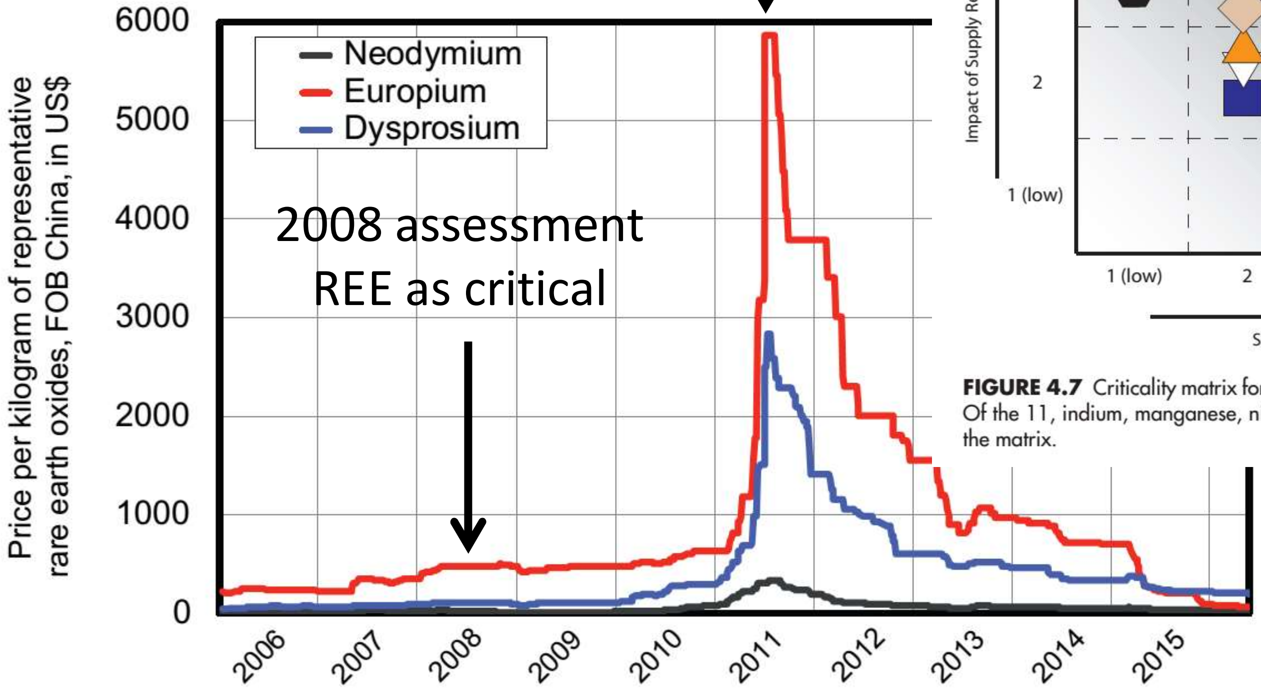
Fig. 5. Network visualization of data sources used by the 39 criticality methods examined in this study (China is excluded as data sources are unspecified). Blue nodes represent data sources, their size is shown proportional to the number of times a data source is being used. Red nodes represent the criticality methods assessed. More details are available in SI-B.

Assessments of materials criticality

Are assessments meaningful?
Are they predictive tools?

2011
REE spike

2008 assessment
REE as critical



(from A. King, «Critical Materials», Elsevier 2021, Source Argusmedia)

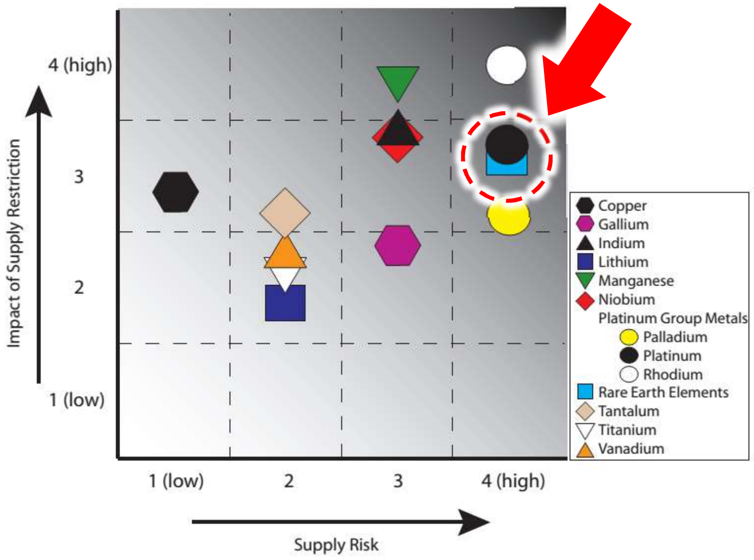
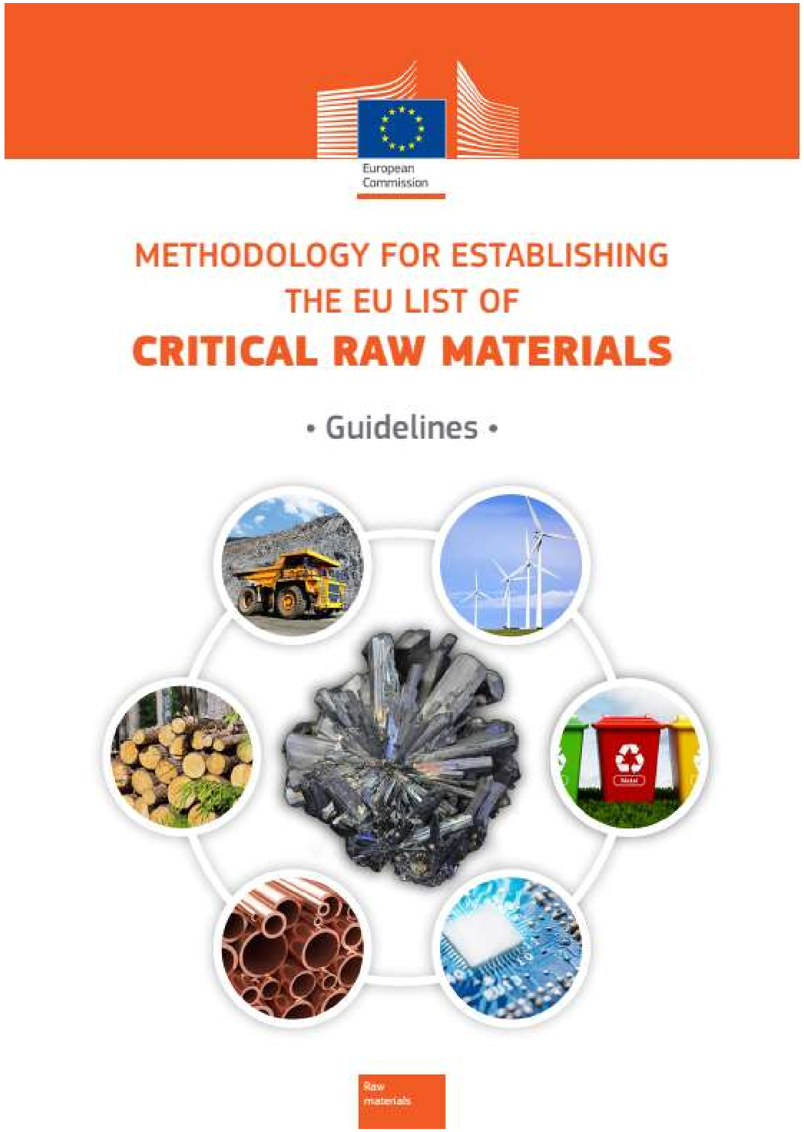


FIGURE 4.7 Criticality matrix for all 11 candidate materials discussed in the chapter. Of the 11, indium, manganese, niobium, PGMs, and REs fall in the critical "zone" of the matrix.

NRC Report
(2008)

EC 2017 criticality methodology

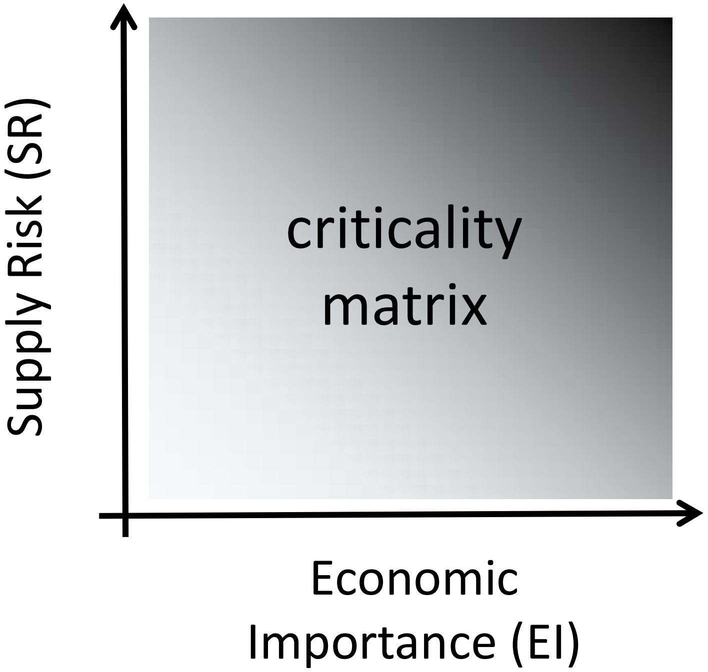


European Commission

METHODOLOGY FOR ESTABLISHING
THE EU LIST OF
CRITICAL RAW MATERIALS

• Guidelines •

Raw materials

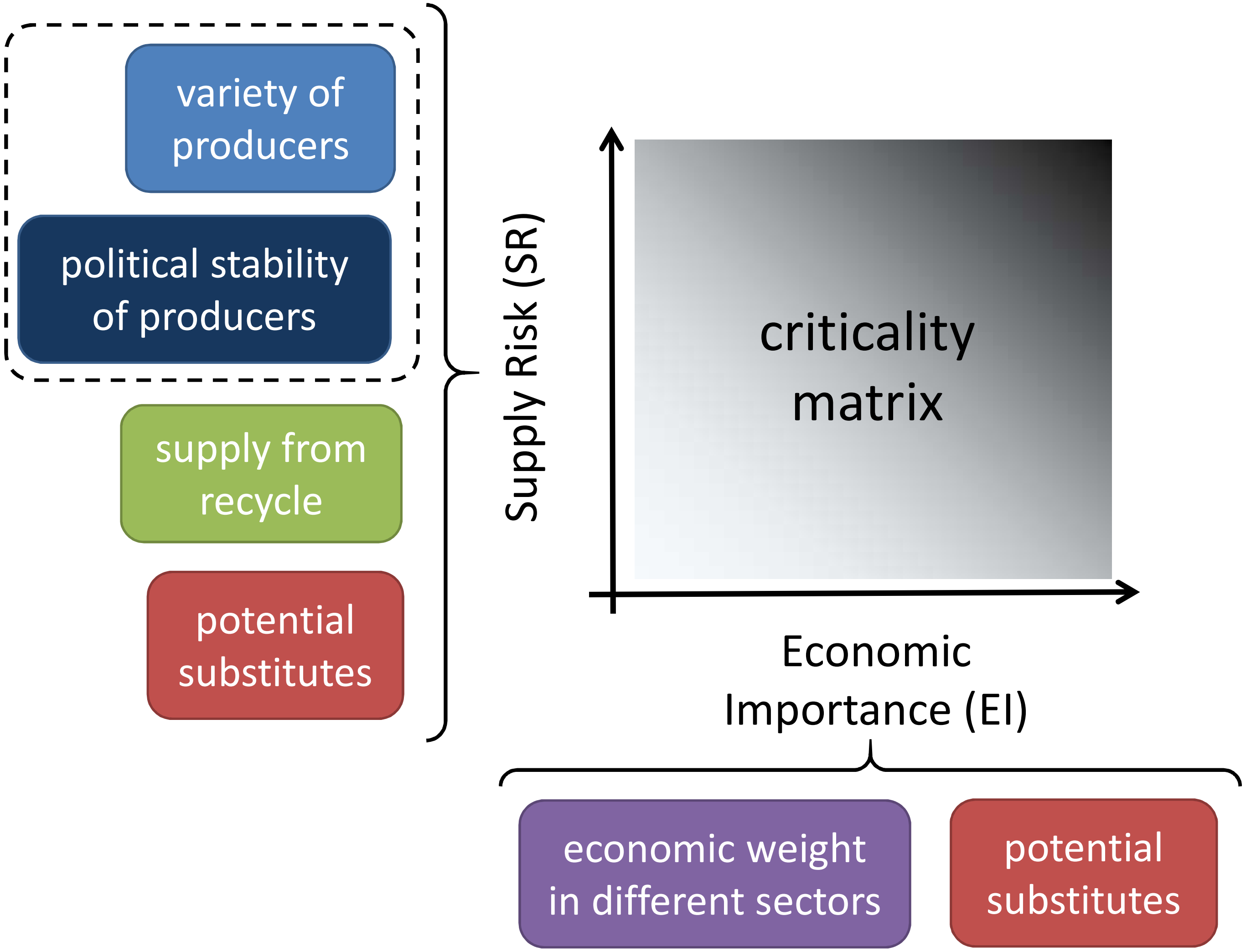


Supply Risk (SR)

criticality matrix

Economic Importance (EI)

EC 2017 criticality methodology



variety of producers

political stability of producers

supply from recycle

potential substitutes

Supply Risk (SR)

criticality matrix

Economic Importance (EI)

economic weight in different sectors

potential substitutes

EC 2017 criticality methodology

IMPORTANT ASPECTS on the DATA used

1. data must be public

2. data are prioritized

official EU data > EU state data > non-EU/international data > industry data

3. data are averaged over last 5 years

4. any exception must be reported and justified

a **detailed list** of the data **sources** used for each material is provided in the **materials factsheets**

EC 2017 criticality methodology

ECONOMIC IMPORTANCE (EI)

share of end-use
of material in a
NACE sector

NACE sector's gross value
added (GVA) in M€

$$EI = \sum_{s} (A_s \cdot Q_s) \cdot SI_{EI}$$

NACE sector

Substitution
Index

EC 2017 criticality methodology

ECONOMIC IMPORTANCE (EI)

$$EI = \sum_{s} (A_s \cdot Q_s) \cdot SI_{EI}$$

takes into account the ECONOMIC WEIGHT into different sectors

takes into account the existence of POSSIBLE SUBSTITUTES for the material

EC 2017 criticality methodology

share of end-use
of material in a
NACE sector

NACE sector's gross value
added (GVA) in M€

$$EI = \sum_{s} (A_s \cdot Q_s) \cdot SI_{EI}$$

NACE sector

Substitution
Index

EC 2017 criticality methodology

Statistical Classification of Economic Activities in the European Community

NACE Rev.2

Nomenclature statistique des Activités économiques dans la Communauté Européenne

4 hierarchical levels to classify each sector:

- **Level 1: 21 sections** identified by **alphabetical letters** A to U;
- **Level 2: 88 divisions** identified by **two-digit numerical codes** (01 to 99);
- Level 3: 272 groups identified by three-digit numerical codes (01.1 to 99.0);
- Level 4: 629 classes identified by four-digit numerical codes (01.11 to 99.00).

Level 1 Code	Economic Area
A	Agriculture, Forestry and Fishing
B	Mining and Quarrying
C	Manufacturing
D	Electricity, Gas, Steam and Air Conditioning Supply
…	…

Level 2 Code (SECTOR)

01 Crop and animal production
02 Forestry and logging
03 Fishing and aquaculture

EC 2017 criticality methodology

* data from EUROSTAT's
Structural Buisiness Statistics

share of end-use
of material in a
NACE sector

NACE sector's gross value
added (GVA) in M€

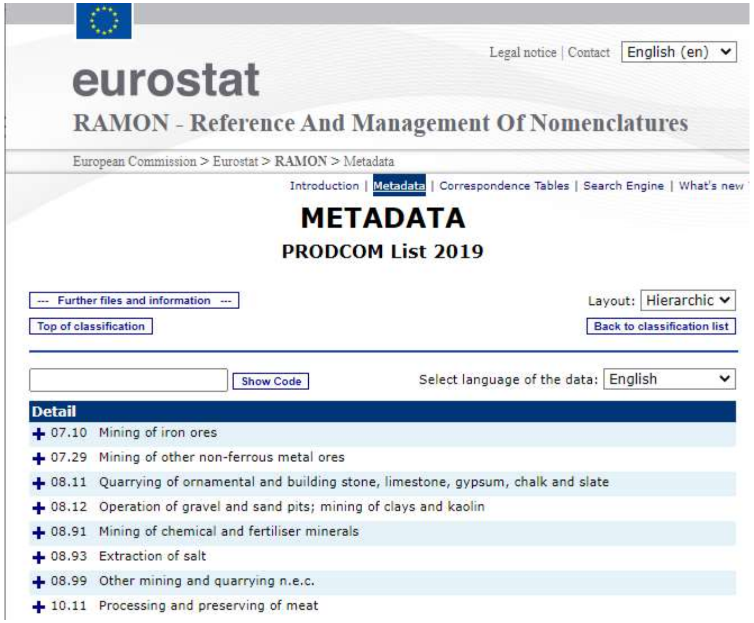
$$EI = \sum_s (A_s \cdot Q_s) \cdot SI_{EI}$$

NACE sector

Substitution
Index

end-use

from PRODCOM (PRODuction COMmunautaire)
list of manufactured goods



RAMON - Reference And Management Of Nomenclatures

European Commission > Eurostat > RAMON > Metadata

METADATA

PRODCOM List 2019

Layout: Hierarchic

Select language of the data: English

07.10	Mining of iron ores
07.29	Mining of other non-ferrous metal ores
08.11	Quarrying of ornamental and building stone, limestone, gypsum, chalk and slate
08.12	Operation of gravel and sand pits; mining of clays and kaolin
08.91	Mining of chemical and fertiliser minerals
08.93	Extraction of salt
08.99	Other mining and quarrying n.e.c.
10.11	Processing and preserving of meat

EC 2017 criticality methodology

share of end-use
of material in a
NACE sector

NACE sector's gross value
added (GVA) in M€

a measure of the value of goods produced in a sector (overall economic importance of that sector)

$$EI = \sum_{s} (A_s \cdot Q_s) \cdot SI_{EI}$$

NACE sector

Substitution
Index

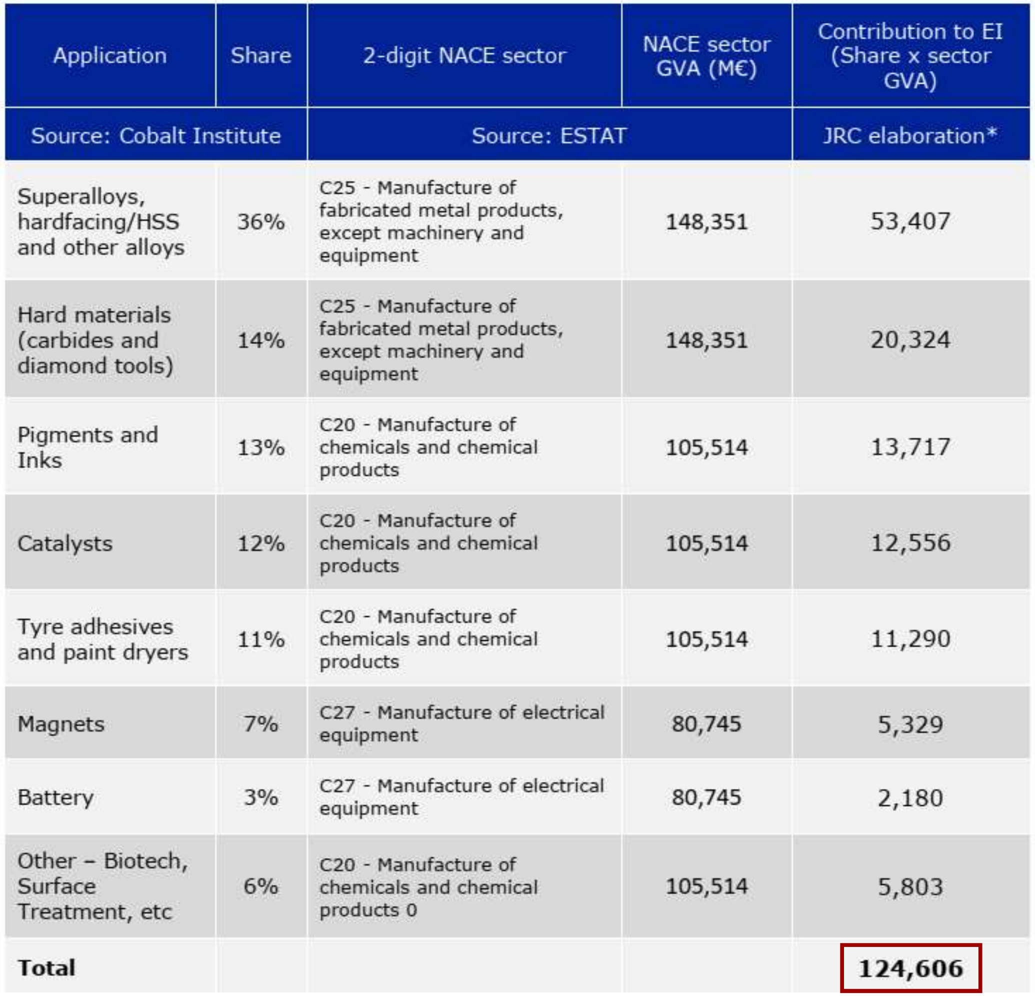
EC 2017 criticality methodology

example*
for Cobalt

$$EI = \boxed{\sum_s (A_s \cdot Q_s)} \cdot SI_{EI}$$

how much money
are worth the
activities in which
a material is used

A_s Q_s



Application	Share	2-digit NACE sector	NACE sector GVA (M€)	Contribution to EI (Share x sector GVA)
Source: Cobalt Institute		Source: ESTAT		JRC elaboration*
Superalloys, hardfacing/HSS and other alloys	36%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351	53,407
Hard materials (carbides and diamond tools)	14%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351	20,324
Pigments and Inks	13%	C20 - Manufacture of chemicals and chemical products	105,514	13,717
Catalysts	12%	C20 - Manufacture of chemicals and chemical products	105,514	12,556
Tyre adhesives and paint dryers	11%	C20 - Manufacture of chemicals and chemical products	105,514	11,290
Magnets	7%	C27 - Manufacture of electrical equipment	80,745	5,329
Battery	3%	C27 - Manufacture of electrical equipment	80,745	2,180
Other – Biotech, Surface Treatment, etc	6%	C20 - Manufacture of chemicals and chemical products 0	105,514	5,803
Total				**124,606**

* from EC, 2020, Study on the EU list of Critical Raw Materials - Final Report

EC 2017 criticality methodology

↑ high SI: no substitutes
↓ low SI: many substitutes

RATIONALE: the availability of **substitute materials** could mitigate the risk of supply disruptions.

$$EI = \sum_s (A_s \cdot Q_s) \cdot SI_{EI}$$

Substitution Index

sub-share of each substitute in within each application

$$SI_{EI} = \sum_i \sum_a SCP_{i,a} \cdot Subshare_{i,a} \cdot Share_a$$

individual substitute material

individual application of candidate material

substitute cost performance parameter

share of RM in an end-use application

only proven substitutes that are available today

EC 2017 criticality methodology

↑ high SI: no substitutes
↓ low SI: many substitutes

RATIONALE: the availability of **substitute materials** could mitigate the risk of supply disruptions.

$$EI = \sum_{s} (A_s \cdot Q_s) \cdot SI_{EI}$$

Substitution Index

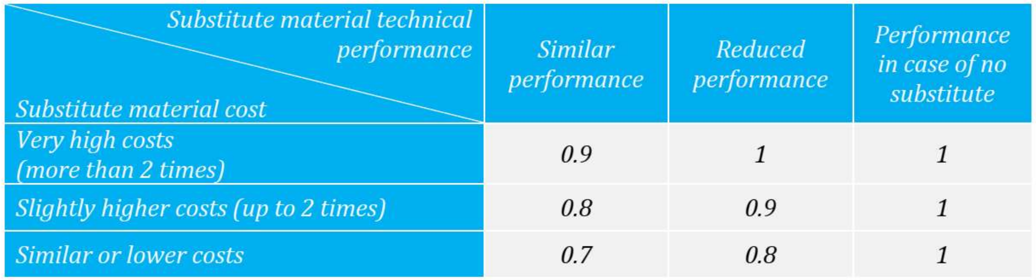
sub-share of each substitute in within each application

$$SI_{EI} = \sum_{i} \sum_{a} SCP_{i,a} \cdot Subshare_{i,a} \cdot Share_{a}$$

substitute cost performance parameter

share of RM in an end-use application

Table 1: **Substitute cost performance (SCP)** evaluation matrix (based on current costs)



Substitute material technical performance *Substitute material cost*	*Similar performance*	*Reduced performance*	*Performance in case of no substitute*
Very high costs (more than 2 times)	*0.9*	*1*	*1*
Slightly higher costs (up to 2 times)	*0.8*	*0.9*	*1*
Similar or lower costs	*0.7*	*0.8*	*1*

EC 2017 criticality methodology

↑ high SI: no substitutes
↓ low SI: many substitutes

RATIONALE: the availability of **substitute materials** could mitigate the risk of supply disruptions.

$$EI = \sum_s (A_s \cdot Q_s) \cdot \boxed{SI_{EI}}$$

Substitution Index

for Cobalt, $SI_{EI} = 0.92$

EC 2017 criticality methodology

example* for Cobalt

* from EC, 2020, Study on the EU list
of Critical Raw Materials - Final Report

$$EI = \underbrace{\sum_s (A_s \cdot Q_s)}_{124.060\ \text{M€}} \cdot \underbrace{SI_{EI}}_{0.92}$$

$$EI = \sum_s (A_s \cdot Q_s) \cdot SI_{EI} = 124.606\ M€ \cdot 0{,}92 = 114.733\ M€$$

$$EI_{scaled} = \frac{114.733\ M€}{\underbrace{106.055\ M€}_{\text{highest value for a NACE sector}}} \cdot 10 = \boxed{5{,}85} \quad \text{(on a 0-10 scale)}$$

EC 2017 criticality methodology

SUPPLY RISK (SR)

2 different **stages** considered

Stage I (Extraction, stage E)

Stage II (Processing, stage P)

SR is calculated for **both stages**:
only **bottleneck stage SR**
(i.e. the stage with the **highest SR value**)
considered for analysis

EC 2017 criticality methodology

SUPPLY RISK (SR)

$$SR = \left[\left(\underset{\text{Herfindahl-Hirschman Index}}{HHI}_{WGI,t}\right)_{\underset{\text{global sourcing}}{GS}} \cdot \frac{\overset{\text{Import Reliance}}{IR}}{2} + \left(HHI_{WGI,t}\right)_{\underset{\text{EU sourcing}}{EU}} \cdot \left(1 - \frac{IR}{2}\right)\right] \cdot \left(1 - \overset{\text{End-of-Life Recycling Input Rate}}{EoL_{RIR}}\right) \cdot \underset{\text{Substitution Index}}{SI}_{SR}$$

EC 2017 criticality methodology

SUPPLY RISK (SR)

takes into account
SOURCES DIVERSITY

take into account
availability of
SUBSTITUTES

$$SR = \left[\left(HHI_{WGI,t}\right)_{GS} \cdot \frac{IR}{2} + \left(HHI_{WGI,t}\right)_{EU} \cdot \left(1 - \frac{IR}{2}\right) \right] \cdot (1 - EoL_{RIR}) \cdot SI_{SR}$$

take into
account
RECYCLING

EC 2017 criticality methodology

SUPPLY RISK (SR)

Import Reliance

takes into account
SOURCES DIVERSITY

$$SR = \left[\left(HHI_{WGI,t}\right)_{GS} \cdot \frac{IR}{2} + \left(HHI_{WGI,t}\right)_{EU} \cdot \left(1 - \frac{IR}{2}\right)\right] \cdot (1 - EoL_{RIR}) \cdot SI_{SR}$$

Herfindahl-Hirschman Index

global sourcing

EU sourcing

$$HHI = \sum_i s_i^2$$

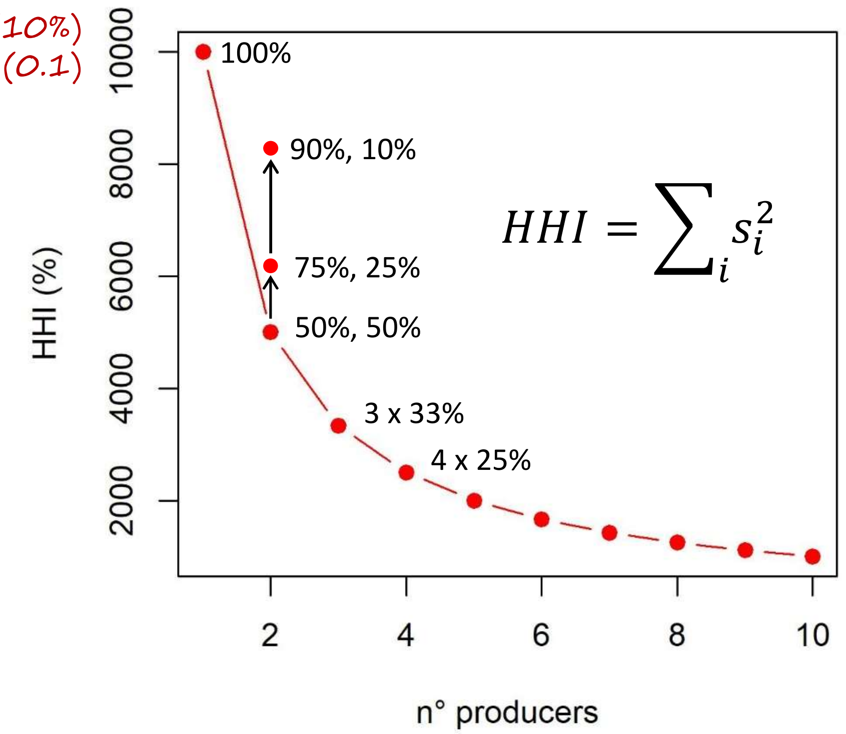
market share of producer i

(a measure of supply diversity)

↑ high HHI: few producers (low supply diversity)
↓ low HHI: many producers (high supply diversity)

EC 2017 criticality methodology

the Herfindahl-Hirschman Index (HHI)

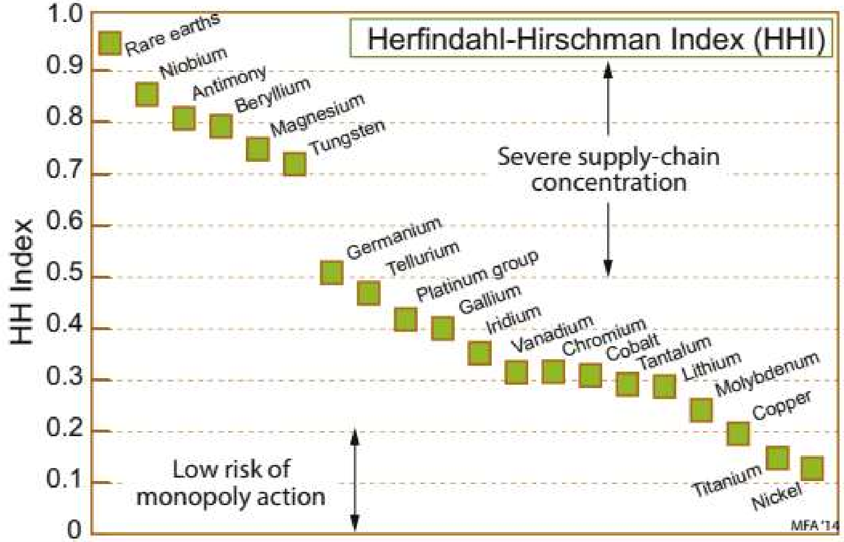


$$HHI = \sum_i s_i^2$$

to max 10000 for % (10%)
to max 1 for 0.x (0.1)

EC 2017 criticality methodology

the Herfindahl-Hirschman Index (HHI)



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

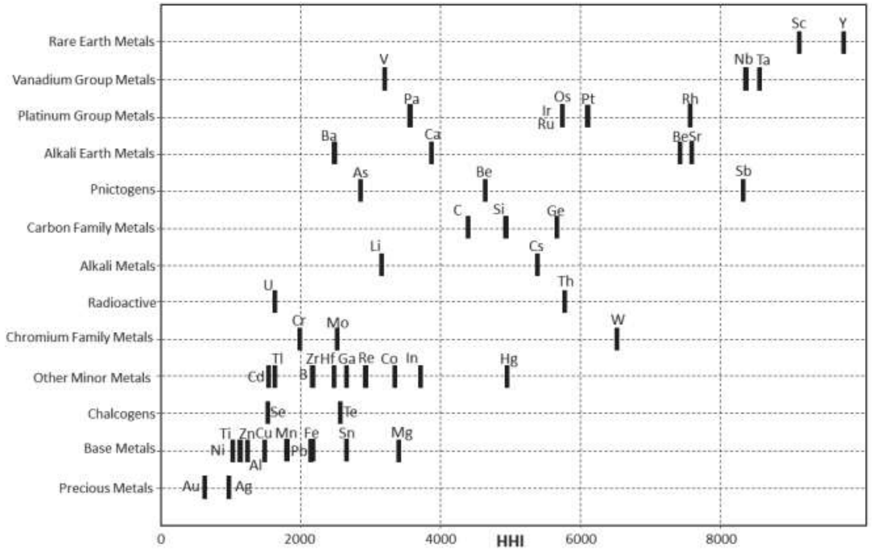


Fig. 7.4. Illustration of the Herfindahl-Hirschman Index for materials based on 2010 production data from the British Geological Survey and the U.S. Geological Survey.

(from S.E.Offerman. Ed., “Critical Materials”, World Scientific 2019)

EC 2017 criticality methodology

SUPPLY RISK (SR)

Import Reliance

takes into account
SOURCES DIVERSITY

$$SR = \left[\left(HHI_{WGI,t}\right)_{GS} \cdot \frac{IR}{2} + \left(HHI_{WGI,t}\right)_{EU} \cdot \left(1 - \frac{IR}{2}\right) \right] \cdot (1 - EoL_{RIR}) \cdot SI_{SR}$$

**Herfindahl-
Hirschman
Index**

global
sourcing

EU
sourcing

"scaled"

$$HHI_{WGI} = \sum\nolimits_{c} s_c^2 \cdot WGI_c$$

↓ the lower, the better

(scaled) World
Governance
Index of country c
(from World Bank)

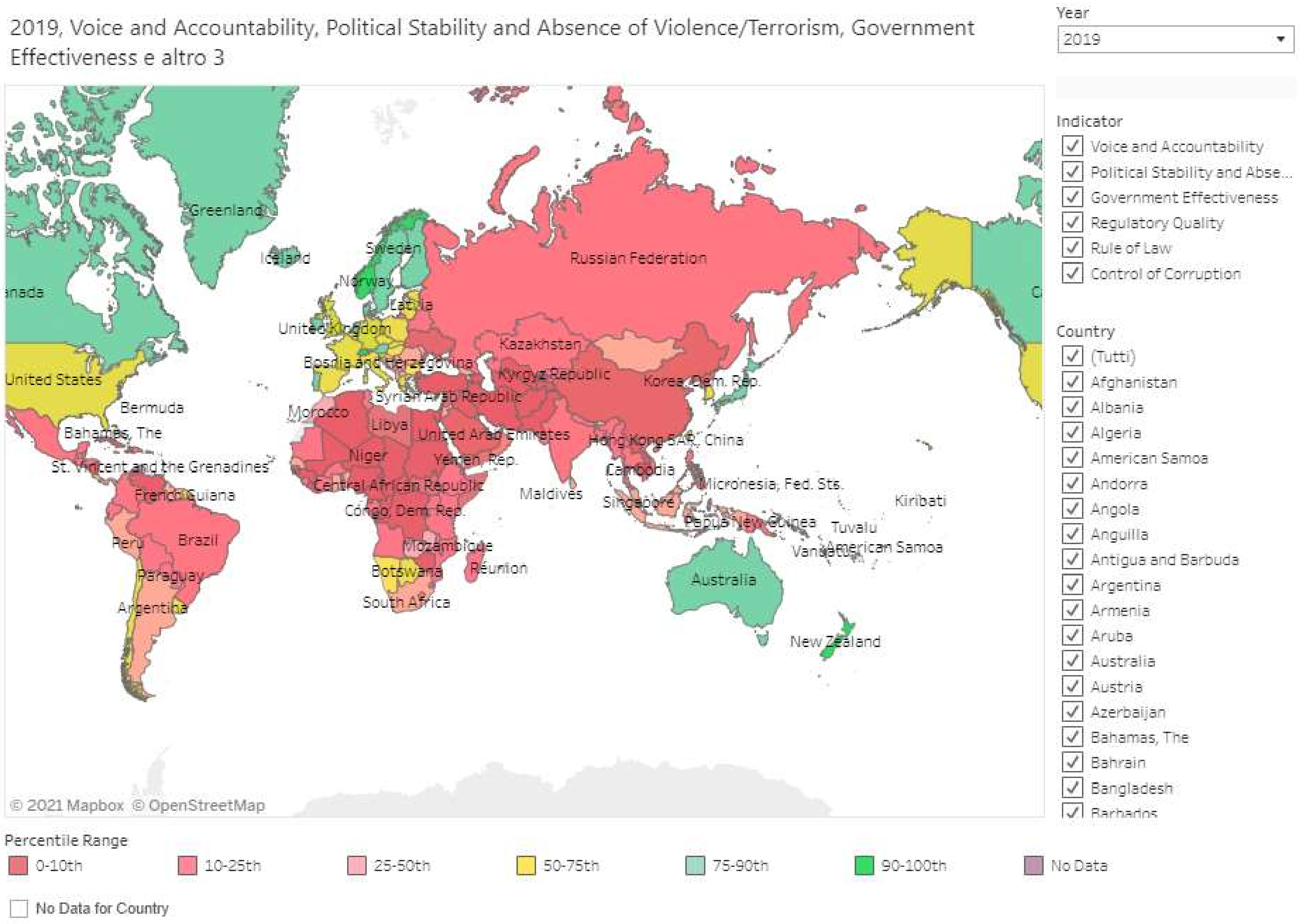
e.g.
Canada: 2.26
DR Congo 7.60

it depends on
→ public security
→ corruption
→ civil/political rights
→ sustainable development
→ human development

EC 2017 criticality methodology

the World Governance Index (WGI)

(also World Governance Indicator)



2019, Voice and Accountability, Political Stability and Absence of Violence/Terrorism, Government Effectiveness e altro 3

Year
2019

Indicator
- ☑ Voice and Accountability
- ☑ Political Stability and Abse...
- ☑ Government Effectiveness
- ☑ Regulatory Quality
- ☑ Rule of Law
- ☑ Control of Corruption

Country
- ☑ (Tutti)
- ☑ Afghanistan
- ☑ Albania
- ☑ Algeria
- ☑ American Samoa
- ☑ Andorra
- ☑ Angola
- ☑ Anguilla
- ☑ Antigua and Barbuda
- ☑ Argentina
- ☑ Armenia
- ☑ Aruba
- ☑ Australia
- ☑ Austria
- ☑ Azerbaijan
- ☑ Bahamas, The
- ☑ Bahrain
- ☑ Bangladesh
- ☑ Barbados

Percentile Range
🟥 0-10th 🟥 10-25th 🟥 25-50th 🟨 50-75th 🟩 75-90th 🟩 90-100th 🟪 No Data

☐ No Data for Country

(source worldbank.org)

EC 2017 criticality methodology

SUPPLY RISK (SR)

Import Reliance

takes into account
SOURCES DIVERSITY

$$SR = \left[\left(HHI_{WGI,t}\right)_{GS} \cdot \frac{IR}{2} + \left(HHI_{WGI,t}\right)_{EU} \cdot \left(1 - \frac{IR}{2}\right)\right] \cdot (1 - EoL_{RIR}) \cdot SI_{SR}$$

Herfindahl-Hirschman Index

global
sourcing

EU
sourcing

$$HHI_{WGI,t} = \sum_{c} s_c^2 \cdot WGI_c \cdot t_c$$

trade
parameter

↓ the lower, the better

takes into account
contributions of trade (e.g.
export restrictions, trade
agreements) to the SR

$$t_c = (ET - TA_c \; or \; EQ_c \; or \; EP_c \; or \; EU_c)$$

EC 2017 criticality methodology

SUPPLY RISK (SR)

Import Reliance

takes into account
SOURCES DIVERSITY

$$SR = \left[\left(HHI_{WGI,t}\right)_{GS} \cdot \frac{IR}{2} + \left(HHI_{WGI,t}\right)_{EU} \cdot \left(1 - \frac{IR}{2}\right)\right] \cdot (1 - EoL_{RIR}) \cdot SI_{SR}$$

Herfindahl-
Hirschman
Index

global
sourcing

EU
sourcing

$$\left(HHI_{WGI,t}\right)_{GS} \qquad \left(HHI_{WGI,t}\right)_{EU}$$

index calculated
for 2 cases

$$HHI_{WGI,t} = \sum_{c} s_c^2 \cdot WGI_c \cdot t_c$$

EC 2017 criticality methodology

SUPPLY RISK (SR)

Import Reliance

takes into account
SOURCES DIVERSITY

$$SR = \left[\left(HHI_{WGI,t}\right)_{GS} \cdot \frac{IR}{2} + \left(HHI_{WGI,t}\right)_{EU} \cdot \left(1 - \frac{IR}{2}\right) \right] \cdot \left(1 - EoL_{RIR}\right) \cdot SI_{SR}$$

**Herfindahl-
Hirschman
Index**

global
sourcing

EU
sourcing

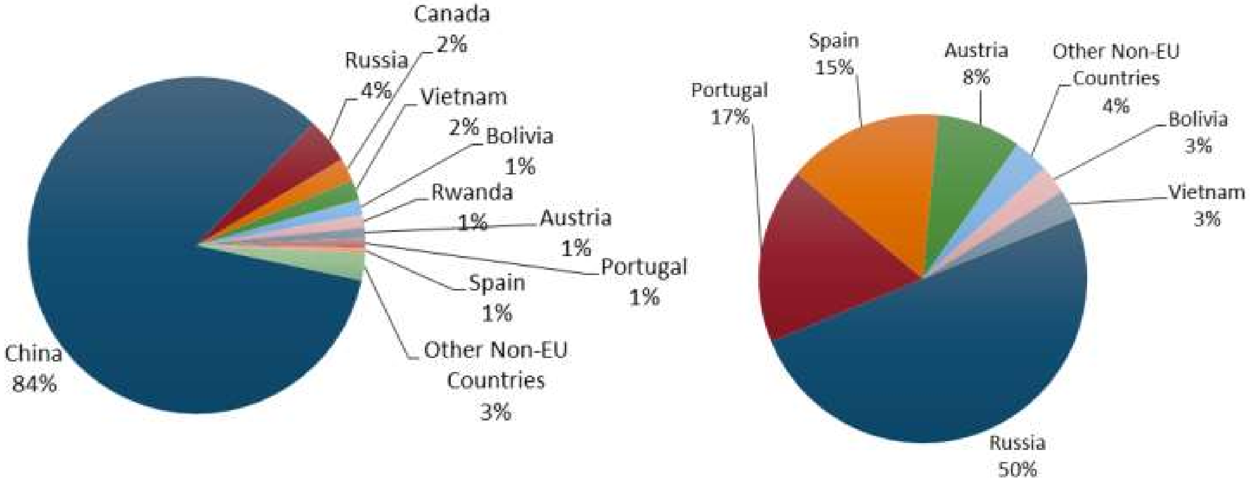


Figure 1b: Example: global supply of tungsten (left) and actual EU sourcing (right).

EC 2017 criticality methodology

example for Cobalt (E stage, GS)

$$HHI_{WGI,t} = \sum_c s_c^2 \cdot WGI_c \cdot t_c$$

s_c WGI_c t_c

Table 19: Stage I (ores and intermediates). Concentration risk for global supply: Global Supply Risk – $(HHI_{WGI-t})_{GS}$

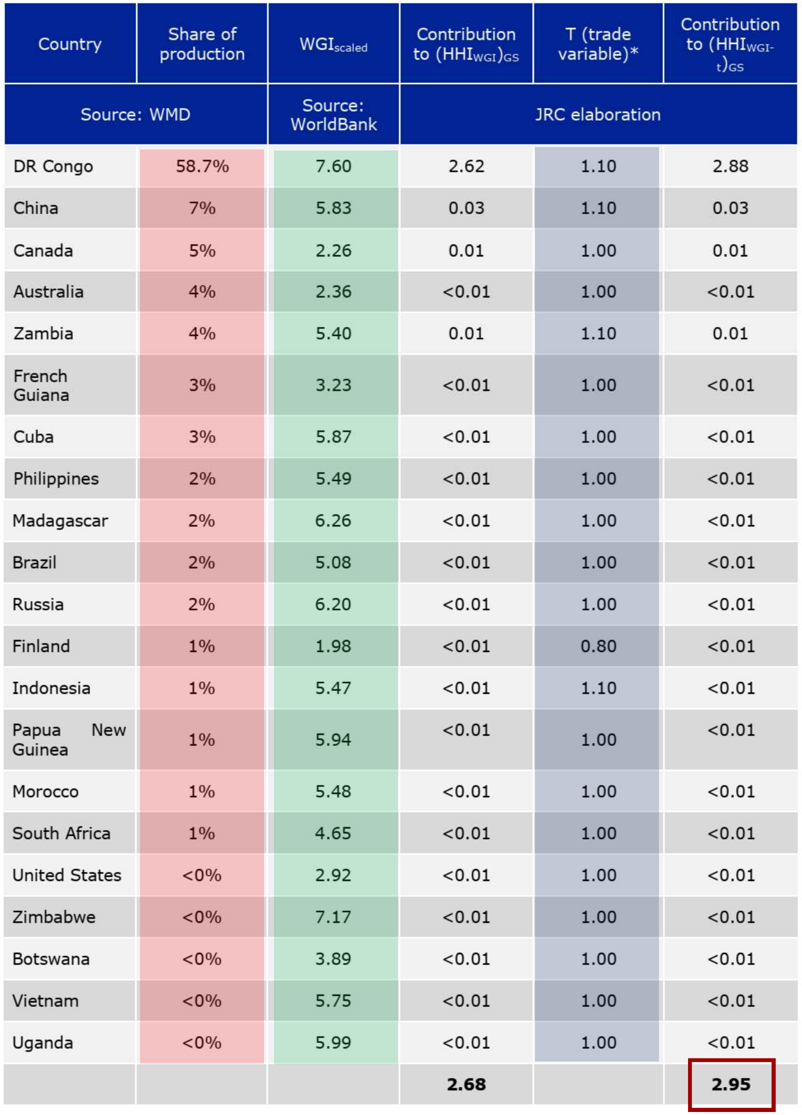
Country	Share of production	WGI_{scaled}	Contribution to $(HHI_{WGI})_{GS}$	T (trade variable)*	Contribution to $(HHI_{WGI-t})_{GS}$
Source: WMD		Source: WorldBank	JRC elaboration		
DR Congo	58.7%	7.60	2.62	1.10	2.88
China	7%	5.83	0.03	1.10	0.03
Canada	5%	2.26	0.01	1.00	0.01
Australia	4%	2.36	<0.01	1.00	<0.01
Zambia	4%	5.40	0.01	1.10	0.01
French Guiana	3%	3.23	<0.01	1.00	<0.01
Cuba	3%	5.87	<0.01	1.00	<0.01
Philippines	2%	5.49	<0.01	1.00	<0.01
Madagascar	2%	6.26	<0.01	1.00	<0.01
Brazil	2%	5.08	<0.01	1.00	<0.01
Russia	2%	6.20	<0.01	1.00	<0.01
Finland	1%	1.98	<0.01	0.80	<0.01
Indonesia	1%	5.47	<0.01	1.10	<0.01
Papua New Guinea	1%	5.94	<0.01	1.00	<0.01
Morocco	1%	5.48	<0.01	1.00	<0.01
South Africa	1%	4.65	<0.01	1.00	<0.01
United States	<0%	2.92	<0.01	1.00	<0.01
Zimbabwe	<0%	7.17	<0.01	1.00	<0.01
Botswana	<0%	3.89	<0.01	1.00	<0.01
Vietnam	<0%	5.75	<0.01	1.00	<0.01
Uganda	<0%	5.99	<0.01	1.00	<0.01
			2.68		$\boxed{\textbf{2.95}}$

$(HHI_{WGI,t})_{GS}$ = 2.95

EC 2017 criticality methodology

s_C WGI_C t_C

Table 19: Stage I (ores and intermediates). Concentration risk for global supply: Global Supply Risk – $(HHI_{WGI\text{-}t})_{GS}$



Country	Share of production	WGI_{scaled}	Contribution to $(HHI_{WGI})_{GS}$	T (trade variable)*	Contribution to $(HHI_{WGI\text{-}t})_{GS}$
Source: WMD		Source: WorldBank	JRC elaboration		
DR Congo	58.7%	7.60	2.62	1.10	2.88
China	7%	5.83	0.03	1.10	0.03
Canada	5%	2.26	0.01	1.00	0.01
Australia	4%	2.36	<0.01	1.00	<0.01
Zambia	4%	5.40	0.01	1.10	0.01
French Guiana	3%	3.23	<0.01	1.00	<0.01
Cuba	3%	5.87	<0.01	1.00	<0.01
Philippines	2%	5.49	<0.01	1.00	<0.01
Madagascar	2%	6.26	<0.01	1.00	<0.01
Brazil	2%	5.08	<0.01	1.00	<0.01
Russia	2%	6.20	<0.01	1.00	<0.01
Finland	1%	1.98	<0.01	0.80	<0.01
Indonesia	1%	5.47	<0.01	1.10	<0.01
Papua New Guinea	1%	5.94	<0.01	1.00	<0.01
Morocco	1%	5.48	<0.01	1.00	<0.01
South Africa	1%	4.65	<0.01	1.00	<0.01
United States	<0%	2.92	<0.01	1.00	<0.01
Zimbabwe	<0%	7.17	<0.01	1.00	<0.01
Botswana	<0%	3.89	<0.01	1.00	<0.01
Vietnam	<0%	5.75	<0.01	1.00	<0.01
Uganda	<0%	5.99	<0.01	1.00	<0.01
			2.68		**2.95**

example for Cobalt

$$HHI_{WGI,t} = \sum_c s_c^2 \cdot WGI_c \cdot t_c$$

$(HHI_{WGI,t})_{GS}$ = 2.95
$(HHI_{WGI,t})_{EU}$ = 3.97
stage I (E)

$(HHI_{WGI,t})_{GS}$ = 1.61
$(HHI_{WGI,t})_{EU}$ = 0.54
stage II (P)

EC 2017 criticality methodology

SUPPLY RISK (SR)

(how much do we rely on import)

Import Reliance

takes into account
SOURCES DIVERSITY

$$SR = \left[\left(HHI_{WGI,t}\right)_{GS} \cdot \frac{IR}{2} + \left(HHI_{WGI,t}\right)_{EU} \cdot \left(1 - \frac{IR}{2}\right) \right] \cdot \left(1 - EoL_{RIR}\right) \cdot SI_{SR}$$

Herfindahl-
Hirschman
Index

global
sourcing

EU
sourcing

(from 0
to 1)

$$IR = \frac{(Import - Export)}{Domestic\ production + (Import - Export)}$$

↓ **low IR: no need to import** (domestic production is high)
↑ **high IR: rely on import** (domestic production is low)

for cobalt: IR (stage I) = 86% IR (stage II) = 27%

EC 2017 criticality methodology

SUPPLY RISK (SR)

End-of-Life
Recycling Input Rate

$$SR = \left[\left(HHI_{WGI,t}\right)_{GS} \cdot \frac{IR}{2} + \left(HHI_{WGI,t}\right)_{EU} \cdot \left(1 - \frac{IR}{2}\right)\right] \cdot \boxed{(1 - EoL_{RIR})} \cdot SI_{SR}$$

take into
account
RECYCLING

(from 0
to 1)

$$EoL_{RIR} = \frac{input\ of\ recycled\ material}{input\ of\ primary\ material + input\ of\ recycled\ material}$$

↓ low EoL_{RIR}: low fraction supply from recycling
↑ high EoL_{RIR} : high fraction of supply from recycling

(the higher, the better)

(for Cobalt, EoL_{RIR} = 22%)

EC 2017 criticality methodology

EOL-RIR values

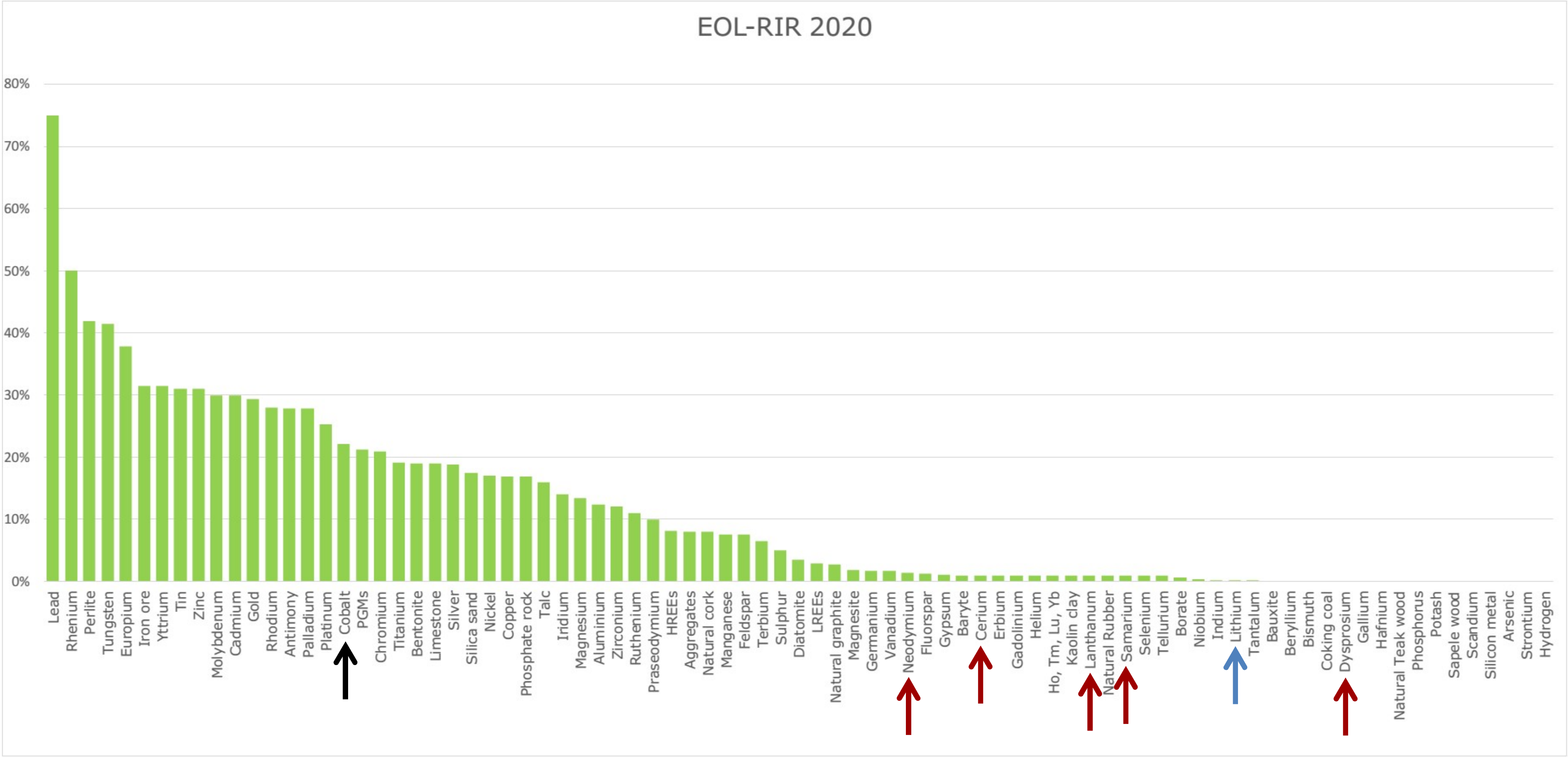


Figure 12: End of life recycling input rate (EOL-RIR)

EC 2017 criticality methodology

SUPPLY RISK (SR)

take into account
availability of
SUBSTITUTES

$$SR = \left[\left(HHI_{WGI,t}\right)_{GS} \cdot \frac{IR}{2} + \left(HHI_{WGI,t}\right)_{EU} \cdot \left(1 - \frac{IR}{2}\right) \right] \cdot (1 - EoL_{RIR}) \cdot SI_{SR}$$

Substitution
Index

substitute
criticality

sub-share of each
substitute in within
each application

$$SI_{SR} = \sum_{i} \left[(SP_i \cdot SCr_i \cdot SCo_i)^{1/3} \cdot \sum_{a} Subshare_{i,a} \cdot Share_a \right]$$

individual
substitute
material

substitute
production

substitute
co-production

individual
application
of candidate
material

share of RM
in an end-use
application

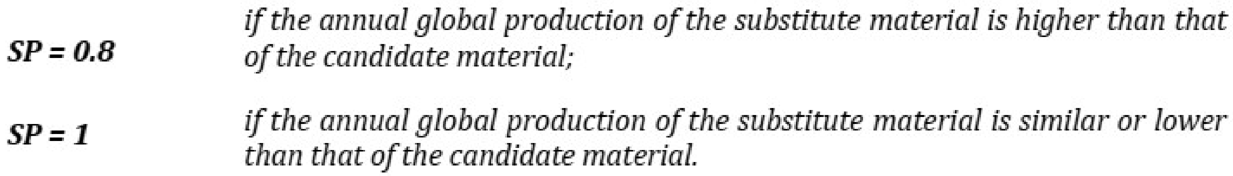
EC 2017 criticality methodology

SUPPLY RISK (SR)

take into account
availability of
SUBSTITUTES

$$SR = \left[\left(HHI_{WGI,t}\right)_{GS} \cdot \frac{IR}{2} + \left(HHI_{WGI,t}\right)_{EU} \cdot \left(1 - \frac{IR}{2}\right) \right] \cdot (1 - EoL_{RIR}) \cdot SI_{SR}$$

Substitution
Index



SP = 0.8	*if the annual global production of the substitute material is higher than that of the candidate material;*
SP = 1	*if the annual global production of the substitute material is similar or lower than that of the candidate material.*

$$SI_{SR} = \sum_i \left[(SP_i \cdot SCr_i \cdot SCo_i)^{1/3} \cdot \sum_a Subshare_{i,a} \cdot Share_a \right]$$

substitute
production

(market size of RM
compared to that of
substitute)

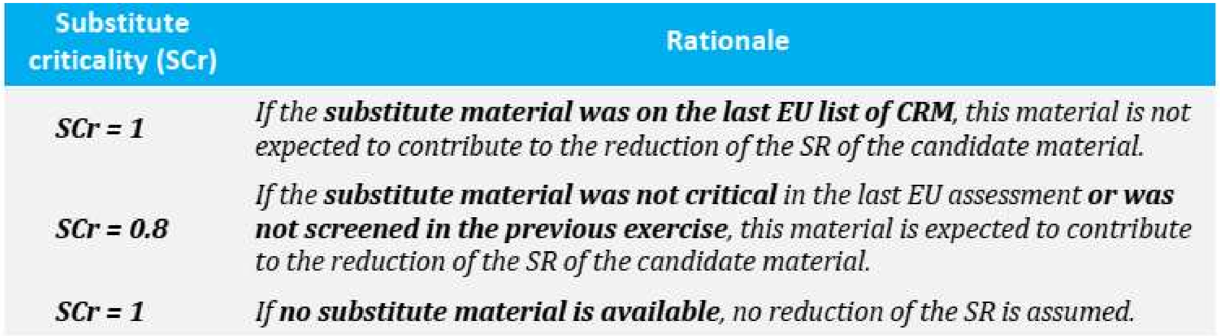
EC 2017 criticality methodology

SUPPLY RISK (SR)

take into account
availability of
SUBSTITUTES

$$SR = \left[\left(HHI_{WGI,t}\right)_{GS} \cdot \frac{IR}{2} + \left(HHI_{WGI,t}\right)_{EU} \cdot \left(1 - \frac{IR}{2}\right) \right] \cdot (1 - EoL_{RIR}) \cdot \boxed{SI_{SR}}$$

Substitution
Index



Substitute criticality (SCr)	Rationale
SCr = 1	*If the **substitute material was on the last EU list of CRM**, this material is not expected to contribute to the reduction of the SR of the candidate material.*
SCr = 0.8	*If the **substitute material was not critical** in the last EU assessment **or was not screened in the previous exercise**, this material is expected to contribute to the reduction of the SR of the candidate material.*
SCr = 1	*If **no substitute material is available**, no reduction of the SR is assumed.*

$$SI_{SR} = \sum_i \left[\left(SP_i \cdot \boxed{SCr_i} \cdot SCo_i\right)^{1/3} \cdot \sum_a Subshare_{i,a} \cdot Share_a \right]$$

substitute
criticality

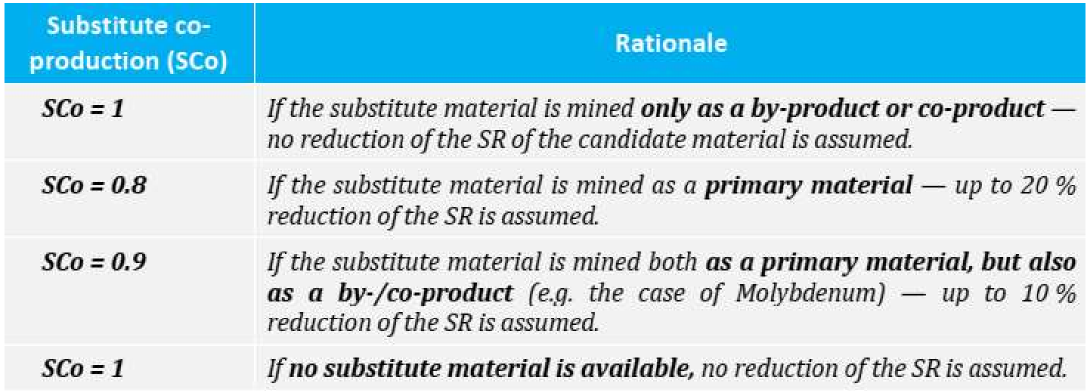
EC 2017 criticality methodology

SUPPLY RISK (SR)

take into account
availability of
SUBSTITUTES

$$SR = \left[\left(HHI_{WGI,t}\right)_{GS} \cdot \frac{IR}{2} + \left(HHI_{WGI,t}\right)_{EU} \cdot \left(1 - \frac{IR}{2}\right)\right] \cdot (1 - EoL_{RIR}) \cdot \boxed{SI_{SR}}$$

Substitution
Index



Substitute co-production (SCo)	Rationale
SCo = 1	*If the substitute material is mined* ***only as a by-product or co-product*** *— no reduction of the SR of the candidate material is assumed.*
SCo = 0.8	*If the substitute material is mined as a* ***primary material*** *— up to 20 % reduction of the SR is assumed.*
SCo = 0.9	*If the substitute material is mined both* ***as a primary material, but also as a by-/co-product*** *(e.g. the case of Molybdenum) — up to 10 % reduction of the SR is assumed.*
SCo = 1	*If* ***no substitute material is available,*** *no reduction of the SR is assumed.*

$$SI_{SR} = \sum_{i}\left[\left(SP_i \cdot SCr_i \cdot \boxed{SCo_i}\right)^{1/3} \cdot \sum_{a} Subshare_{i,a} \cdot Share_a\right]$$

substitute
co-production

EC 2017 criticality methodology

SUPPLY RISK (SR)

take into account
availability of
SUBSTITUTES

$$SR = \left[\left(HHI_{WGI,t}\right)_{GS} \cdot \frac{IR}{2} + \left(HHI_{WGI,t}\right)_{EU} \cdot \left(1 - \frac{IR}{2}\right)\right] \cdot (1 - EoL_{RIR}) \cdot SI_{SR}$$

Substitution
Index

(for Cobalt, SI_{SR} = 0.92)

$$SI_{SR} = \sum_{i} \left[(SP_i \cdot SCr_i \cdot SCo_i)^{1/3} \cdot \sum_{a} Subshare_{i,a} \cdot Share_a \right]$$

EC 2017 criticality methodology

SUPPLY RISK (SR) for Cobalt

$$SR = \left[\underset{\substack{2.95\ (E)\\ 1.61\ (P)}}{\left(HHI_{WGI,t}\right)_{GS}} \cdot \overset{\substack{86\%\ (E)\\ 17\%\ (P)}}{\frac{IR}{2}} + \underset{\substack{3.97\ (E)\\ 0.54\ (P)}}{\left(HHI_{WGI,t}\right)_{EU}} \cdot \left(1 - \overset{\substack{86\%\ (E)\\ 17\%\ (P)}}{\frac{IR}{2}}\right) \right] \cdot \left(1 - \overset{22\%}{EoL_{RIR}}\right) \cdot \underset{0.92}{SI_{SR}}$$

$$\underset{(E)}{SR} = \left[2.95 \cdot \frac{86}{2} + 3.97 \cdot \left(1 - \frac{86}{2}\right)\right] \cdot (1 - 22) \cdot 0.92 = 2.5$$

for stage I (E)

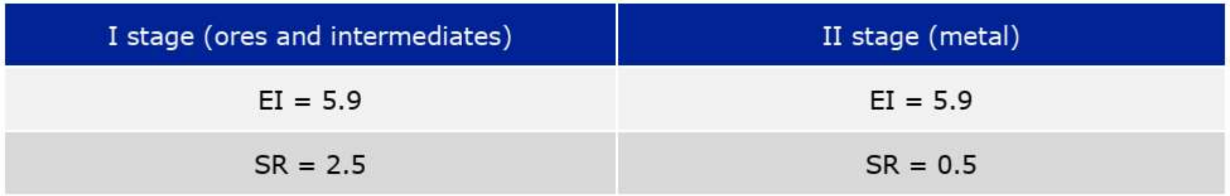
$$\underset{(P)}{SR} = \left[1.61 \cdot \frac{17}{2} + 0.54 \cdot \left(1 - \frac{17}{2}\right)\right] \cdot (1 - 22) \cdot 0.92 = 0.5$$

for stage II (P)

EC 2017 criticality methodology

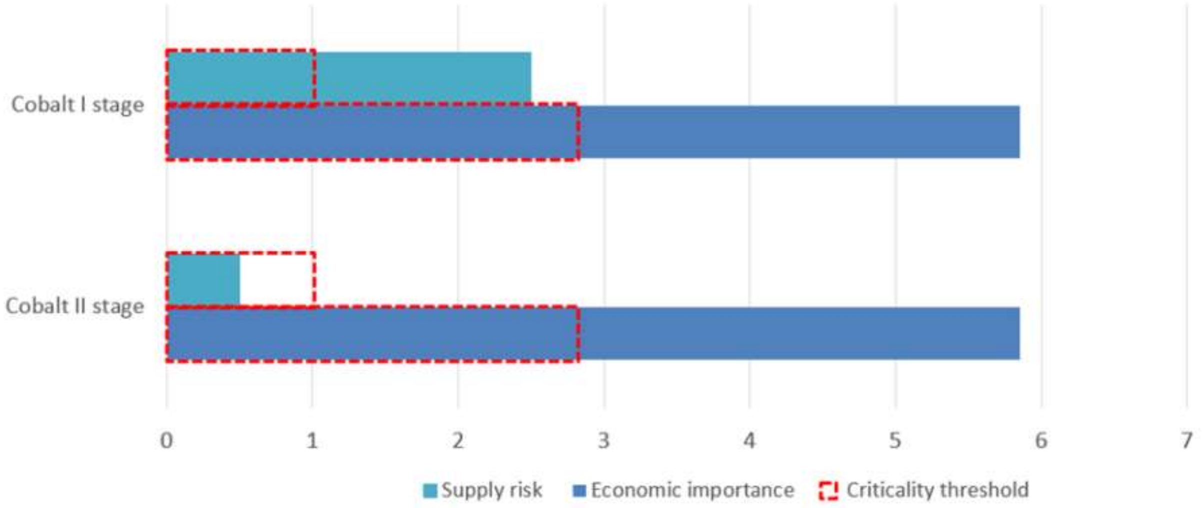
CRITICALITY ANALYSIS *for Cobalt*

Table 23: EI and SR results for cobalt



I stage (ores and intermediates)	II stage (metal)
EI = 5.9	EI = 5.9
SR = 2.5	SR = 0.5

Figure 15: EI and SR results for cobalt



EC 2017 criticality methodology

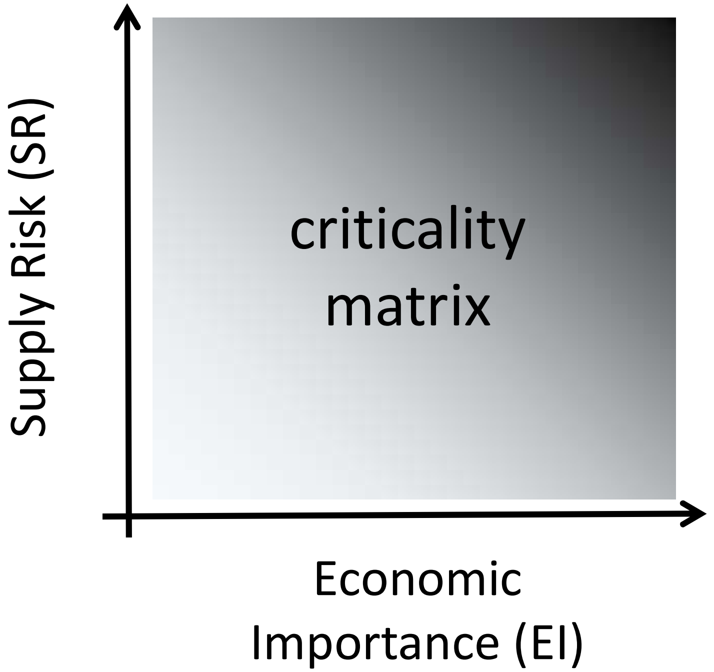
potential substitutes

supply from recycle

variety of producers

political stability of producers

$$SR = \left[(HHI_{WGI,t})_{GS} \cdot \frac{IR}{2} + (HHI_{WGI,t})_{EU} \cdot \left(1 - \frac{IR}{2}\right)\right] \cdot (1 - EoL_{RIR}) \cdot SI_{SR}$$



$$EI = \sum_{s} (A_s \cdot Q_s) \cdot SI_{EI}$$

economic weight in different sectors

potential substitutes

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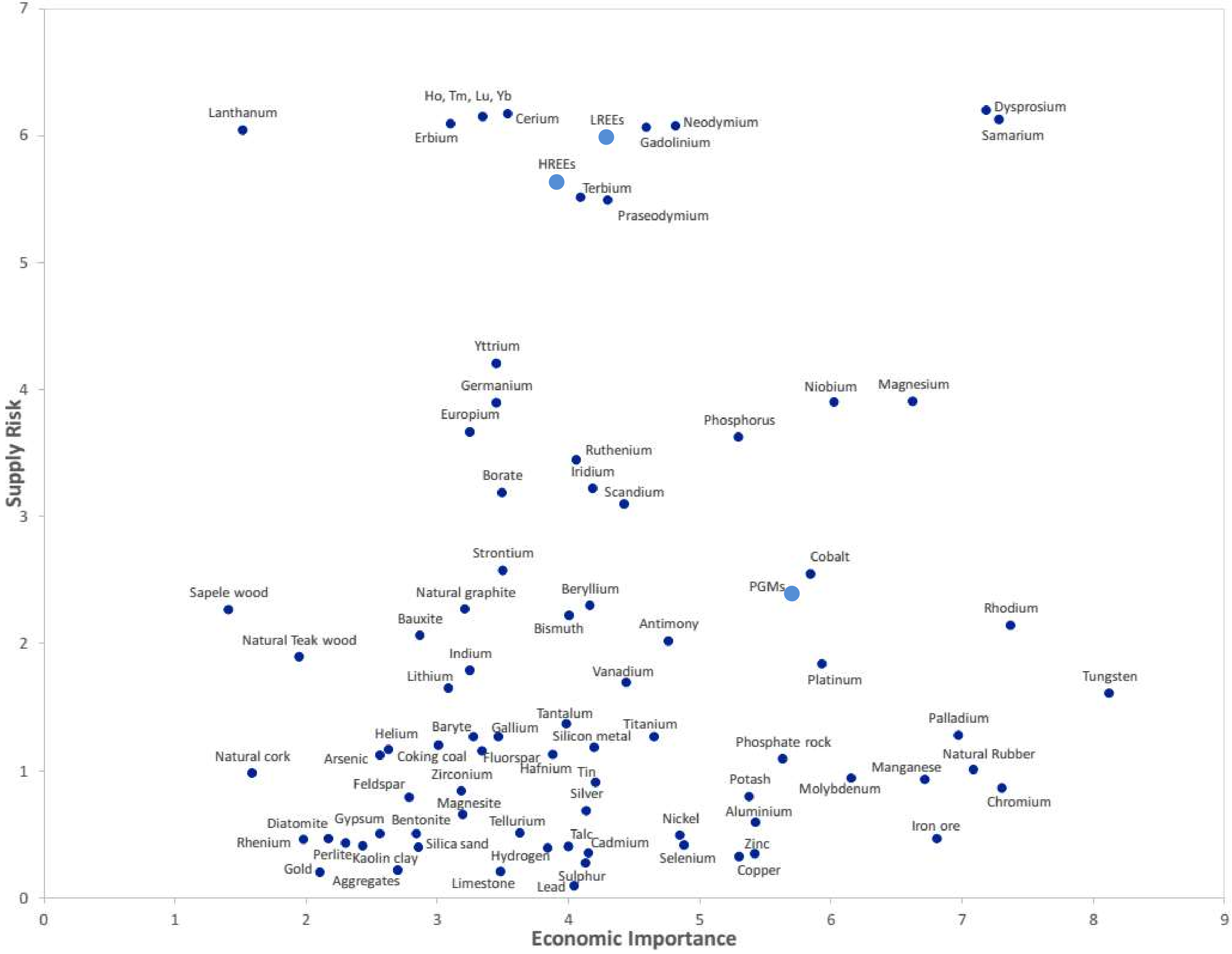
candidate materials considered for analysis

Industrial and construction minerals	aggregates, baryte, bentonite, borates, diatomite, feldspar, fluorspar, gypsum, kaolin clay, limestone, magnesite, natural graphite, perlite, phosphate rock, phosphorus, potash, silica sand, sulphur, talc
Iron and ferro-alloy metals	chromium, cobalt, manganese, molybdenum, nickel, niobium, tantalum, titanium, tungsten, vanadium
Precious metals	gold, silver, and Platinum Group Metals (iridium, palladium, platinum, rhodium, ruthenium)
Rare earths	Heavy rare earths (dysprosium, erbium, europium, gadolinium, holmium, lutetium, terbium, thulium, ytterbium, yttrium); Light rare earths (cerium, lanthanum, neodymium, praseodymium and samarium); and scandium
Other non-ferrous metals	aluminium, antimony, arsenic, beryllium, bismuth, cadmium, copper, gallium, germanium, gold, hafnium, indium, lead, lithium, magnesium, rhenium, selenium, silicon metal, silver, strontium, tellurium, tin, zinc, zirconium
Bio and other materials	natural cork, natural rubber, natural teak wood, sapele wood, coking coal, hydrogen and helium

EC 2020 CRMs Final Report *(results!)*



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all other relevant data in a table

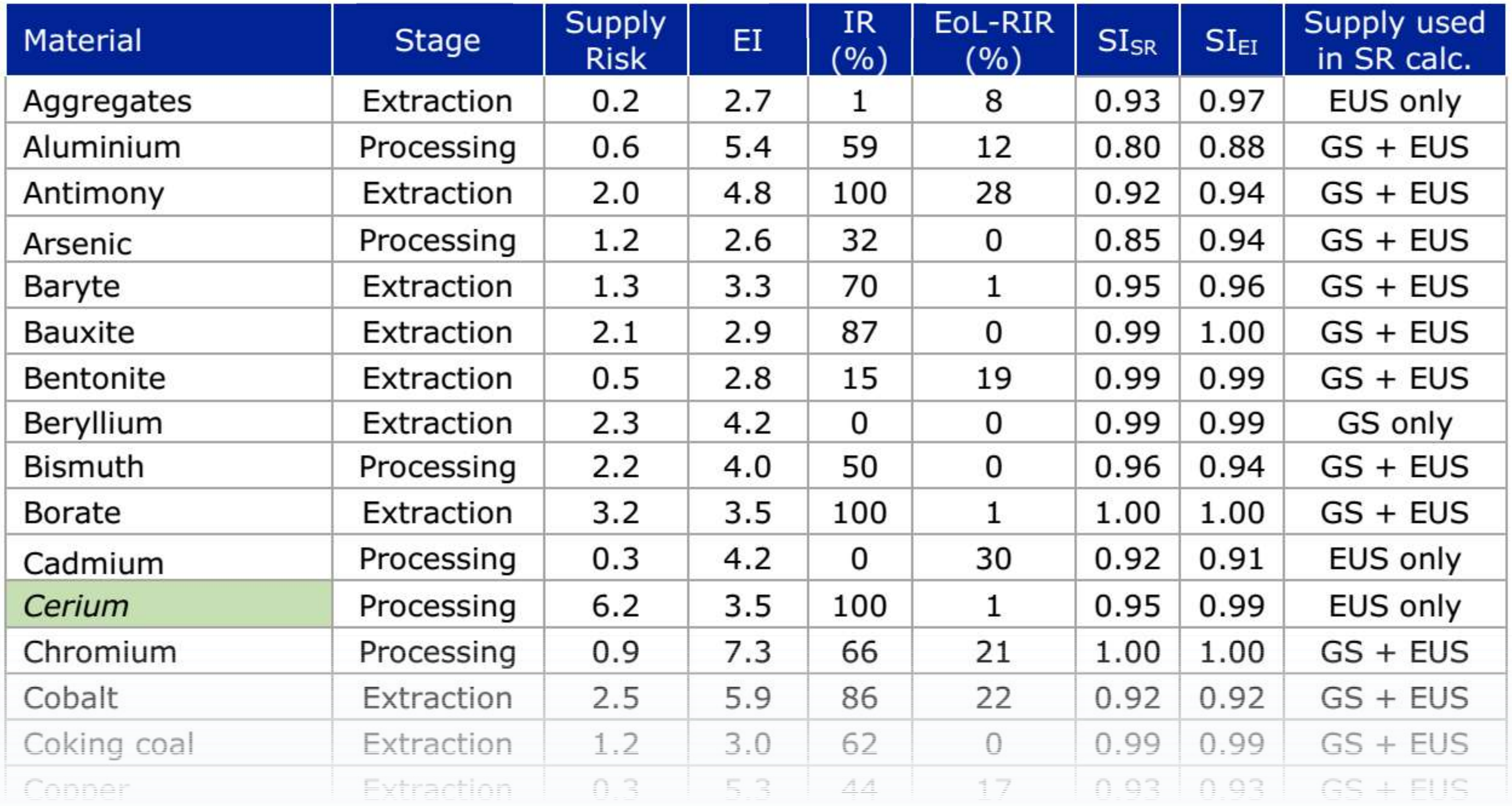
bottleneck stage (highest SR)

Import Reliance

Recycle Input Rate

Substit. Indexes

type of SR used



Material	Stage	Supply Risk	EI	IR (%)	EoL-RIR (%)	SI_{SR}	SI_{EI}	Supply used in SR calc.
Aggregates	Extraction	0.2	2.7	1	8	0.93	0.97	EUS only
Aluminium	Processing	0.6	5.4	59	12	0.80	0.88	GS + EUS
Antimony	Extraction	2.0	4.8	100	28	0.92	0.94	GS + EUS
Arsenic	Processing	1.2	2.6	32	0	0.85	0.94	GS + EUS
Baryte	Extraction	1.3	3.3	70	1	0.95	0.96	GS + EUS
Bauxite	Extraction	2.1	2.9	87	0	0.99	1.00	GS + EUS
Bentonite	Extraction	0.5	2.8	15	19	0.99	0.99	GS + EUS
Beryllium	Extraction	2.3	4.2	0	0	0.99	0.99	GS only
Bismuth	Processing	2.2	4.0	50	0	0.96	0.94	GS + EUS
Borate	Extraction	3.2	3.5	100	1	1.00	1.00	GS + EUS
Cadmium	Processing	0.3	4.2	0	30	0.92	0.91	EUS only
Cerium	Processing	6.2	3.5	100	1	0.95	0.99	EUS only
Chromium	Processing	0.9	7.3	66	21	1.00	1.00	GS + EUS
Cobalt	Extraction	2.5	5.9	86	22	0.92	0.92	GS + EUS
Coking coal	Extraction	1.2	3.0	62	0	0.99	0.99	GS + EUS
Copper	Extraction	0.3	5.3	44	17	0.93	0.93	GS + EUS

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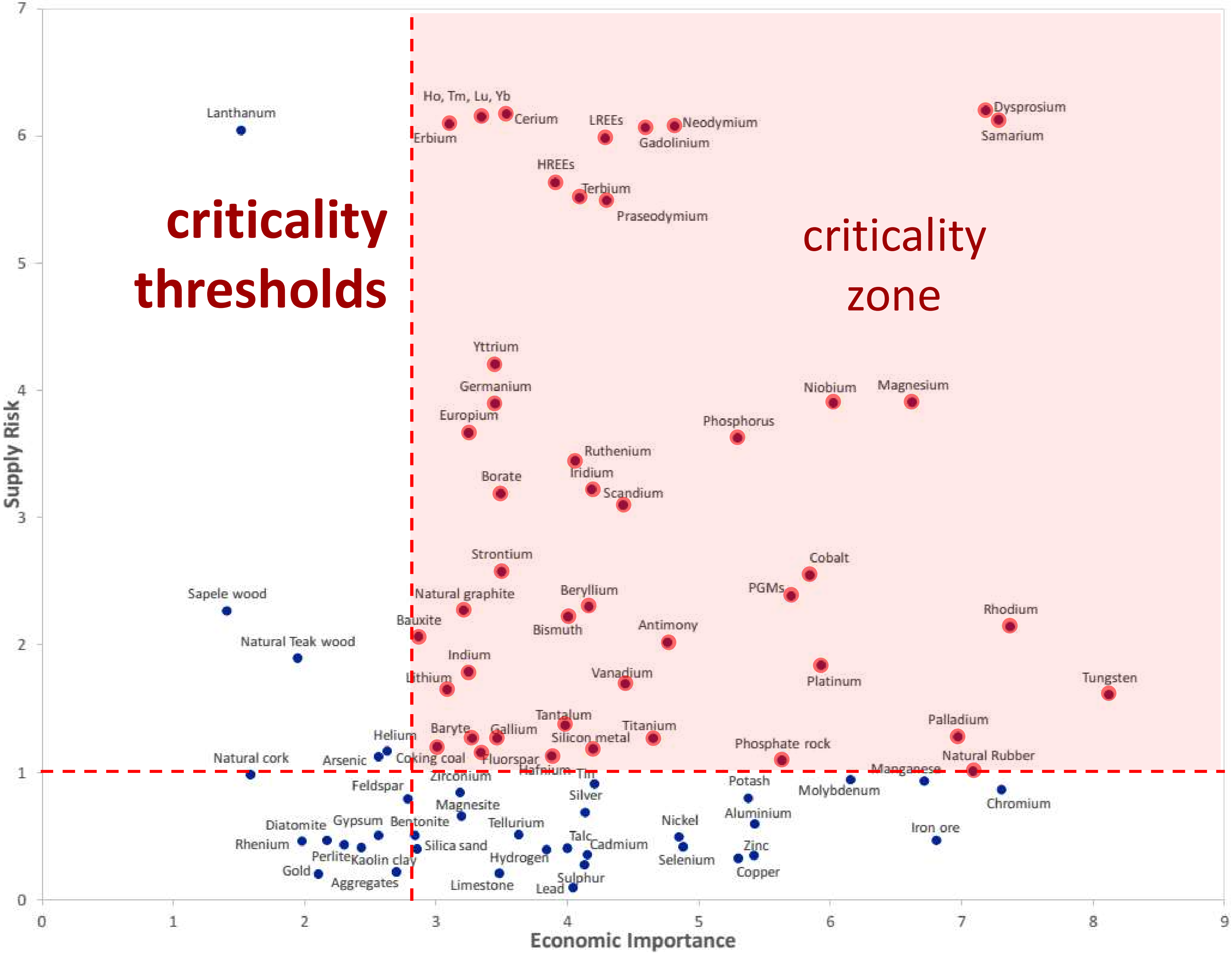

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criticality thresholds

(we don't know how they are determined)

«The decision of thresholds is perhaps the most sensible element in the context of the EU policies, and DG GROW (i.e. Directorate-General) keeps this decision for itself.»

a co-author of the Report,
personal communication

«The determination of the threshold value is not a scientific excercise but can be motivated politically»

Schrijvers et al., Res. Conserv. Recycl. 155 (2020) 104617

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main result: CRMs list (for EU!)

Table 5: 2020 Critical raw materials for the EU

2020 Critical Raw Materials (30)

- Antimony
- Baryte
- Bauxite
- Beryllium
- Bismuth
- Borates
- Cobalt
- Coking Coal
- Fluorspar
- Gallium
- Germanium
- Hafnium
- HREEs
- Indium
- Lithium
- LREEs
- Magnesium
- Natural Graphite
- Natural Rubber
- Niobium
- PGMs
- Phosphate rock
- Phosphorus
- Scandium
- Silicon Metal
- Tantalum
- Titanium
- Tungsten
- Vanadium
- Strontium

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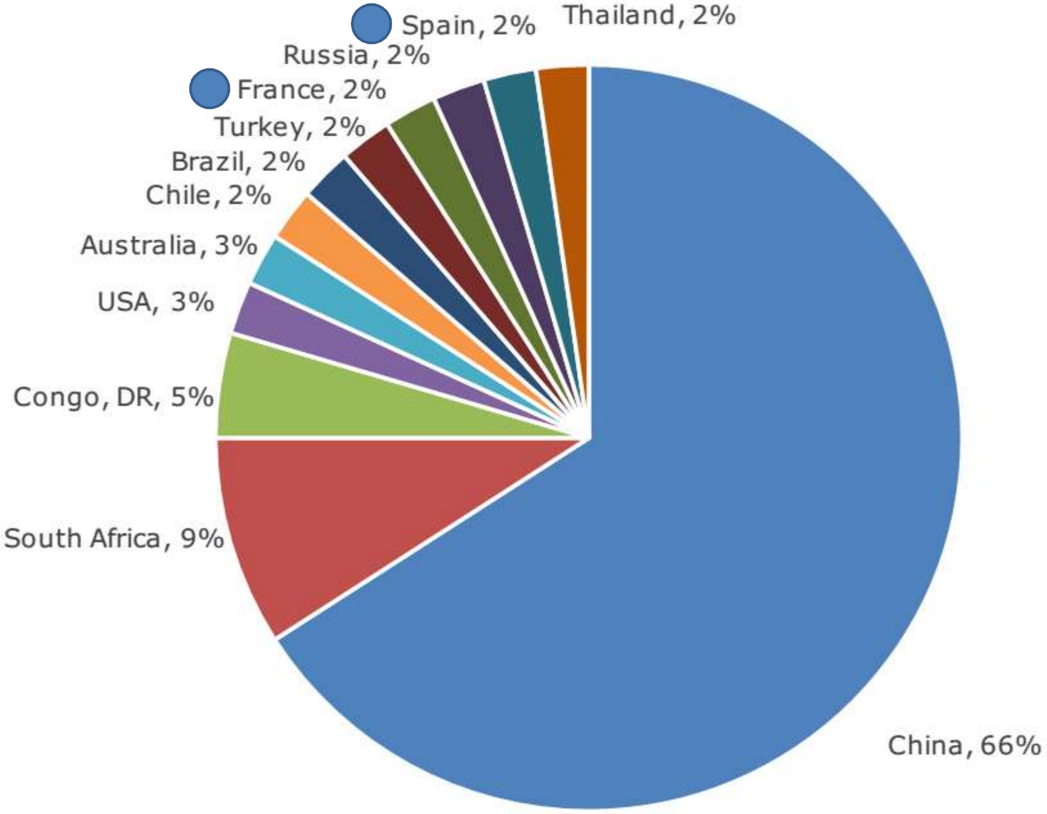
Figure 8: Main global suppliers of CRMs (based on number of CRMs supplied), average from 2012-2016



global suppliers of CRMs

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Figure B: Countries accounting for largest share of global supply of CRMs

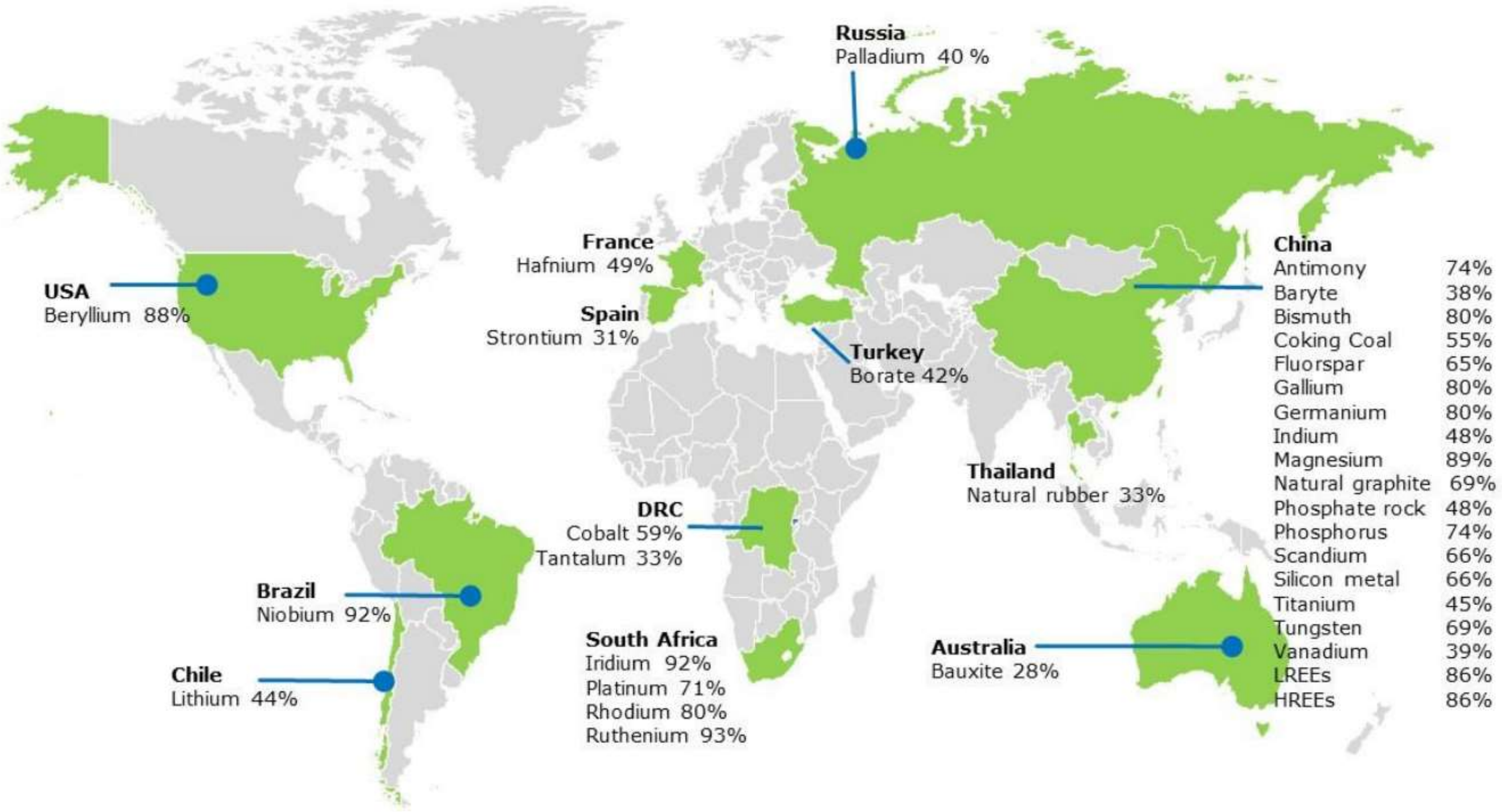

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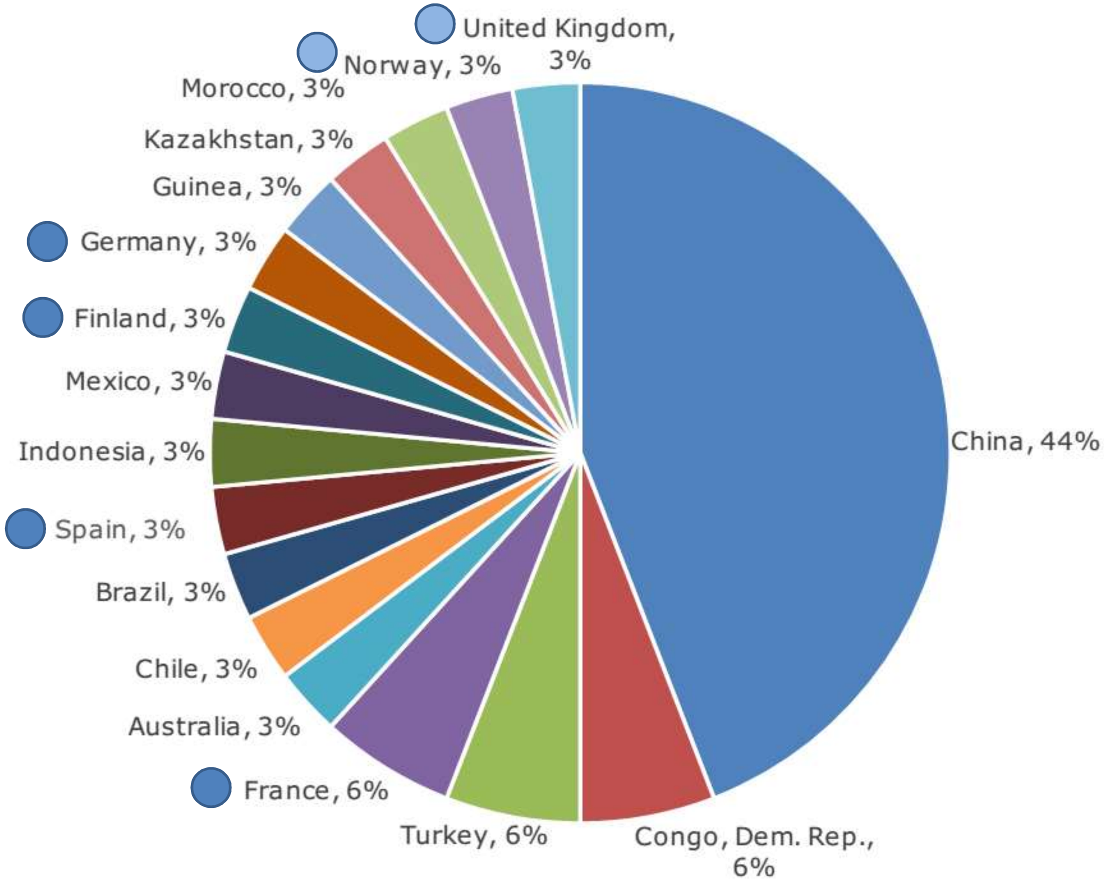
Figure 9: Main EU sourcing countries of CRMs (based on number of CRMs supplied), average from 2012- 2016 (REEs 2016-2018).



EU suppliers of CRMs

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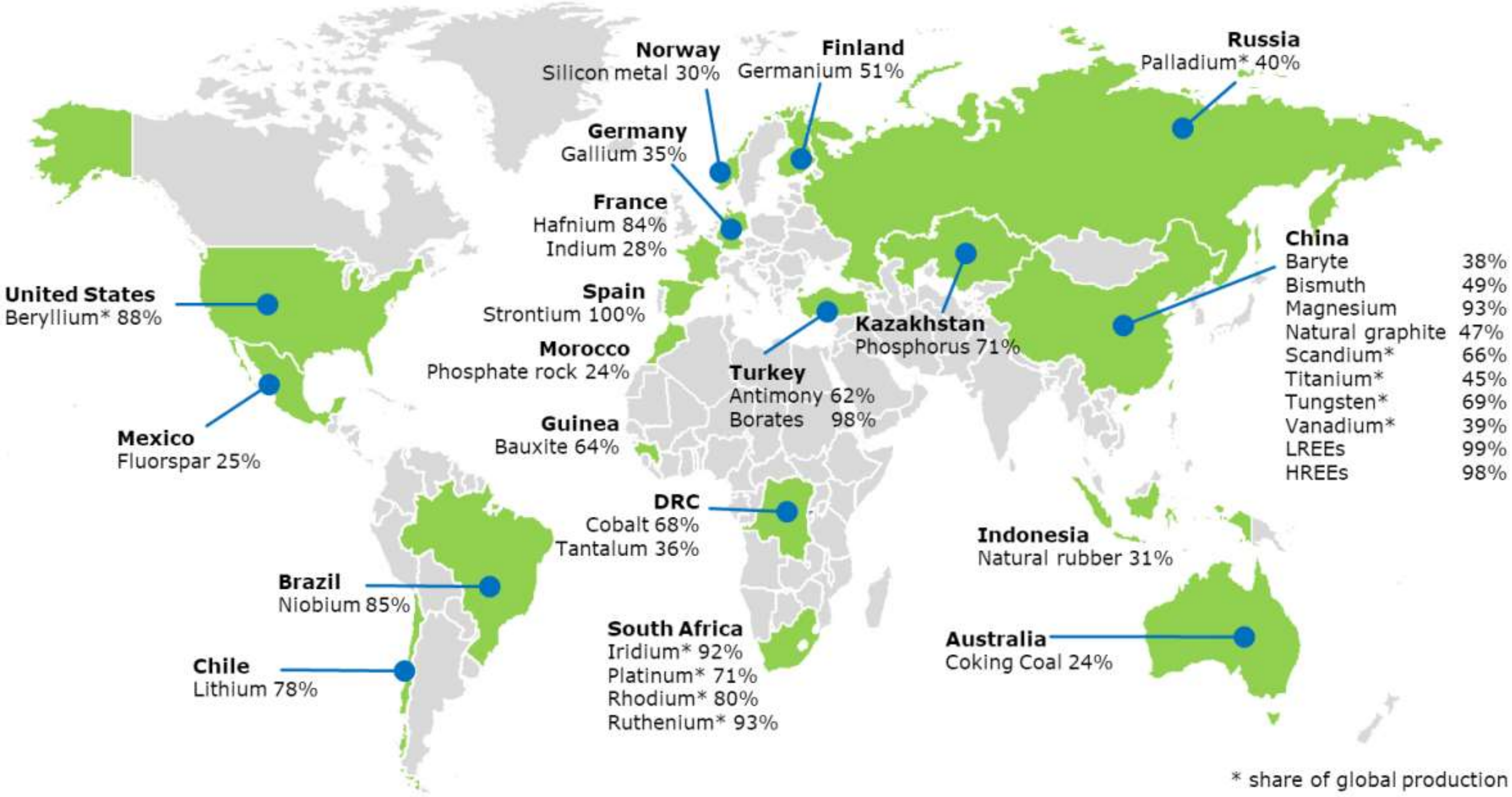
Figure E: Countries accounting for largest share of EU sourcing of CRMs



* share of global production

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EU countries
producing CRMs

Figure D: EU producers of CRMs, in brackets shares of global supply, 2012-2016[9]

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major output:

CRMs FACTSHEETS

819 pages

for each CRM

- Market analysis, trade and prices
- Uses and end-uses in EU
- Substitutes
- Geology
- Recycling
- Enviromental & Health issues
- Socio-economic issues
- (...)