LECTURE SCHEDULE

		Date	Topic
1.	Wed	07.09.	Course Introduction & Short Review of the Elements
2.	Fri	09.09.	Periodic Properties & Periodic Table & Main Group Elements (starts)
3.	Mon	12.09.	Short Survey of the Chemistry of Main Group Elements (continues)
4.	Fri	16.09.	Zn + Ti, Zr, Hf & Atomic Layer Deposition (ALD)
5.	Mon	19.09.	Transition Metals: General Aspects & Pigments
6.	Wed	21.09.	Redox Chemistry
7.	Fri	23.09.	Crystal Field Theory (Linda Sederholm)
8.	Mon	26.09.	V, Nb, Ta & Perovskites & Metal Complexes & MOFs & MLD
9.	Wed	28.09.	Cr, Mo, W & 2D materials & Mxenes & Layer-Engineering
10.	Fri	30.09.	Mn, Cu, Ru
11.	Mon	03.10.	Ag, Au, Pt, Pd & Catalysis (Antti Karttunen)
12.	Fri	07.10.	Lanthanoids + Actinoids & Luminescence
13.	Mon	10.10.	Mn, Fe, Co, Ni, Cu & Magnetism & Superconductivity
14.	Wed	12.10.	Resources of Elements & Rare/Critical Elements
15.	Fri	14.10.	Inorganic Materials Chemistry Research

EXAM: Oct. 18, 9:00-12:00

PRESENTATION TOPICS/SCHEDULE

Fri 16.09.	Zn:	Rautakorpi, Stenbrink & Hyvärinen
Mon 26.09.	Nb:	Souza, Rahikka & Tong
Wed 28.09.	Mo:	Alimbekova & Tran (Nhi)
	Ti:	Mäki & Israr
Fri 30.09.	Mn:	Tao & Song (Zonghang)
	Cu:	Marechal, Weppe & Ishtiaq
	Ru:	Järvinen & Verkama
Fri 07.10.	Eu:	Bardiau, Wolfsberger & Klingerhöfer
	Nd:	Helminen, Olsio & Keskimaula
Mon 10.10.	U:	Airas & Holopainen
Wed 12.10.	In:	Antila & Wallius
	Te:	Peussa & Heylen
Fri 14.10.	Co:	Song (Yutong) & Lone

QUESTIONS: Lecture 14

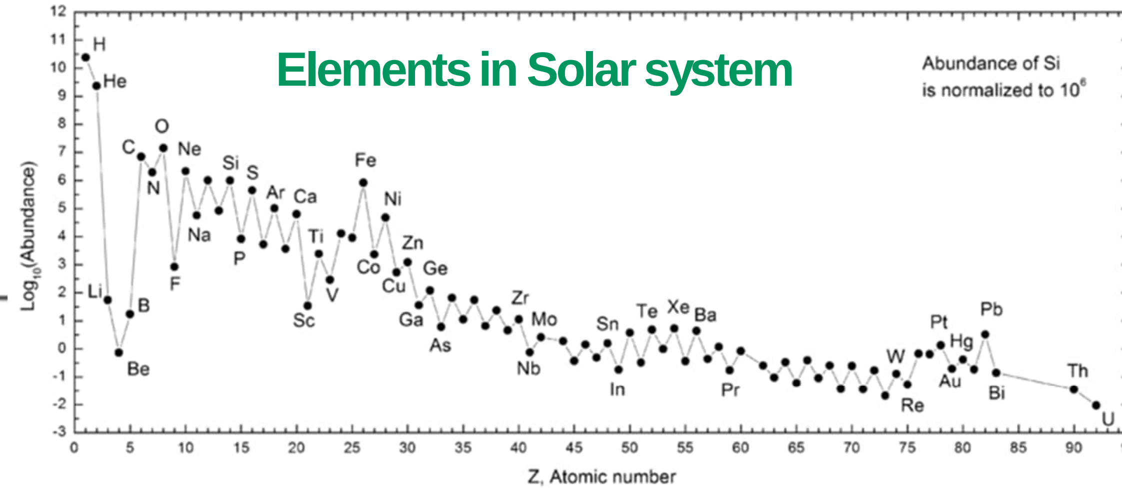
Select two examples of critical elements, and describe why the element is critical, and how you think would be the best way to mitigate the criticality.

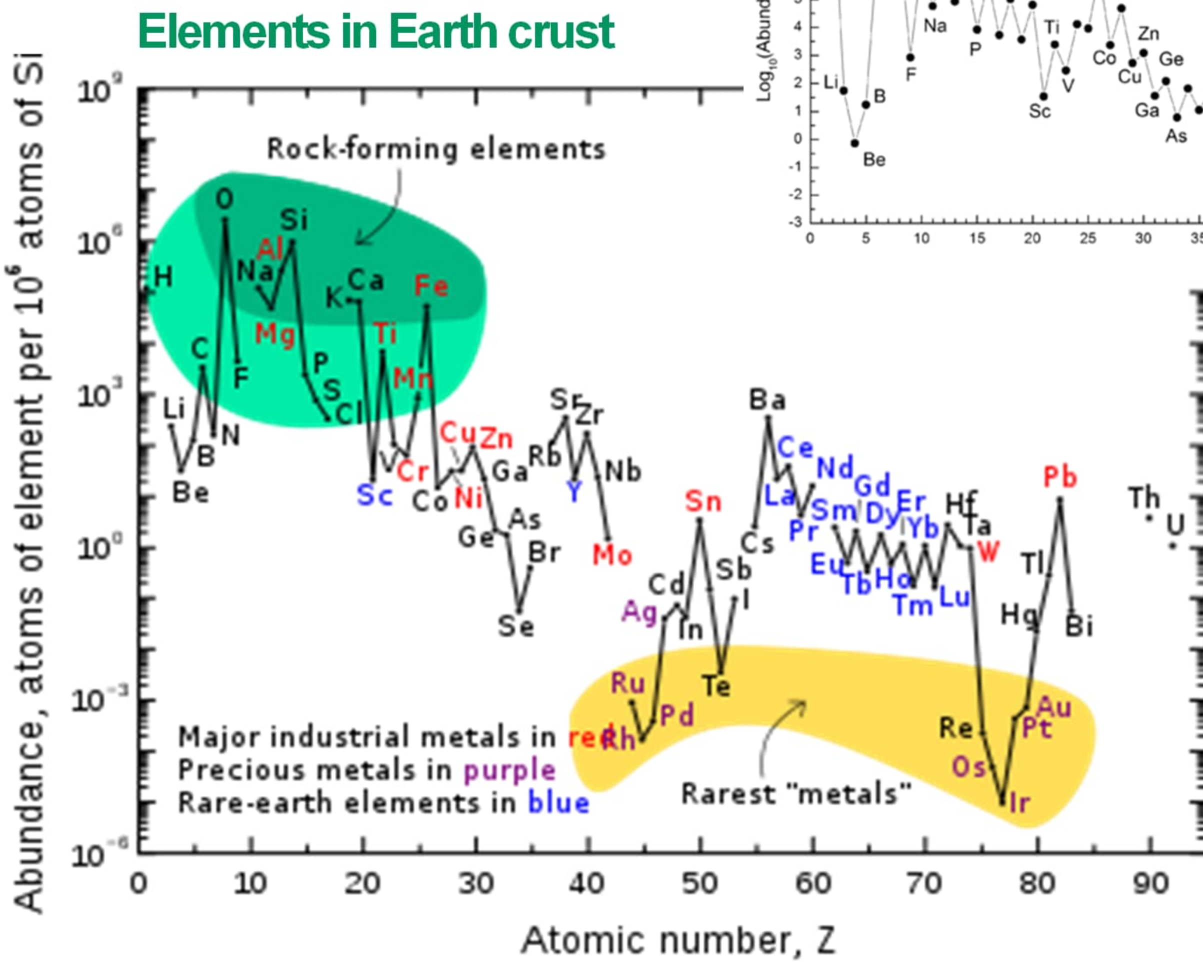
WHAT MAKES US CALL ELEMENTS RARE

- **Absolute abundance ?**
- **Accessible resources** (distribution, technical skills, etc.) ?
- **Availability** (politics, etc.) ?

WHAT MAKES US CALL ELEMENTS CRITICAL

- **Essential to human health ?**
- **Needed to make crucial/desired devices ?**
- **Needed to generate/store energy ?**
- **Needed but not readily available ?**

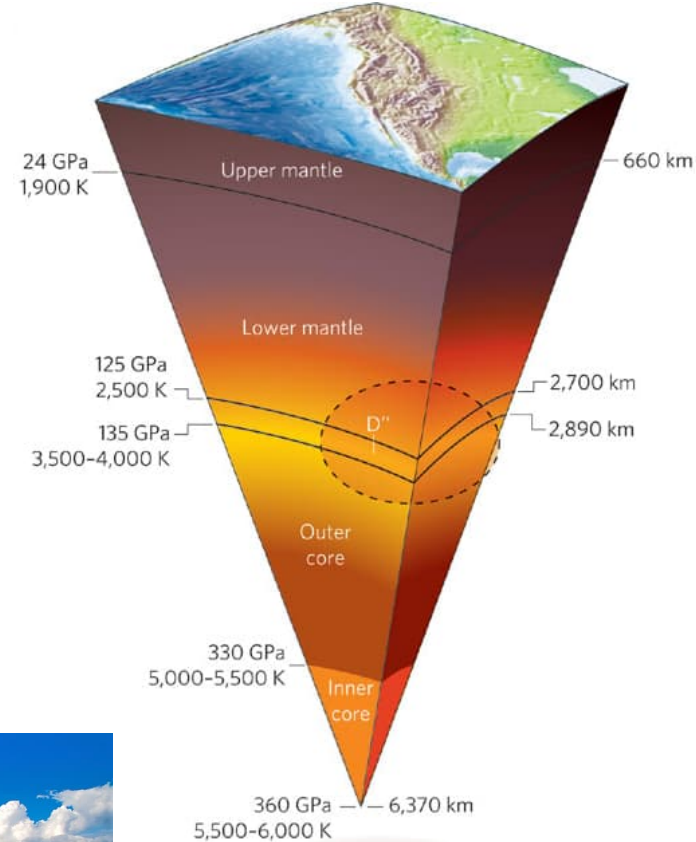




ABSOLUTE ABUNDANCE

ACCESSIBLE RESOURCES

- **Distribution of the elements**
- **Mineral variety**
- **Mining/separation technologies**
- ***Mponeng gold* mine in South Africa is the deepest mine in the world at a depth of ca. 4 km**



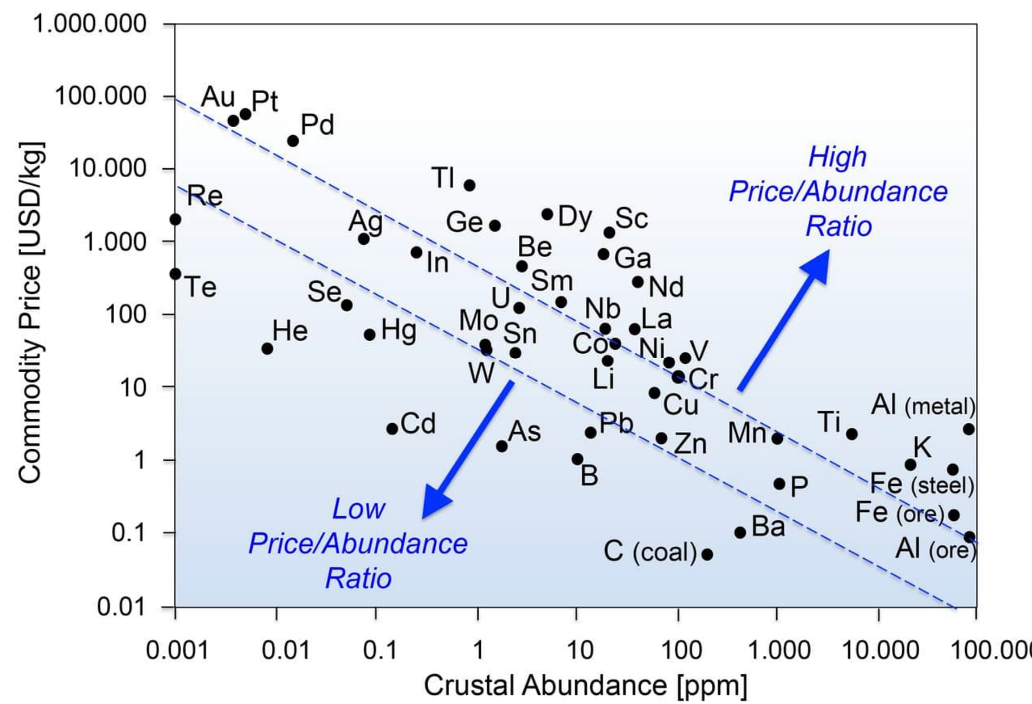
London metal exchange

	Official price
Aluminium	1,454.00
Aluminium Alloy	1,585.00
NASAAC	1,708.00
Copper	4,669.00
Lead	1,573.50
Nickel	8,955.00
Tin	14,660.00
Zinc	1,511.50
Cobalt	24,000.00
Molybdenum	10,800.00
Steel Billet	220.00

New York metal exchange

Top 10 Metals Products | Precious | Base | Ferrous | Other

Clearing	CME Globex	Floor	CME ClearPort	Product Name	Sub Group	Exchange	Volume	Open Interest
GC	GC	-	GC	Gold Futures	Precious	COMEX	187,052	428,212
SI	SI	-	SI	Silver Futures	Precious	COMEX	63,572	172,527
OG	OG	OG	OG	Gold Options	Precious	COMEX	25,194	1,515,879
PL	PL	-	PL	Platinum Futures	Precious	NYMEX	14,805	75,822
SO	SO	SO	SO	Silver Options	Precious	COMEX	6,498	165,506
PA	PA	-	PA	Palladium Futures	Precious	NYMEX	6,257	28,558
MGC	MGC	-	-	E-micro Gold Futures	Precious	COMEX	2,038	2,116
GCK	GCK	-	GCK	Gold Kilo Futures	Precious	COMEX	544	17
SIL	SIL	-	SIL	1,000-oz. Silver Futures	Precious	COMEX	206	2,003
QO	QO	-	-	miNY Gold Futures	Precious	COMEX	180	1,396



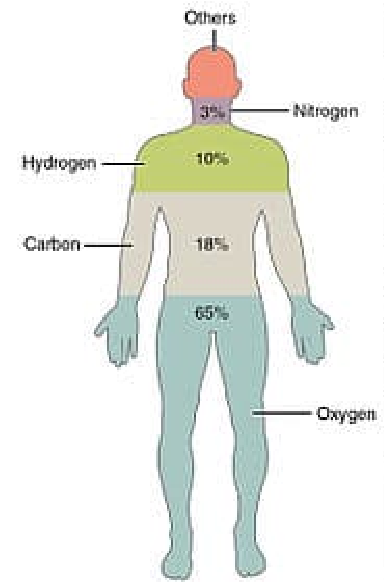
The Price

Price: affected by the rarity but also by fashion, speculation, politics, …

CRITICAL for Health & Wellbeing

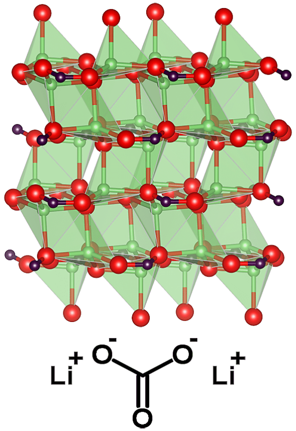
H																		He
Li	Be												B	C	N	O	F	Ne
Na	Mg												Al	Si	P	S	Cl	Ar
K	Ca		Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr		Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	*	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	**	Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Uut	Fl	Uup	Lv	Uus	Uuo
			*	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	
			**	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	

The four organic basic elements | Quantity elements | Essential trace elements | Possible structural or functional role in mammals

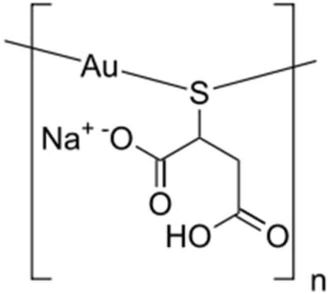


Supplement industry: $5 billion in sales

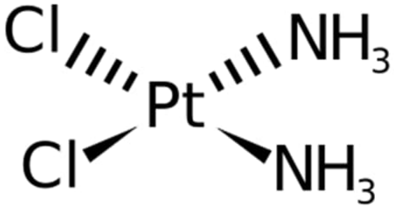
CRITICAL as MEDICINE



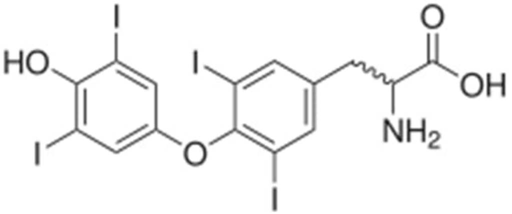
Li_2CO_3 for depression



Au for RA
(Rheumatoid Arthritis)



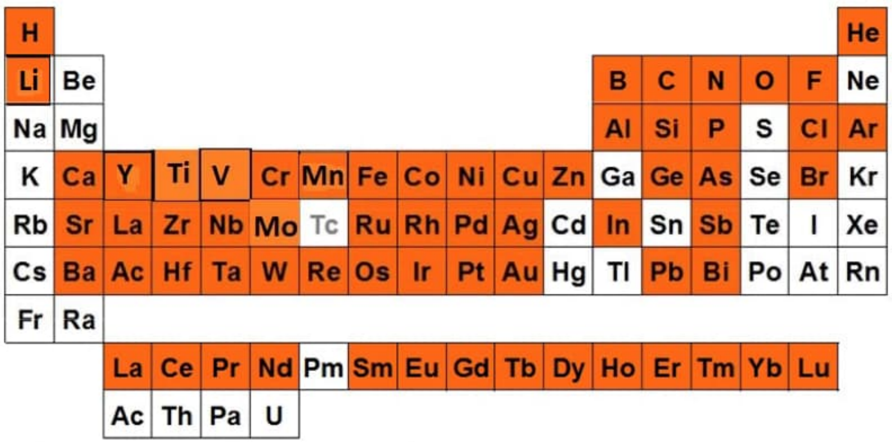
Cis-Pt complex for cancer



Iodine for thyroid hormones

Medicines are based not only on organics but on a much wider variety of elements

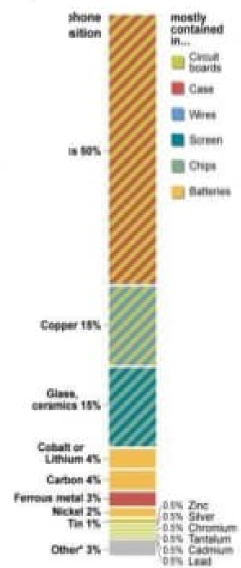
Almost the entire Periodic Table is being used ...



Elements used in the production of components for computers

CRITICAL
for
Modern Devices

Elements in a Mobile Phone



Roughly 40 different elements

H, Li, Be, C, N, O, F, Al, Si, S, Cl, K, Ca, Ti, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, As, Br, Sr, Y, Zr, Ru, Pd, Ag, Cd, In, Sn, Sb, Ba, Ta, W, Pt, Au, Hg, Pb, Bi, Nd.

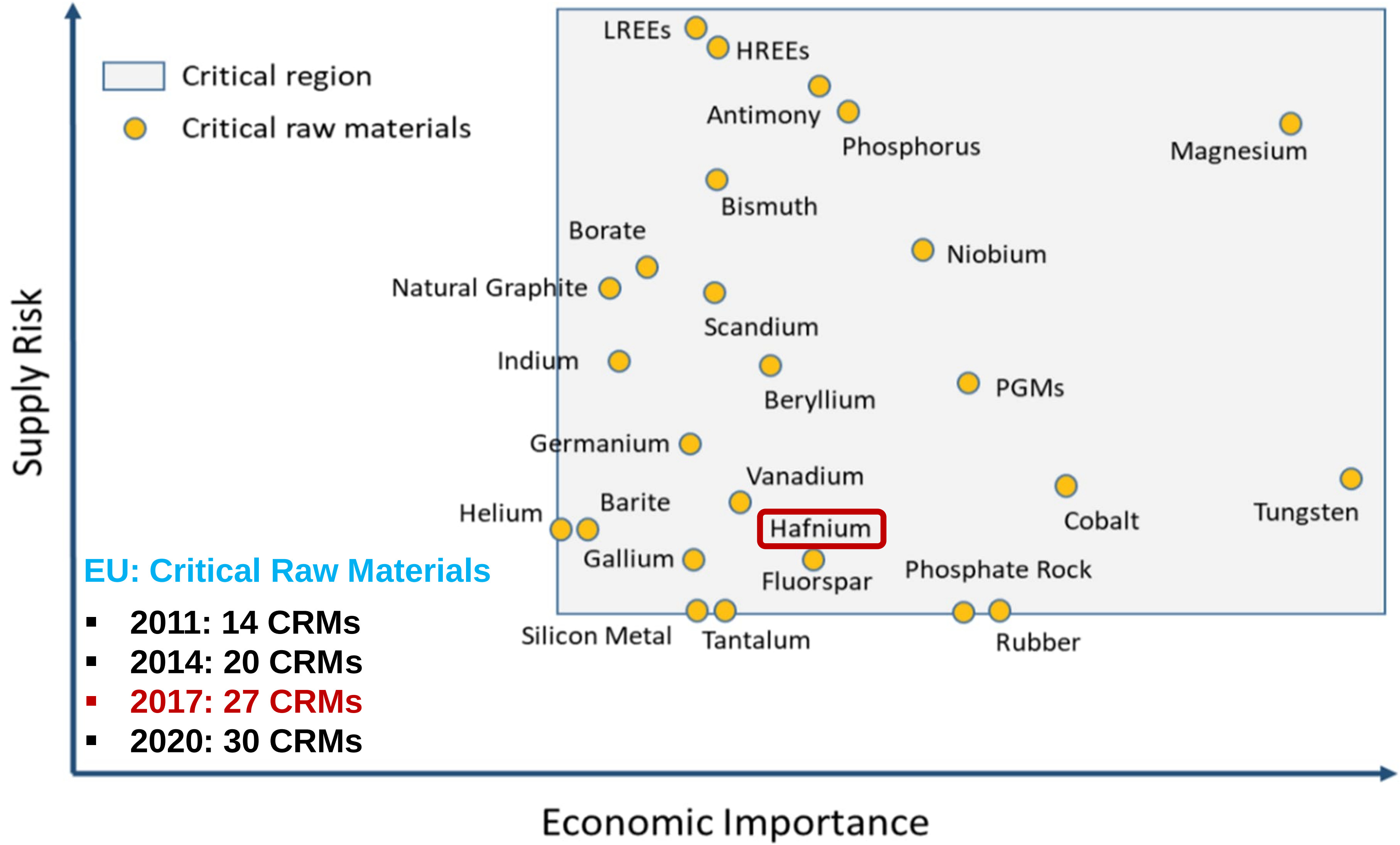
A mobile phone weighing 100 g contains:

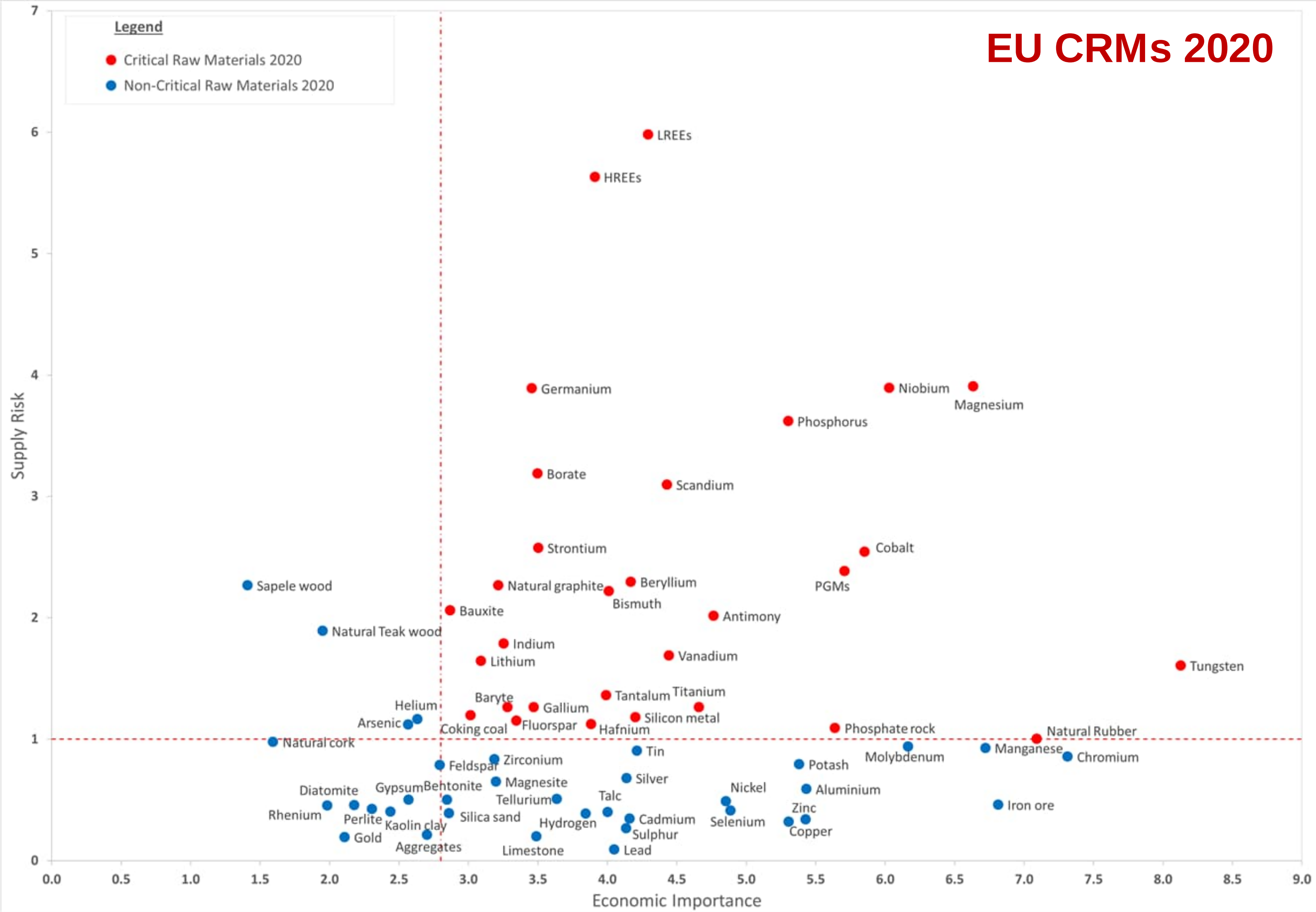
- 13.7 g of copper
- 0.189 g of silver
- 0.028 g of gold
- 0.014 g of palladium

Source: Basel Convention, 2006; Lindholm (Nokia report), 2003

Courtesy of Dr Mike Pitts
Sustainability Manager

https://rmis.jrc.ec.europa.eu/?page=crm-list-2020-e294f6

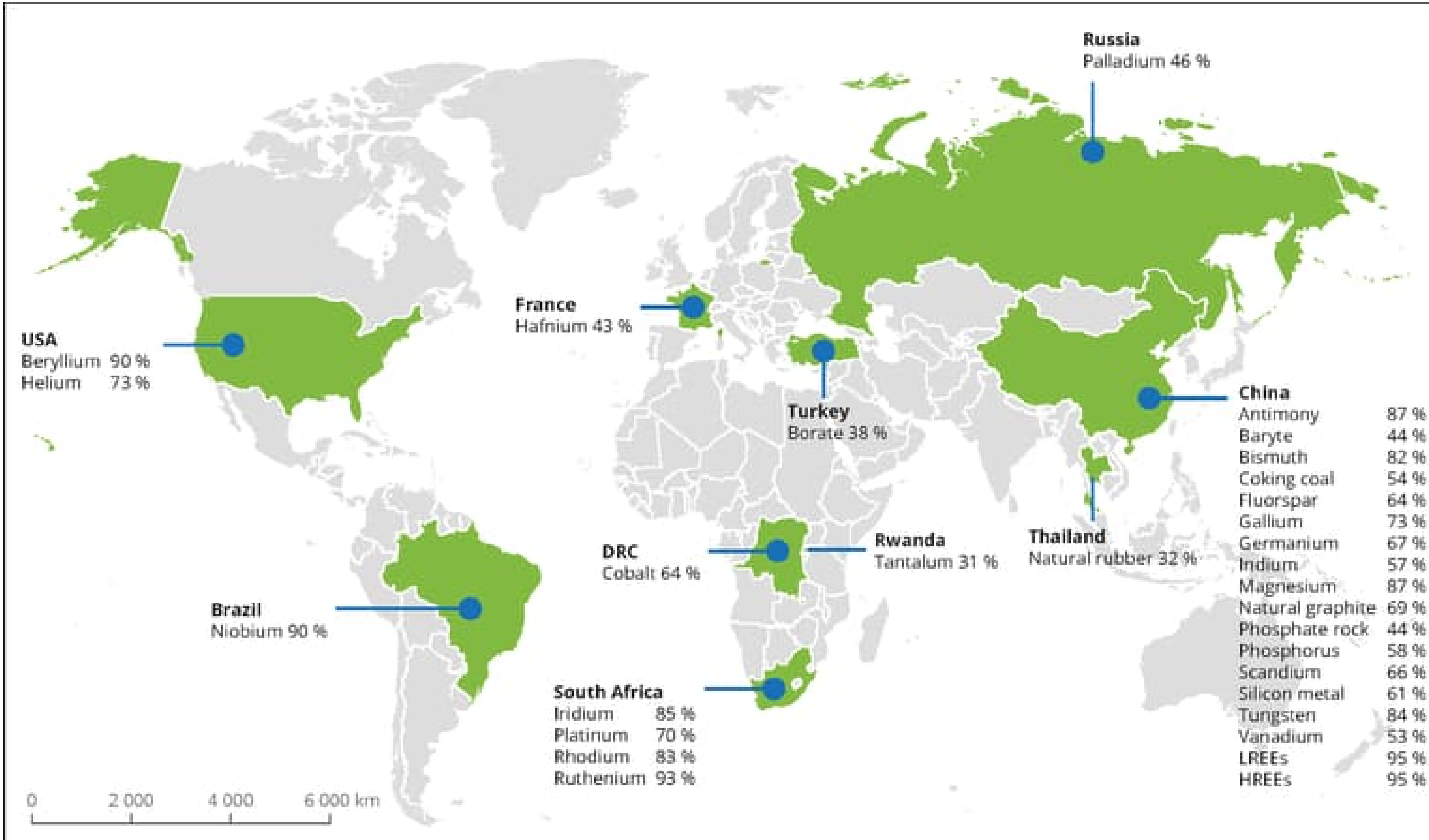




EU CRMs 2020
Legend
Critical Raw Materials 2020
Non-Critical Raw Materials 2020
Supply Risk
Economic Importance
0
1
2
3
4
5
6
7
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
9.0
LREEs
HREEs
Germanium
Niobium
Magnesium
Phosphorus
Borate
Scandium
Strontium
Cobalt
PGMs
Sapele wood
Natural graphite
Beryllium
Bismuth
Bauxite
Antimony
Natural Teak wood
Indium
Lithium
Vanadium
Tungsten
Baryte
Tantalum
Titanium
Helium
Gallium
Silicon metal
Arsenic
Coking coal
Fluorspar
Hafnium
Phosphate rock
Natural Rubber
Natural cork
Tin
Molybdenum
Manganese
Chromium
Feldspar
Zirconium
Potash
Magnesite
Silver
Diatomite
Gypsum
Bentonite
Tellurium
Talc
Nickel
Aluminium
Iron ore
Rhenium
Perlite
Silica sand
Hydrogen
Cadmium
Selenium
Zinc
Kaolin clay
Sulphur
Copper
Gold
Aggregates
Limestone
Lead

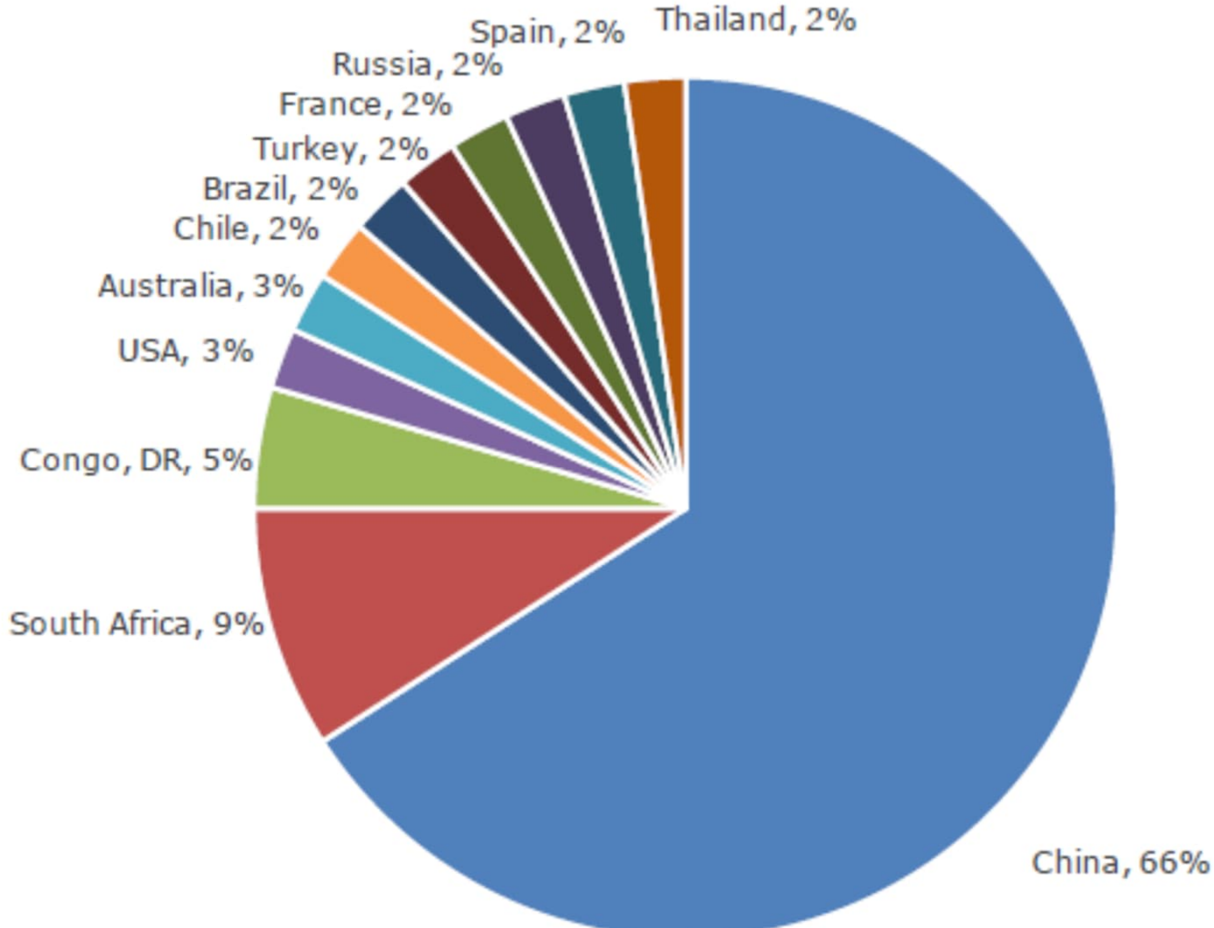
2020 Critical Raw Materials (new as compared to 2017 in bold)		
Antimony	Hafnium	Phosphorus
Baryte	Heavy Rare Earth Elements	Scandium
Beryllium	Light Rare Earth Elements	Silicon metal
Bismuth	Indium	Tantalum
Borate	Magnesium	Tungsten
Cobalt	Natural Graphite	Vanadium
Coking Coal	Natural Rubber	**Bauxite**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

WHICH COUNTRIES PRODUCE THE CRITICAL ELEMENTS/RAW MATERIALS ?



Reference data: ©ESRI

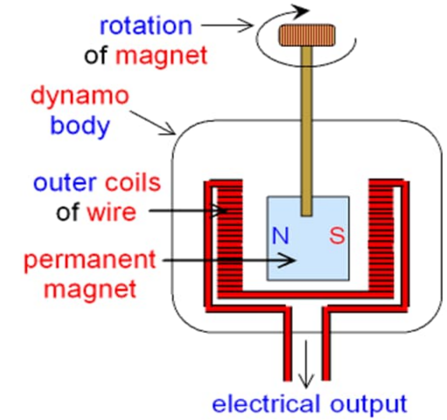
FROM WHICH COUNTRIES THE CRITICAL ELEMENTS/RAW MATERIALS COME TO EU CURRENTLY ?



MATERIALS for ENERGY

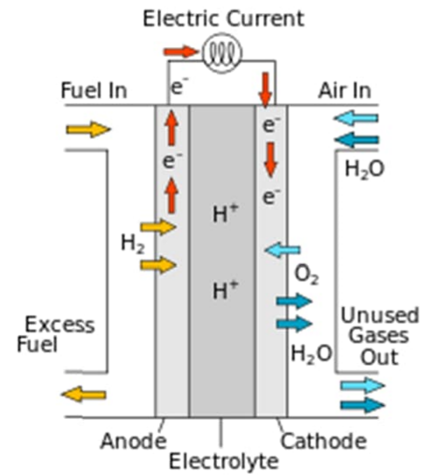
TURBINES: production of electricity from hydro, tidal, nuclear & fossil fuels

- *REs* (= *Ln*) for magnets
- (Cu), Ag, Au for wires



FUEL CELLS

- PEM: Pt, Pd; SOFC: Ni, Co, Ga, *Ln*

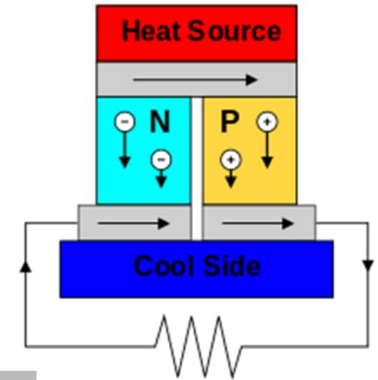


PHOTOVOLTAICS

- In, Ga, etc. …

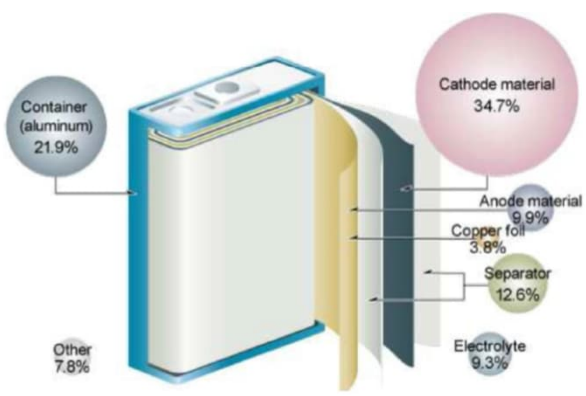
THERMOELECTRICS

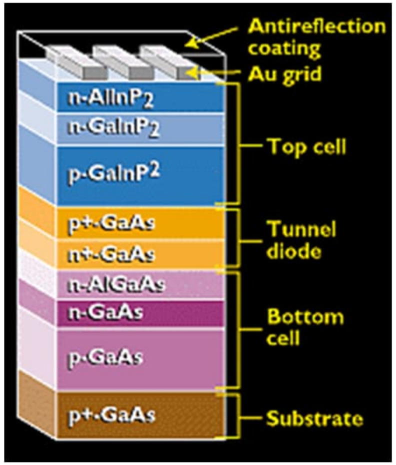
- Bi, Te, Se, Co, etc.

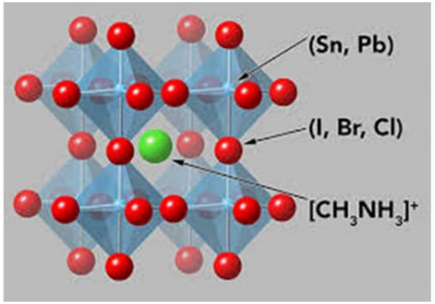


BATTERIES

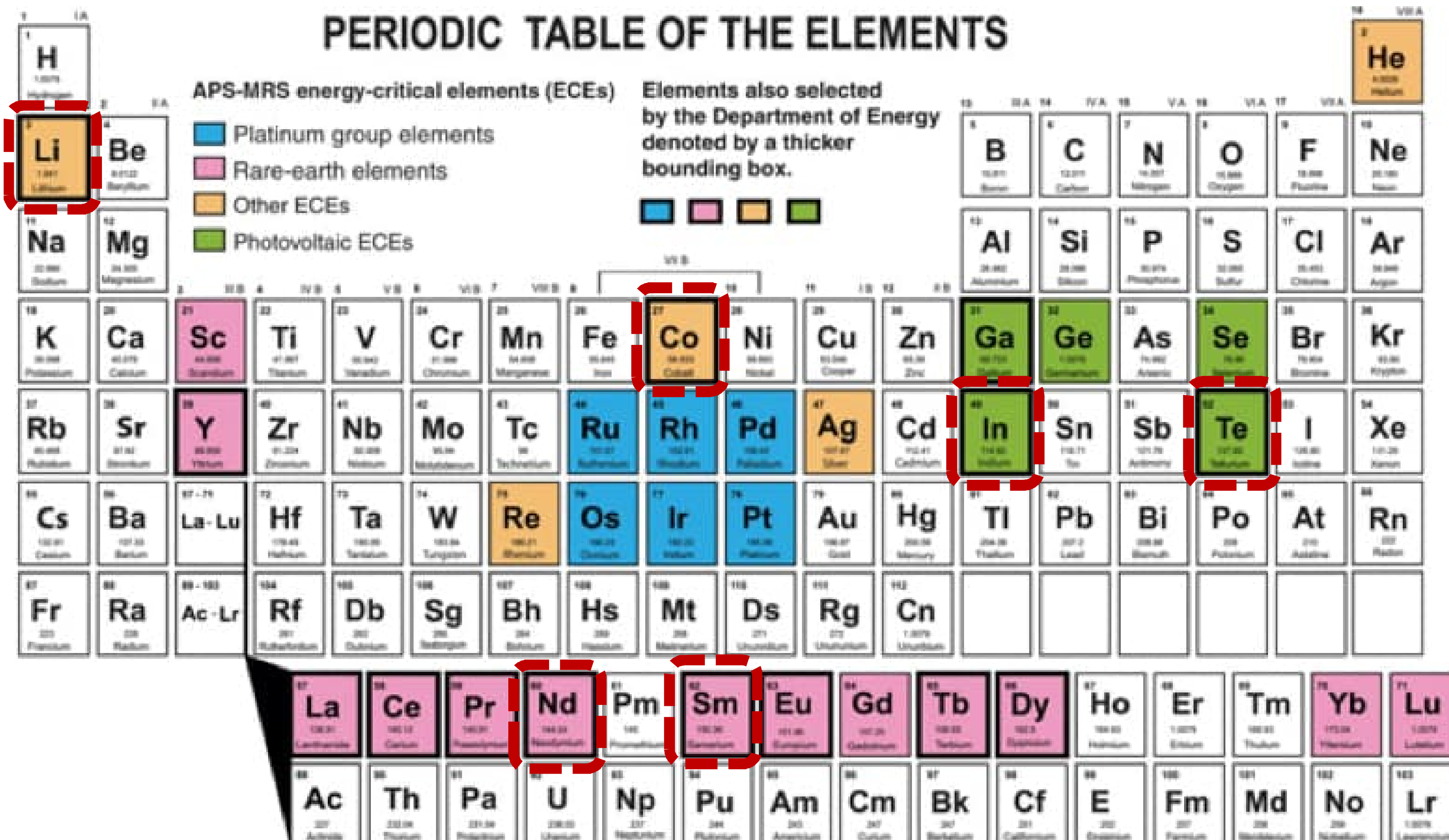
- Li, Co







ECE: Energy Critical Elements (by APS & MRS)



WHAT SHOULD WE DO ?

- **Re-use & Re-cycle**
- **Substitute critical by non-critical**

CONTRIBUTION of RECYCLING: TOO SMALL !

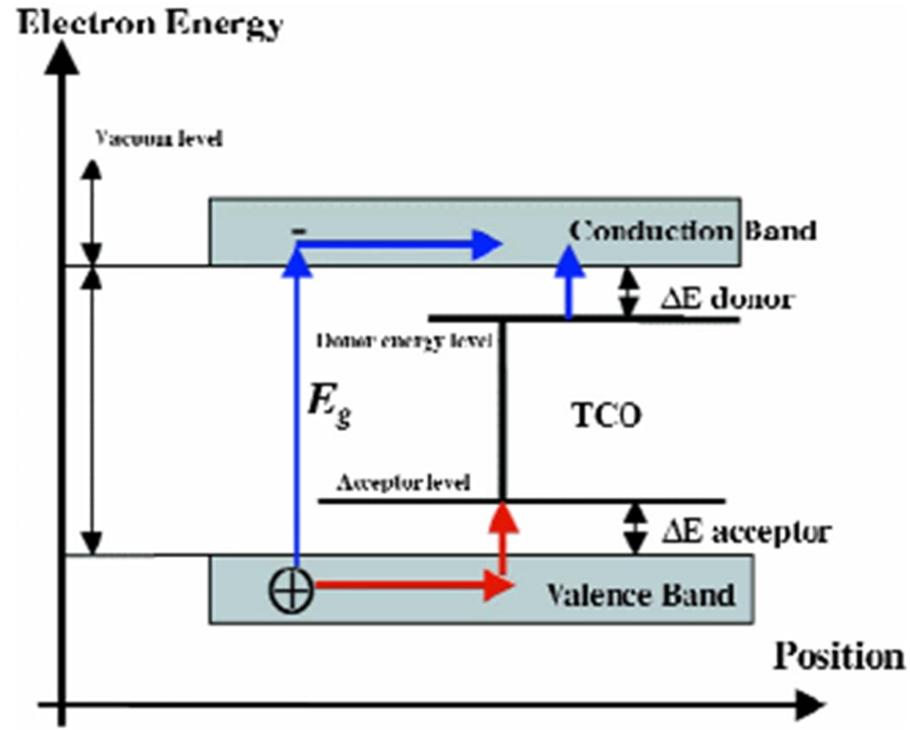
End-of-life recycling input rate (EOL-RIR) [%]

- > 50%
- > 25-50%
- > 10-25%
- 1-10%
- < 1%

H																	He 1%
Li 0%	Be 0%											B* 0.6%	C	N	O	F* 1%	Ne
Na	Mg 13%											Al 12%	Si 0%	P* 17%	S 5%	Cl	Ar
K* 0%	Ca	Sc 0%	Ti 19%	V 44%	Cr 21%	Mn 12%	Fe 24%	Co 35%	Ni 34%	Cu 55%	Zn 31%	Ga 0%	Ge 2%	As	Se 1%	Br	Kr
Rb	Sr	Y 31%	Zr	Nb 0%	Mo 30%	Tc	Ru 11%	Rh 9%	Pd 9%	Ag 55%	Cd	In 0%	Sn 32%	Sb 28%	Te 1%	I	Xe
Cs	Ba 1%	La-Lu[1]	Hf 1%	Ta 1%	W 42%	Re 50%	Os	Ir 14%	Pt 11%	Au 20%	Hg	Tl	Pb 75%	Bi 1%	Po	At	Rn
Fr	Ra	Ac-Lr[2]	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Uut	Fl	Uup	Lv	Uus	Uuo

[1]Group of Lanthanide	La 1%	Ce 1%	Pr 10%	Nd 1%	Pm	Sm 1%	Eu 38%	Gd 1%	Tb 22%	Dy 0%	Ho 1%	Er 0%	Tm 1%	Yb 1%	Lu 1%
[2]Group of Actinide	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

SUBSTITUTIONS



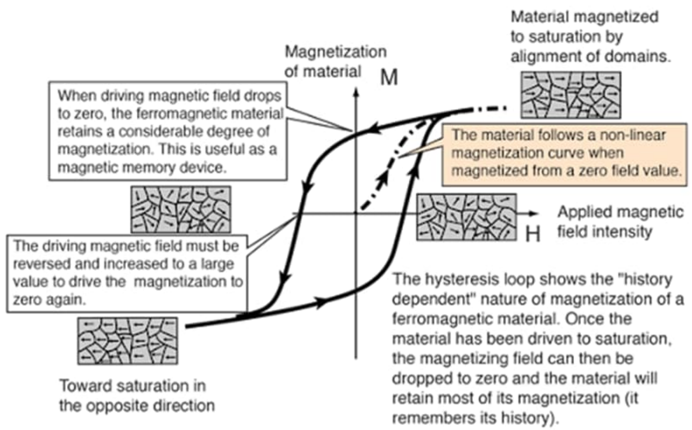
TRANSPARENT CONDUCTING OXIDES (TCOs)

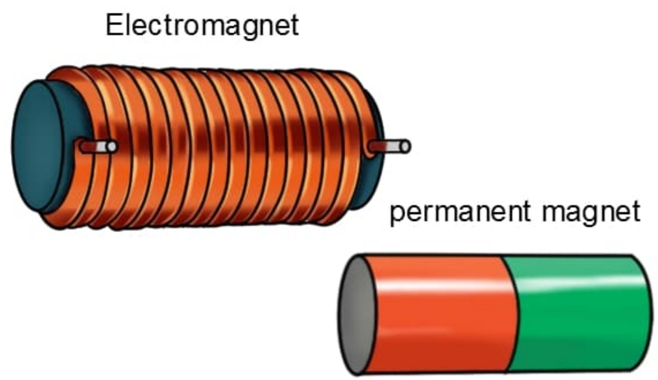
- ITO (In-Sn-O) is the current commercial leader, but the waste recovery is very much limited
- F-doped SnO_2 is a good candidate
- Al-doped ZnO would be a highly sustainable replacement

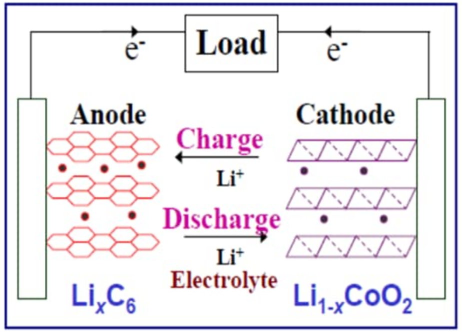
Strongest permanent magnets: $Nd_2Fe_{14}B$ & $SmCo_5$

"Non-Critical" ALTERNATIVES – Are there such ?

- **REQUIREMENTS: Curie temperature, Magnetization, Coersivity**
- **AlNiCo: "best of the rest"**
- **ε-Fe_2O_3 (difficult synthesis)**
- **Electromagnets**







EC: ethylene carbonate

DEC: dimethyl carbonate

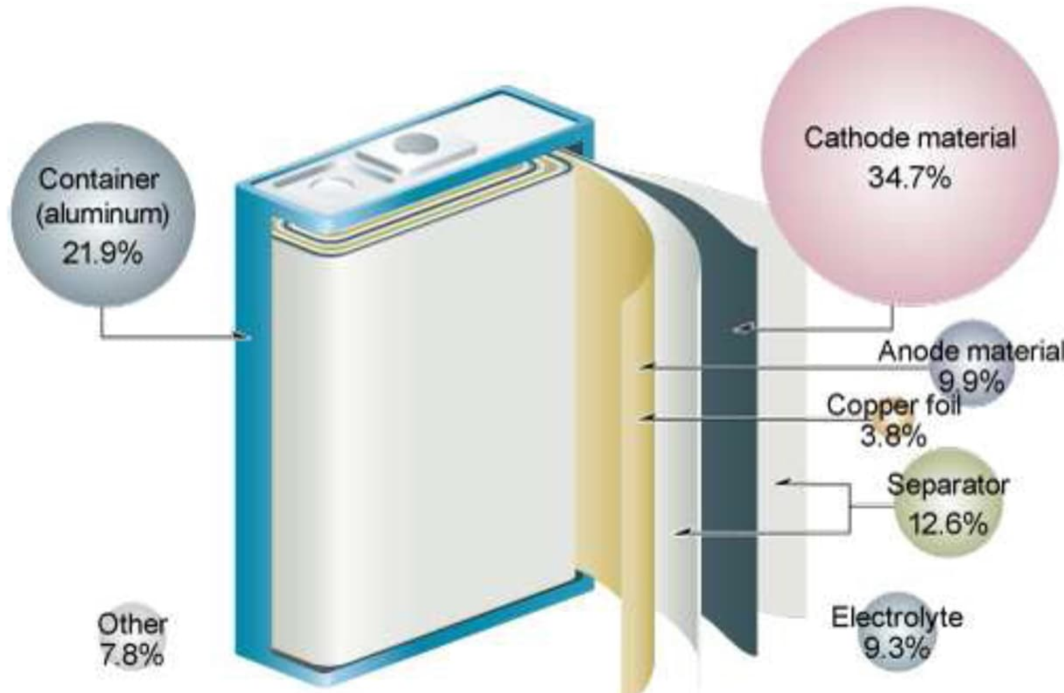
Li-ion battery
Cathode: $LiCoO_2$

Cell: (-) C | $LiPF_6$-(EC+DEC) | $LiCoO_2$ (+)

Cathode: $LiCoO_2 \underset{D}{\overset{C}{\rightleftarrows}} Li_{1-x}CoO_2 + xLi^+ + xe^-$

Anode: $6C + xLi^+ + xe^- \underset{D}{\overset{C}{\rightleftarrows}} Li_xC_6$

Total: $LiCoO_2 + 6C \underset{D}{\overset{C}{\rightleftarrows}} Li_{1-x}CoO_2 + Li_xC_6$



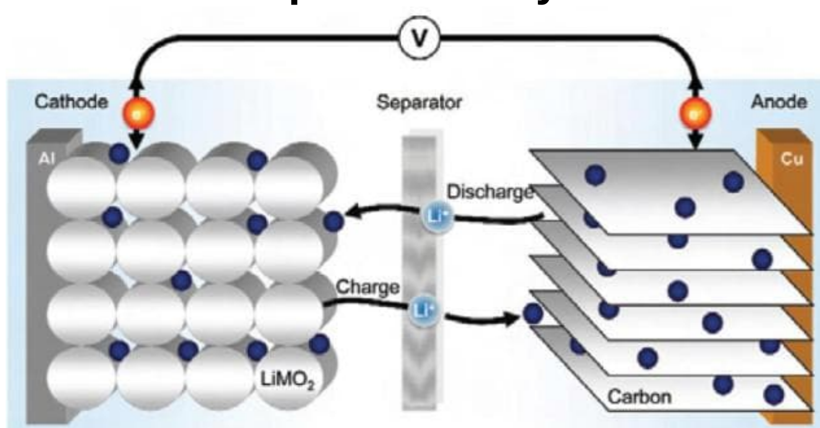
PRESENT Li-ion battery MATERIAL VARIETY

(under intense research)

CATHODE	$LiCoO_2$
	$Li(Co,Ni,Mn)O_2$ (raw mat., perfor.), $LiMn_2O_4$, $LiFePO_4$ (safety)
ANODE	Graphite
	Silicon (energy density), $Li_4Ti_5O_{12}$ (safety)
ELECTRO-	$LiPF_6$ + ethylene carbonate solution
LYTE	Solid electrolytes (safety)

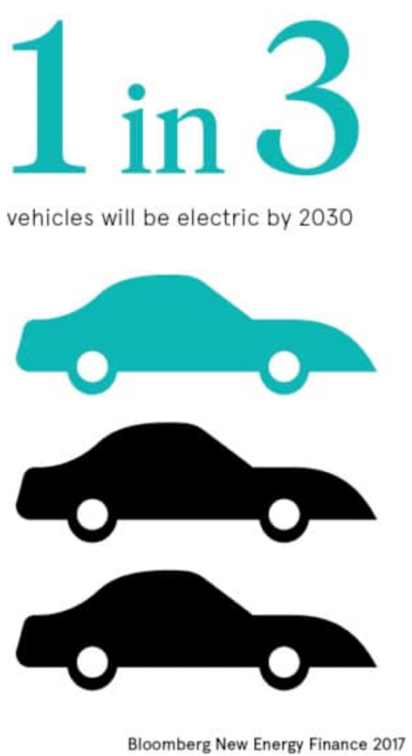
Liquid electrolyte

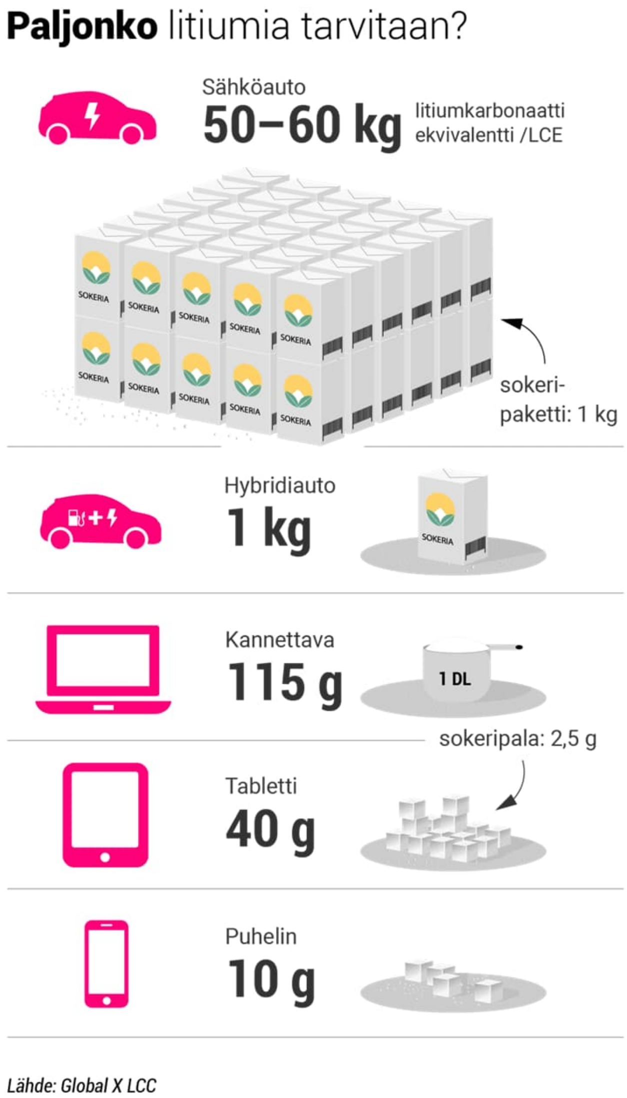
$LiCoO_2$



Graphite

In 2030 one third of cars will be electric !





How much metals needed in 600 kg battery:

- 8 kg Li
- 7 kg Co
- 50 kg Ni

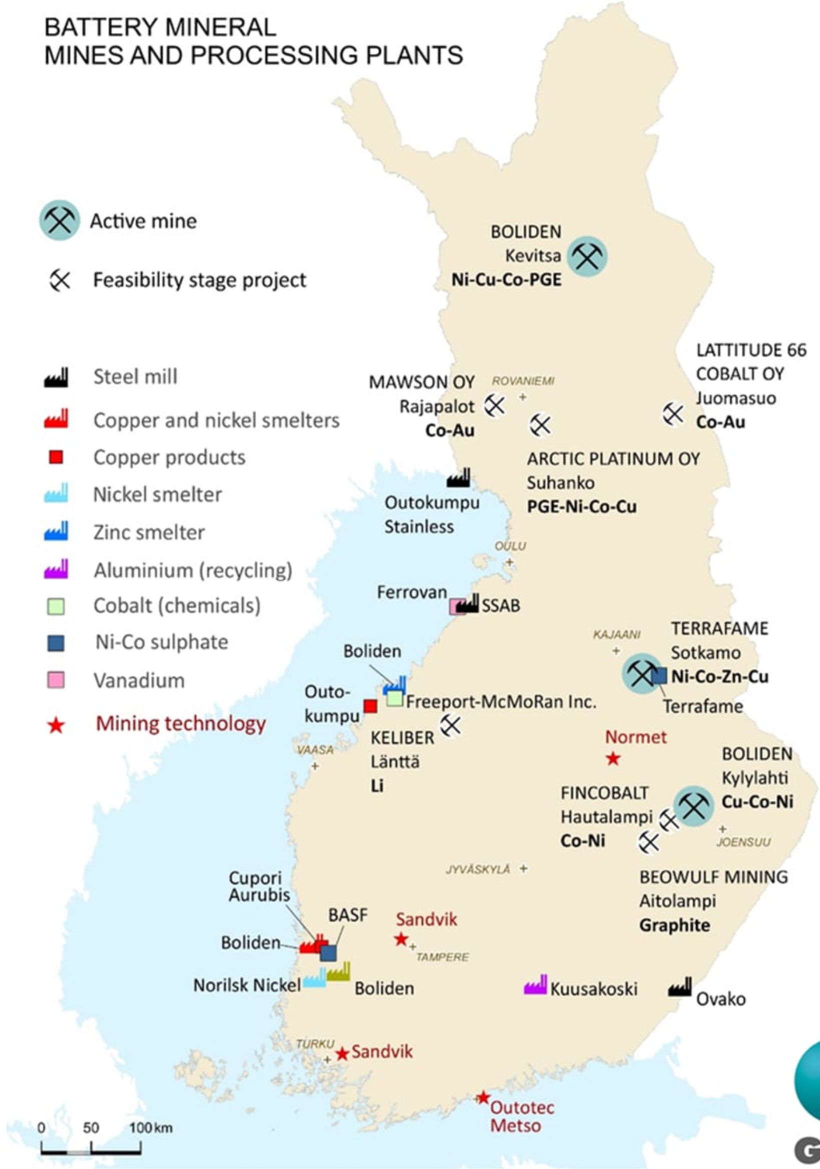
60 % of cobalt in the world is mined in Republic of Congo

Cobolt mining place in Congo close to Kasulo. Valokuvat: Siddharth Kara

Battery Minerals in FINLAND

- **Mining: Ni, Cu, Co**
- **Refining: Co (13 %), Ni, Cu**
- **Planned mining/refining: Li, Co (→ 2-4 %)**

"Ethical Cobalt/Metals"



Battery metals (Co, Li) from used batteries

Prof. Maarit Karppinen
Inorgaanic material chemistry

Prof. Mari Lundström
Hydrometallurgy

AALTO-CHEM COLLABORATION !

Electrode materials from recycled metals

Performance of batteries made from recycled metals

Prof. Tanja Kallio
Electrochemistry

C. Peng, K. Lahtinen, E. Medina, P. Kauranen, M. Karppinen, T. Kallio, B.P. Wilson & M. Lundström, Role of impurity copper in Li-ion battery recycling to $LiCoO_2$ cathode materials, *Journal of Power Sources* **450**, 227630 (2020).

Energy Live News

Finance & Markets

Finland to lead EU battery recycling research

It will cover the whole process starting from their collection and processing

By **Priyanka Shrestha**

Outotec tackling battery recycling with Aalto University and Business Finland

Posted by Paul Moore on 1st November 2018

The European Commission has invited Finland to coordinate the research related to recycling in the battery industry. Outotec will lead the project together with Aalto University's Department of Chemical and Metallurgical Engineering. Business Finland, a public research funding agency, is also strongly involved in advancing the project.

Outotec and Aalto University to coordinate European research related to recycling in the battery industry

Published: 01.11.2018

Company: **Outotec** Recommendation: **Lisää** Target price: **3.90 EUR** Share price: **3.74 EUR**

EMAIL FACEBOOK LINKEDIN TWITTER

0 0

OUTOTEC OYJ PRESS RELEASE NOVEMBER 1, 2018 AT 1:00 PM

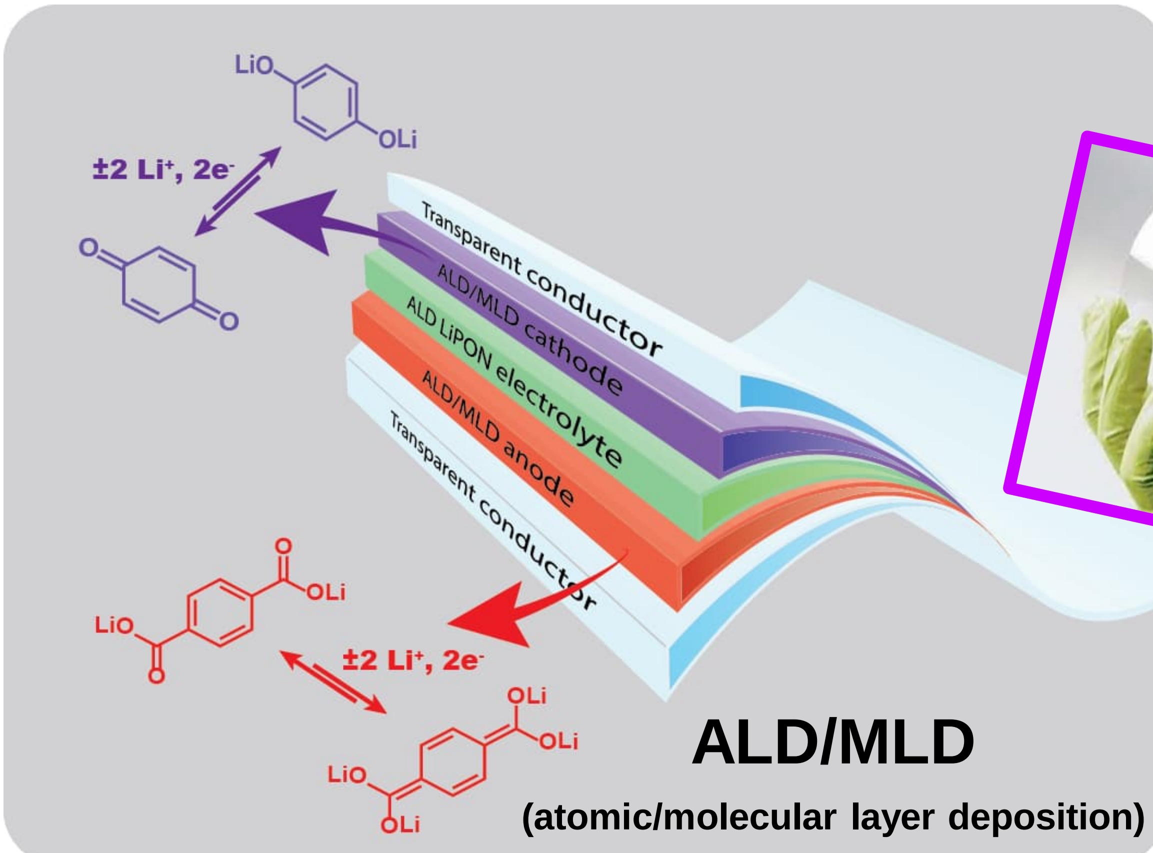
Outotec and Aalto University to coordinate European research related to recycling in the battery industry

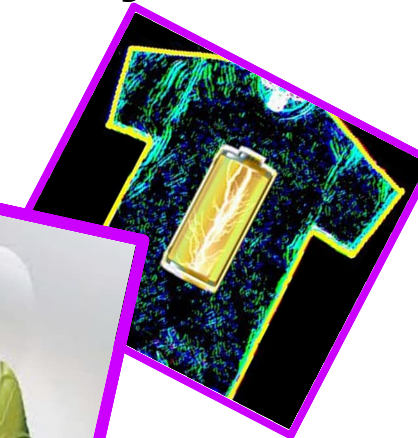
The European Commission has invited Finland to coordinate the research related to recycling in the battery industry. Outotec will lead the project together with Aalto University's Department of Chemical and Metallurgical Engineering. Business Finland, a public research funding agency, is also strongly involved in advancing the project.

Due to the rapidly growing demand for electric cars, the recycling of battery raw materials and equipment will become ever more important. The European Commission has compiled a

Key figures	2017	2018e	2019e
Turnover	1 143,8	1 335,4	1 430,4
Growth rate	8,1%	16,8%	7,1%
EBIT	26,0	-41,7	95,2
EBIT margin	2,3%	-3,1%	6,7%
Adjusted EPS	-0,03	0,19	0,30

Flexible safe “metal-sparing” Li-organic battery





Aalto University
School of Engineering

TOYOTA

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