CRITICAL MINERALS AND MATERIALS FOR ENERGY TRANSITION

INDIAN INSTITUTE OF SCIENCE EDUCATION AND RESEARCH, KOLKATA
SUSTAINABILITY AND CHEMISTRY: A SYSTEMS APPROACH
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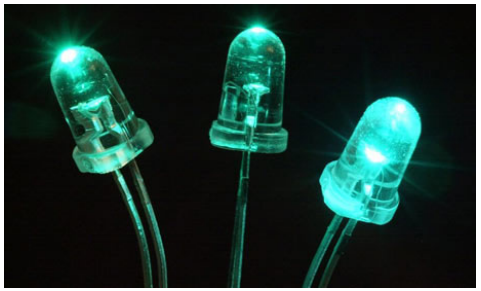
IISER PUNE

MINERALS AND METALS FOR CLEAN ENERGY

- Decarbonizing Mobility: Electrical Vehicles
- Decarbonizing Electricity
    - Hydrogen
    - Solar and Wind
    - Nuclear
- Information, Communication and Digital Technologies

ELEMENTS FOR CLEAN ENERGY

- ***Energy***
  - -Solar : Silicon, copper, Tin, Lead, Silver, Indium
  - -Perovskites : Lead
  - -CIGS : Indium and Selenium
  - -Cd/Te :Cadmium and Tellurium
  - -Wind : Copper, Iron, Nickel, Zinc, Neodymium, Dysprosium, Praseodymium, Samarium, Boron and Rhenium



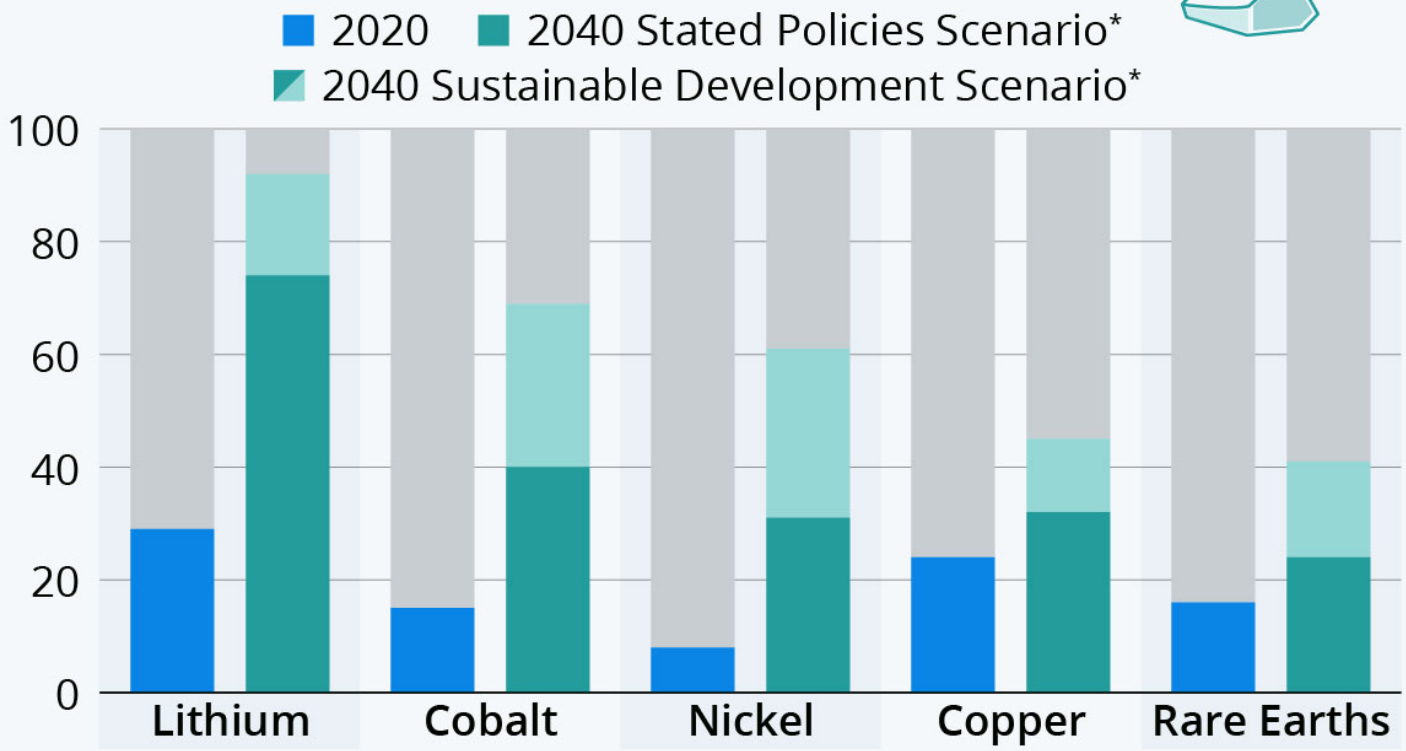
- ***Lighting***
  - - LED : Indium, Gallium, Lanthanum, Cerium, Europium, Terbium
- ***Electric Mobility***
  - - Batteries : Lithium, Cobalt, Manganese, Nickel, Aluminum, Copper
  - - EV : Neodymium, Samarium, Dysprosium, Boron

- ***Fuel Cells / Electrolysers*** : Platinum, Ruthenium, Iridium, Yttrium, Zirconium
- ***Electric Grid*** : Aluminum, Copper, Nickel, Yttrium, Zirconium, Lanthanum, Gold, Titanium
- ***Nuclear energy*** : Uranium, Thorium, Helium, Nickel, Hafnium, Zirconium, Berylium

Elements of Clean Energy, L. Reade, Chem. & Ind., 2011, 14

Clean Energy Transition Drives Demand For Minerals

Clean energy technologies' share of demand for selected minerals (in percent)



* forecast

Source: IEA

ELEMENTS NEEDED FOR PRODUCING CLEAN ENERGY

"There is no way of mass producing either wind turbines or silicon wafers for solar panels without the use of metals. Based on one calculation, we will need to mine more copper in the next 22 years than we have in the entirety of the past 5000 years of human history"

Ed Conway in "Material World"

DE-CARBONIZING THE ECONOMY IS A MATERIAL-INTENSIVE ENDEAVOUR

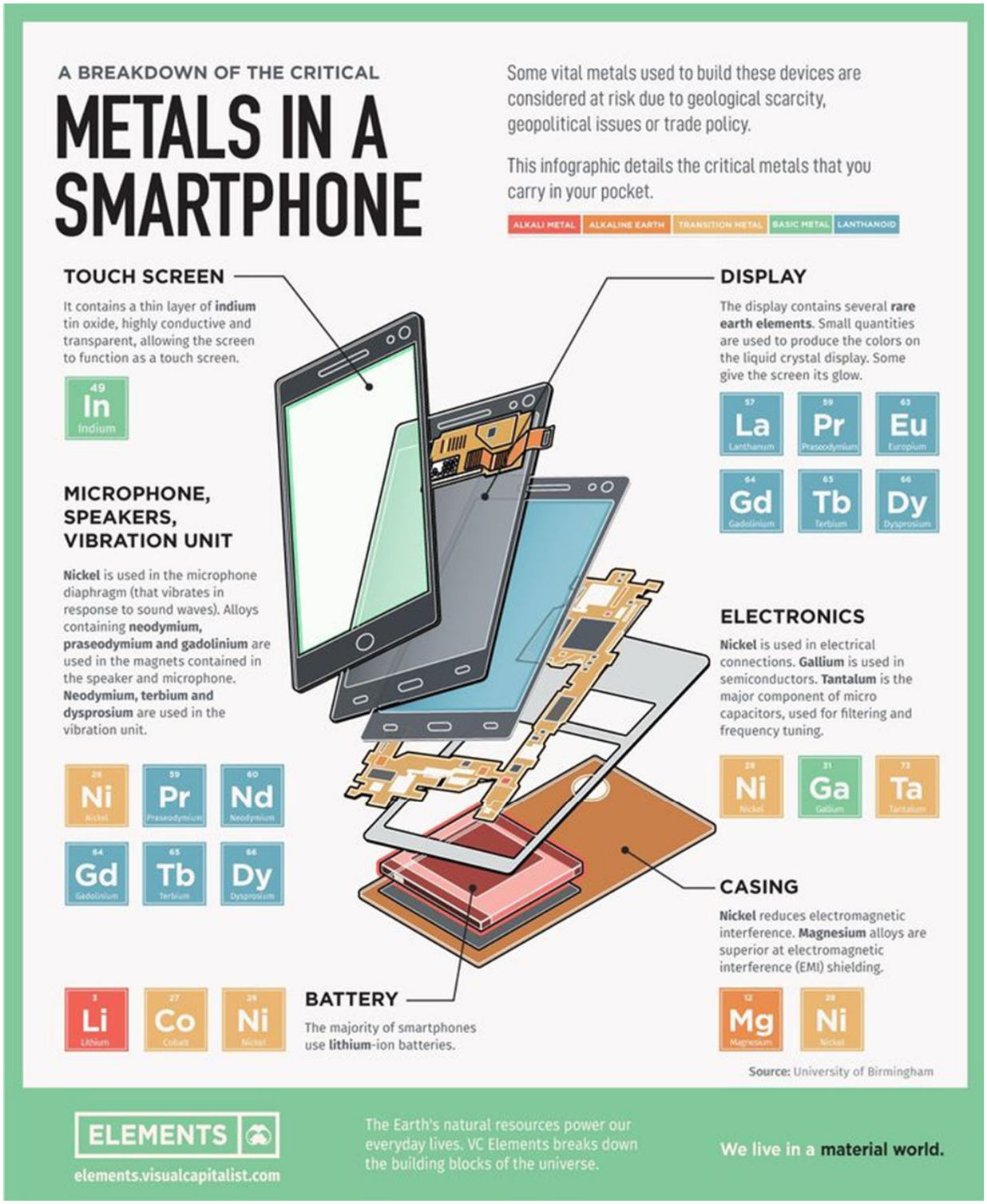
Drivers: Low-carbon energy, electric mobility and digital revolution

- An EV requires six times more mineral inputs (Cu, Mn, Ni, Co and Li) than a car running on IC engine
- Fuel Cell: Pt at cathode; 25 reactions /sec/site; Pt cost alone is $3000 per cost of an automobile engine
- One megawatt of solar energy will require 80 tons of aluminum and 0.05 tons of silver. Silver used for making solar panels at 5 % of current power demand will consume 50 % of silver produced across the world
- An on-shore wind farm requires nine times more mineral resources than a natural gas fired power station of the same capacity. One megawatt of wind turbine installation requires about 100 tons of steel, 400 tons of concrete, 7 tons of fiber glass and several other materials (polymers, copper, cast iron) etc.
- Compared to current technologies, the material intensity of solar energy is 1.5x, Offshore wind is 6.3 x, onshore wind is 2.4 x and EV is 1.2x

To meet COP 21 targets, mineral demand will grow 4x between 2020 and 2040; More than 3 billion tons of minerals and metals will have to be mined for decarbonization of the global economy

DECARBONIZING THE WORLD ECONOMY : THE PARADOX

- **The paradox**: The harder we push the agenda to contain climate change and transition to a cleaner economy, the more expensive the campaign becomes
- Many ”clean energy” solutions will require more “dirty” materials (steel, aluminum, cement). Decarbonizing these industries must be high on priority
- Public policies are driving the demand for metals and materials needed to build a cleaner economy. At the same time tightening environmental regulation is limiting supply and discouraging investment in mines, smelters or any other source that emits carbon



Element	grams
Fe	33
Si	13
Cr	7
W	0.90
Co+ Mo	0.070
Nd	0.160
Ag	0.090
Au	0.036

There is 100 x more gold and 10 X more W in a mobile phone than a high grade mineral resource

https://www.plymouth.ac.uk/news/scientists-use-a-blender-to-reveal-whats-in-our-smartphones; Smart Phones, Smart Chemistry, Chem Matters, April/May 2015, p.10

CONFLICT MINERALS : TANTULUM

A single smartphone has 40 milligrams of tantalum

- Ea… of Congo …a and Ug… n Mercenar…
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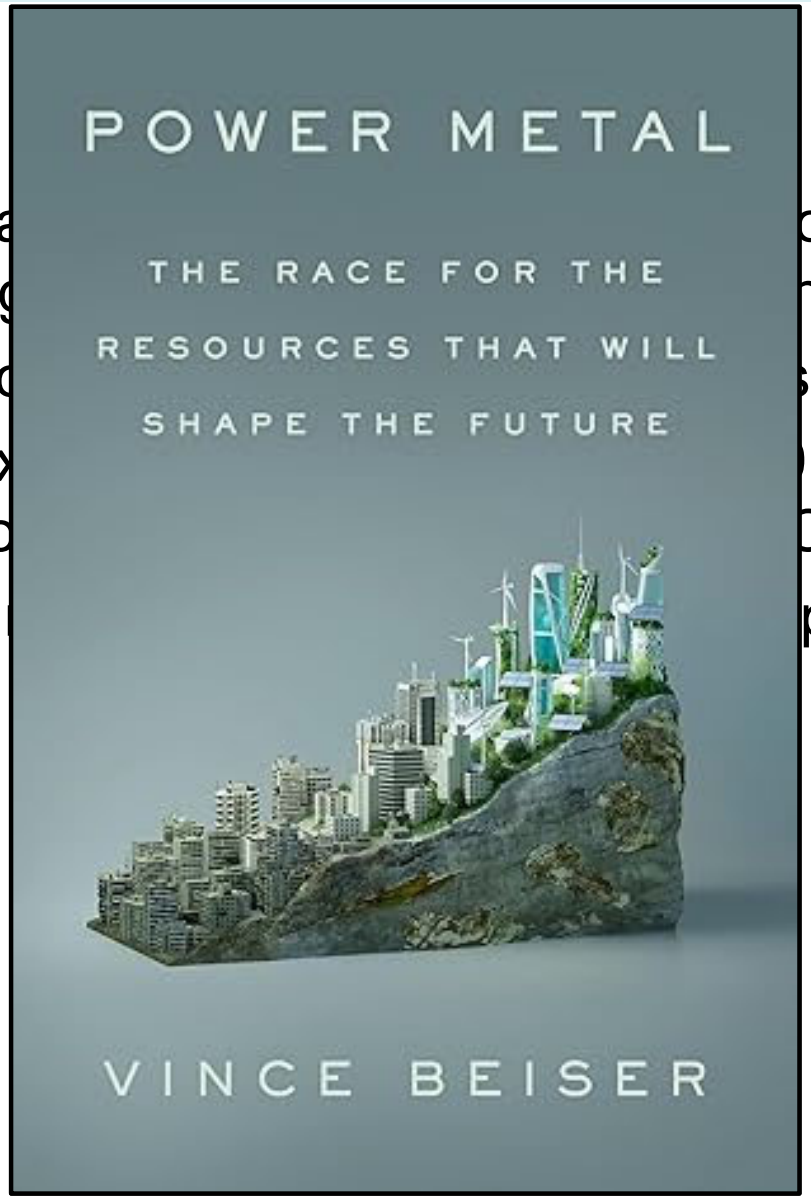


Rare Earths Bring Us Abundant Violence

Count the costs of the electro-digital future

We're living on the cusp of the electro-digital age. Digital tech, renewable energy and EVs are going to be central to our world, faster than we think. ***Power Metal: The Race for the Resources That Will Shape the Future*** by ***Vince Beiser*** lays out the enormous costs of this transformation. Environmental catastrophes, child labour, slavery, murder and geopolitical upheaval are part of the deal.

The raw materials from which our dematerialised digital lives are built include lithium, cobalt, nickel and gold, and exotic metals like indium, yttrium and neodymium. One iPhone requires 75 pounds of copper ore. Even to capture sunlight and air, we need machines – turbines, panels, charging stations, cables and batteries. By 2027, renewables are likely to be the largest source of electricity.

These metals are ripped from the earth, and mining can cause centuries-worth of damage, chemical runoffs and leaks, and dam failures. It's bitterly resisted by residents and indigenous groups around the world; anti-mining activists have been killed.

Electric cars have unstoppable momentum. In 2012, only 120,000 were sold annually. By 2022, people bought more than that in a week. This will reshape global power equations. If Saudi Arabia was central because of its petroleum resources, places like New Caledonia, Greenland, Bolivia, Congo and Afghanistan hold much-needed metal resources. They're sent to China for refining and processing, giving China a commanding role in this transition.

Today, environmental concerns have become more central. But the book points out that there is no benefit without a hidden cost – all we can hope is that this energy transition can be made more mindfully than the last. Global finance, the internet, satellite surveillance, oil transport, jet engines, television, GPS and emergency rooms all depend on rare earths.

Up till the 1990s, US and the West led rare earth mining, but then decided to ship heavy industry and its polluting effects to China and the East. As even China steps back from destructive mining, the dirty work is handed over to Myanmar, where brutal militias seize land from indigenous people. In Peru, Pakistan, Papua New Guinea, copper mining has brought violence, separatist movements and war. In Chile and South Africa, widespread criminal activity.

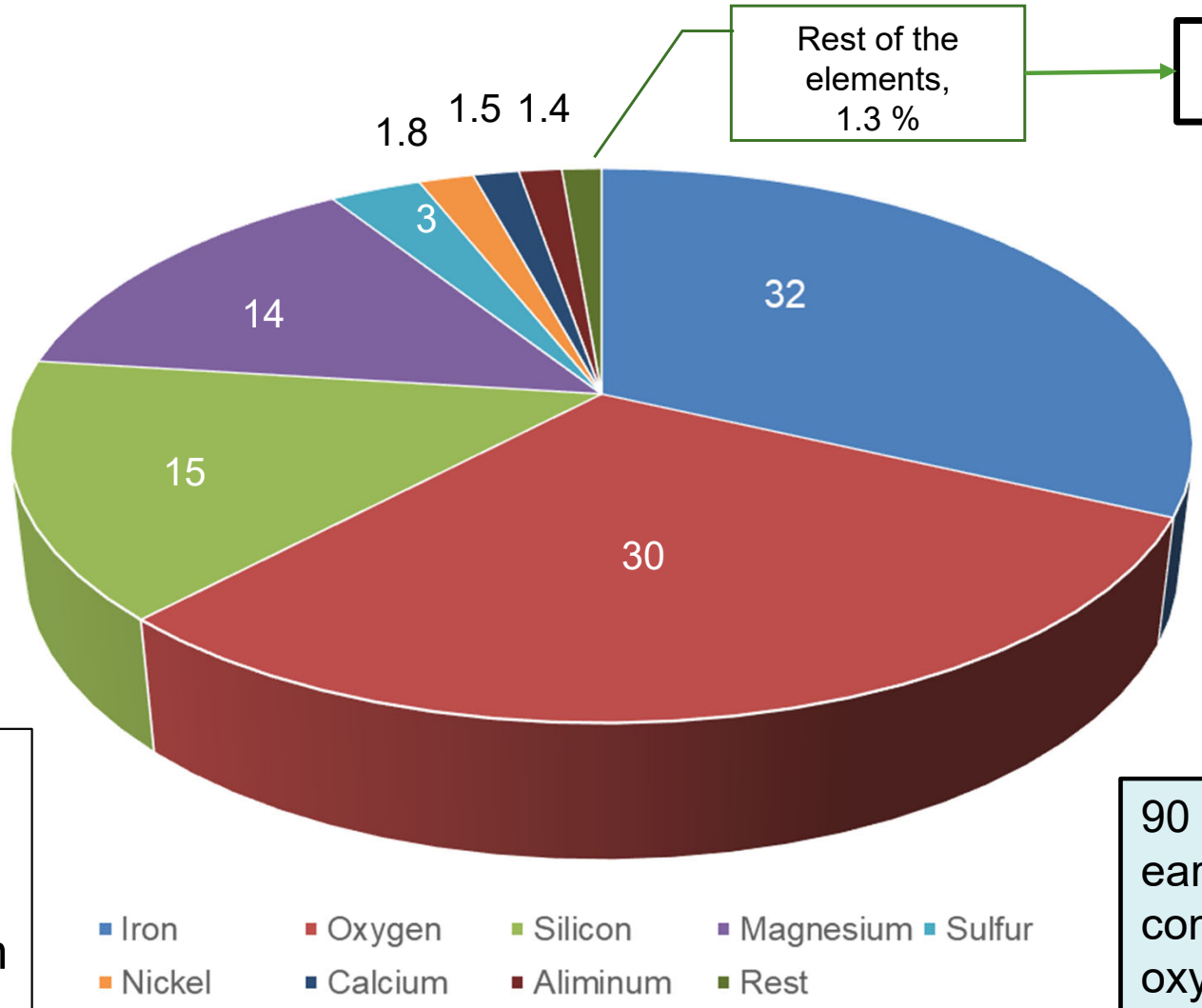
Batteries hold power, in every sense of the word. And Russia controls much of the world's nickel supply. Mining it is destroying rainforests and rivers in Indonesia and Philippines. In Congo, which holds 70% of the world's cobalt, titanic companies take out the metal, consigning the humans who mine it to extreme suffering and poverty.

Lithium demand is also soaring and the Atacama desert of Chile is paying a heavy cost for a change that will benefit most people in most places. Other sources are being sought – deep ocean and outer space are being explored for mineral prospects.

These resources are not an end to chase, they are a means to live a decent life. Even so, it's not just the supply of critical metals we need to address, but also our appetite for them. Reusing and repairing devices is essential, even if electronics manufacturers often make it hard to do. Cutting consumption, heating and cooling less, wasting less, are all ways to help. The best thing to do is not to buy an electric car, but not to buy a car at all, the book shows.

mindfield
SHORT TAKES ON BIG IDEAS

ABUNDANCE OF ELEMENTS ON EARTH, % WEIGHT

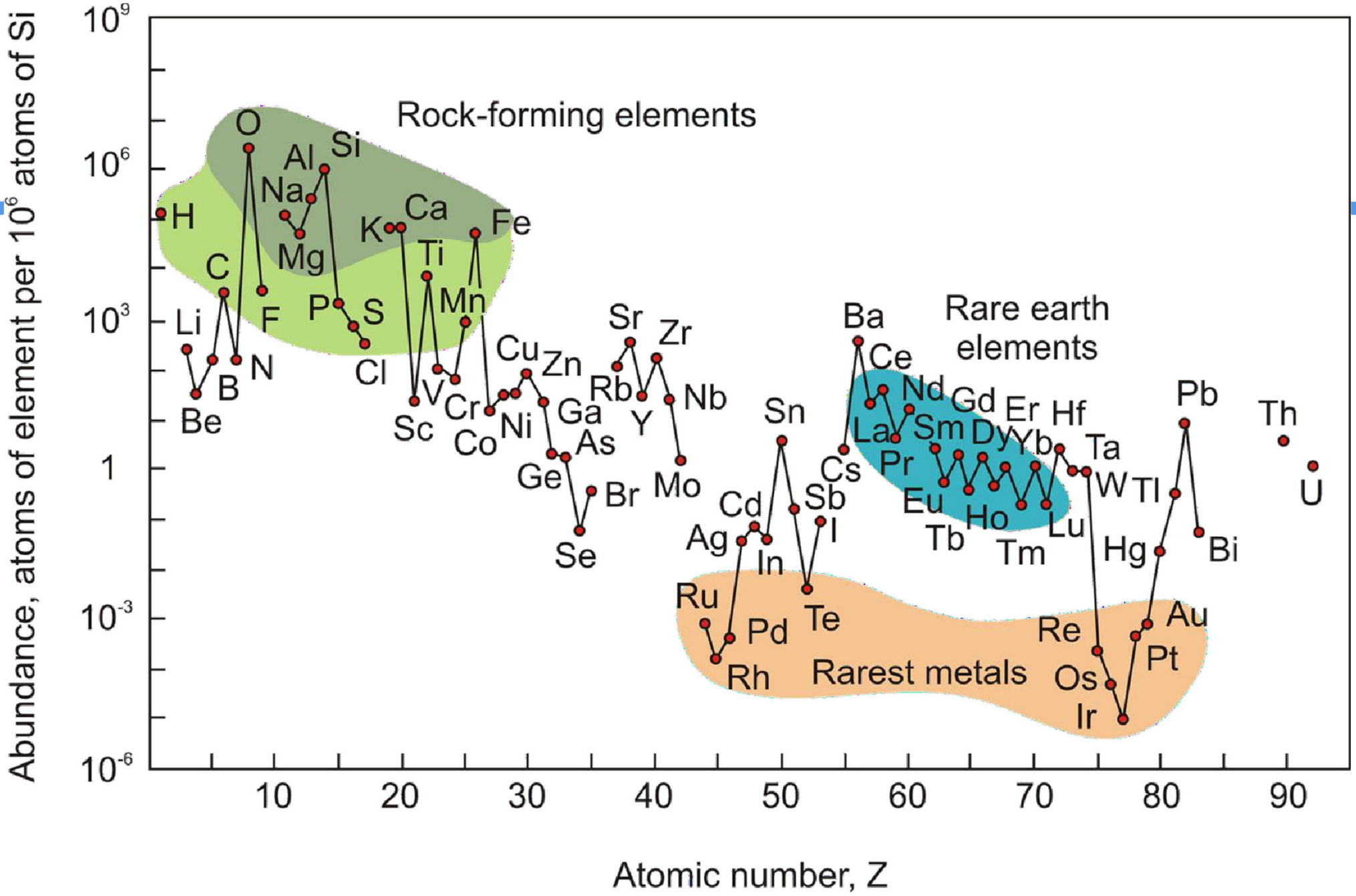


Core : Iron
Mantle: Oxygen, Silicon and Magnesium
Crust : Others

90 % by weight of earth's elements are comprised of iron, oxygen, silicon and magnesium

Mass of earth : ~ 6x 10^{21} tons

www.gov.uk/government/publications/uk-critical-mineral-strategy/resilience-for-the-future-the uks-critical-mineral-strategy


Abundance, atoms of element per 10^6 atoms of Si
10^9
10^6
10^3
1
10^{-3}
10^{-6}
Rock-forming elements
Rare earth elements
Rarest metals
H
O
Si
Al
Na
Mg
Ca
K
Fe
Ti
C
Mn
P
S
Li
F
N
B
Be
Cl
Sc
V
Cr
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Rb
Sr
Y
Zr
Nb
Mo
Ba
Ce
La
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Hf
Ta
W
Re
Os
Ir
Pt
Au
Hg
Tl
Pb
Bi
Th
U
Cs
Sn
Sb
I
Te
Cd
Ag
In
Ru
Rh
Pd
10
20
30
40
50
60
70
80
90
Atomic number, Z

ANNUAL GROWTH RATES FOR CRITICAL METALS

LITHIUM

95% of lithium demand is expected to come from batteries by 2030.

SOURCE: ReportLinker (CAGR), McKinsey & Company

SILVER

Silver is essential for contacts in solar panels because of its high electrical and thermal conductivity.

SOURCE: ReportLinker (CAGR), The Silver Institute

RARE EARTHS

Neodymium, praseodymium, dysprosium, and terbium are key components in the magnets used in EVs and wind turbines.

SOURCE: Technavio (CAGR), IRENA

URANIUM

Nuclear power is the second-largest contributor of low-carbon electricity.

SOURCE: Technavio (CAGR), International Energy Agency

COPPER

Renewable energy systems can use up to six times more copper than traditional sources.

SOURCE: Technavio (CAGR), Copper Alliance

COBALT

Cobalt enhances battery power density and is part of 63% of EV batteries worldwide.

SOURCE: 360 Market Updates (CAGR), Cobalt Institute

GRAPHITE

Graphite is the largest component in a lithium-ion battery by volume.

SOURCE: IndustryARC (CAGR), European Carbon and Graphite Association

NICKEL

Nickel-based battery cathodes offer high energy density and increased driving ranges for EVs.

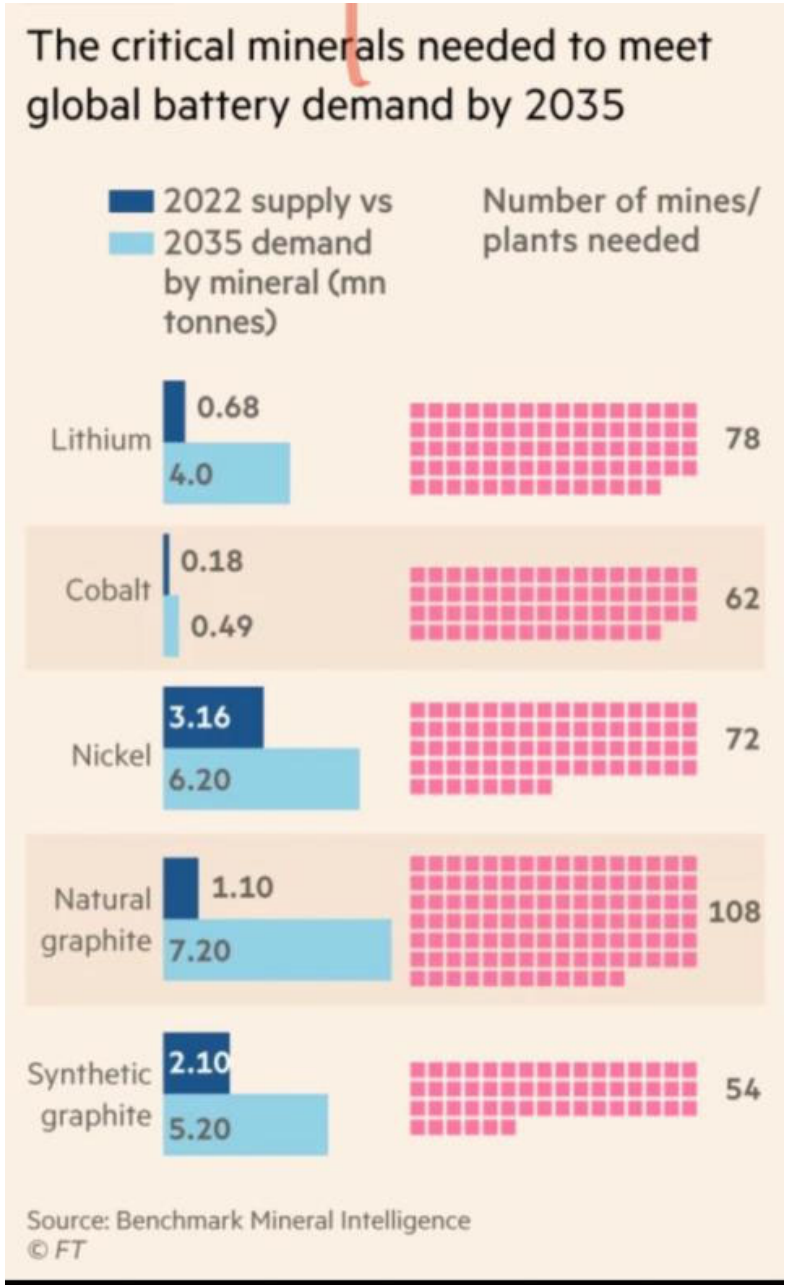
SOURCE: Market Research Future (CAGR), Reuters

MANGANESE

Manganese is crucial for its use as a stabilizing component in many lithium batteries for EVs.

SOURCE: IndustryARC (CAGR), Umicore

CRITICAL MINERALS NEEDED TO MEET GLOBAL BATTERY DEMAND BY 2035



WHY THE SUDDEN INTEREST AND CONCERNS REGARDING CRITICAL MINERALS?

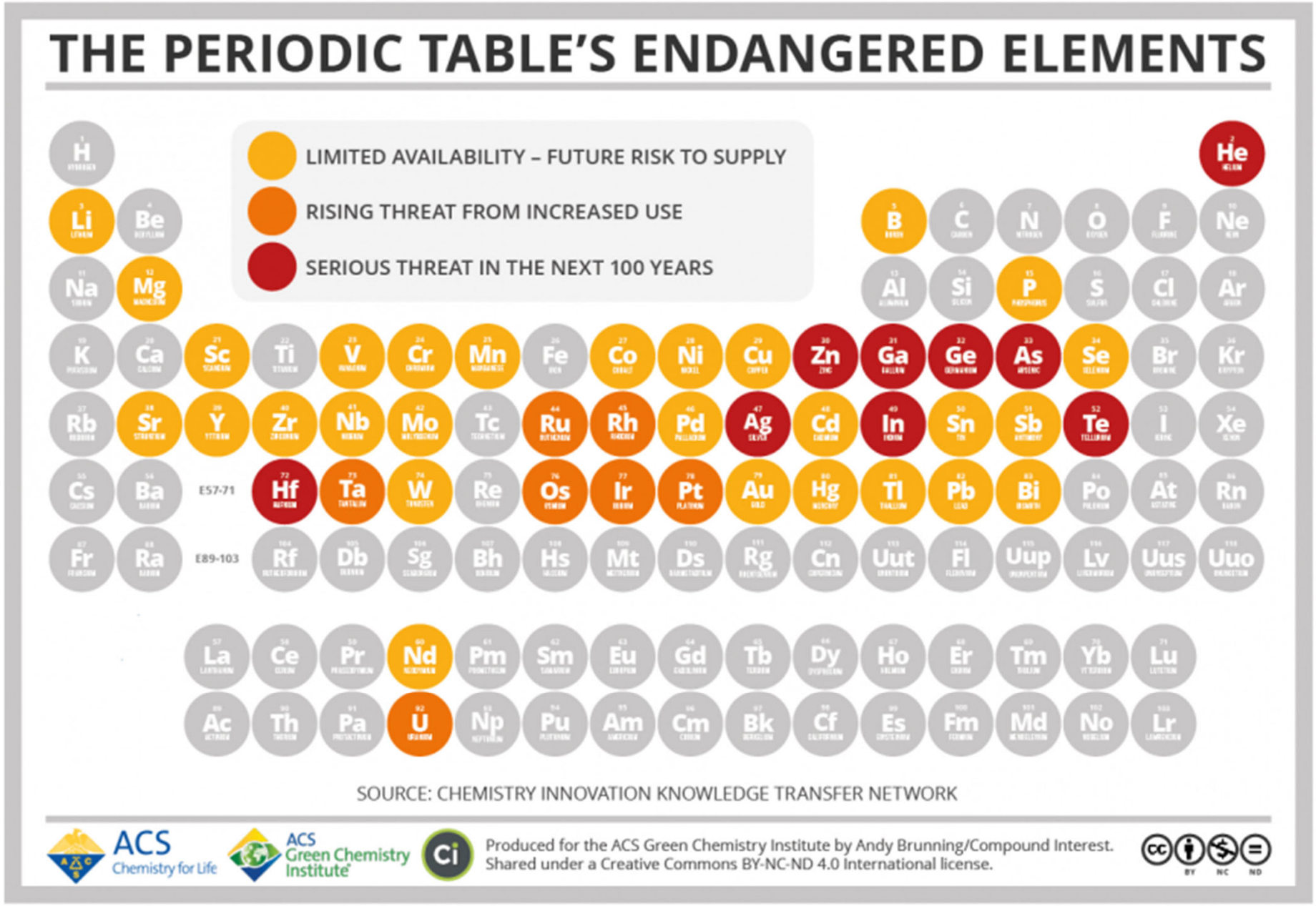
- Supply chain disruptions due to pandemic / regional wars and skirmishes
- Uneven geographical distribution of geological resources for critical minerals
- Location of geological resources in politically fragile economies of the world
- Increasing trends in protectionism and abandoning the principles of free trade dictated by market forces and use of the economic principle of comparative advantage
- Concentration of manufacturing scale in certain geographies, leading to skewed or manipulated supply chains
- Increasing polarization of the world, in terms of, politics and ideology

The single most important trigger for concerns regarding critical minerals is the anticipated exponential increase in demand for low carbon intensity energy technologies to meet the goals of decarbonization and limiting global warming to less than 2º C by the end of this century

THREE RISKS IN CRITICAL MINERALS SUPPLY CHAIN

1. Endangered elements and elements nearing extinction
2. Inequitable geographical distribution of critical minerals
3. Distance traveled by critical minerals from its source to the product consumer

RISKS IN CRITICAL MINERAL SUPPLY CHAIN-1



Endangered elements, critical raw materials and conflict materials, C.J. Rhodes, Science Progress, 2019, 102, 304

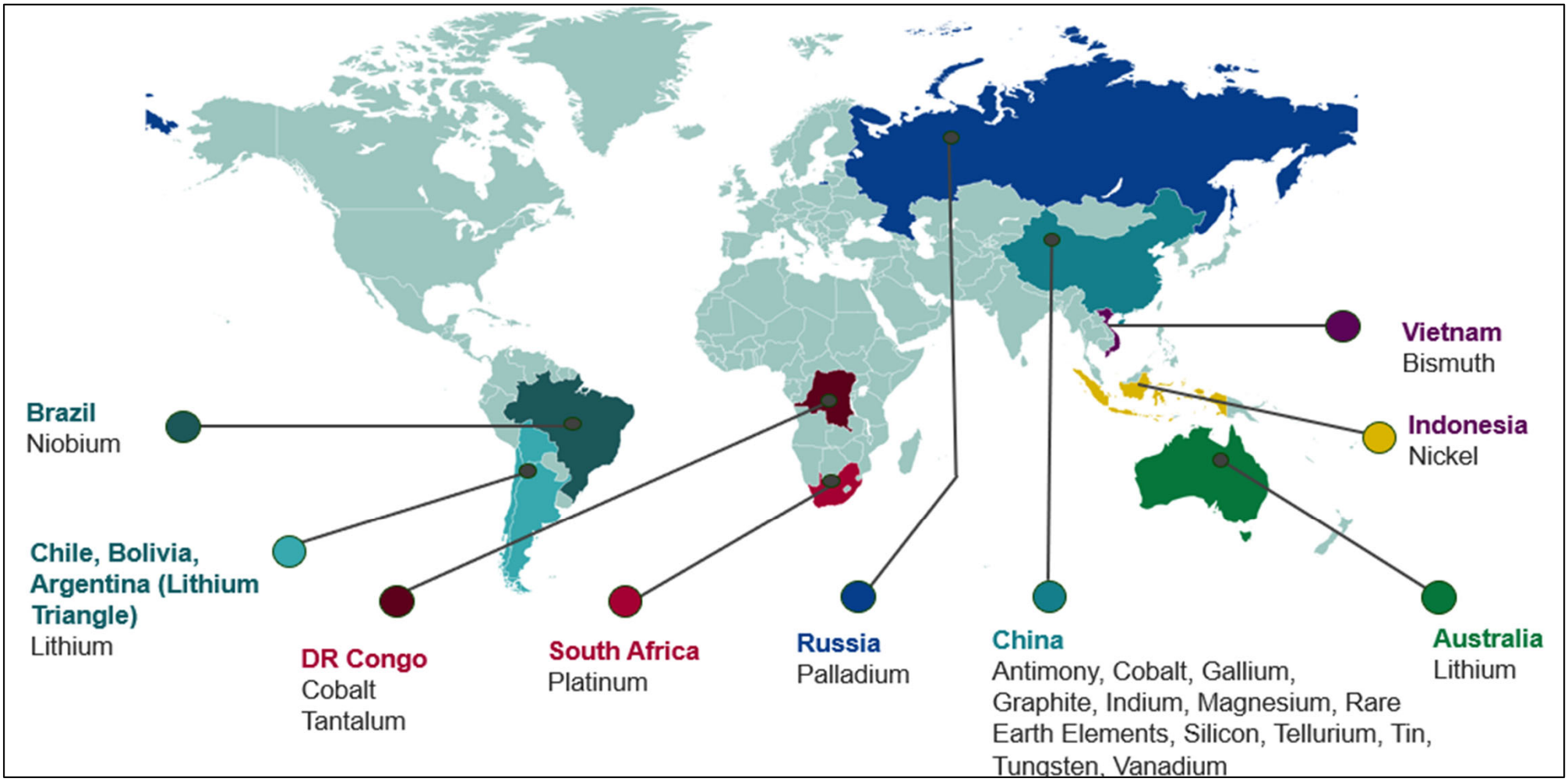
SUSTAINABILITY OF THE ELEMENTS IN THE PERIODIC TABLE

- Except uranium all elements are indestructible.
- Helium and neon being lighter than air escape into the stratosphere and are lost to earth
- Carbon fixed in the lithosphere is lost as carbon dioxide to the atmosphere upon combustion
- However, metals cannot become extinct because atoms are immutable

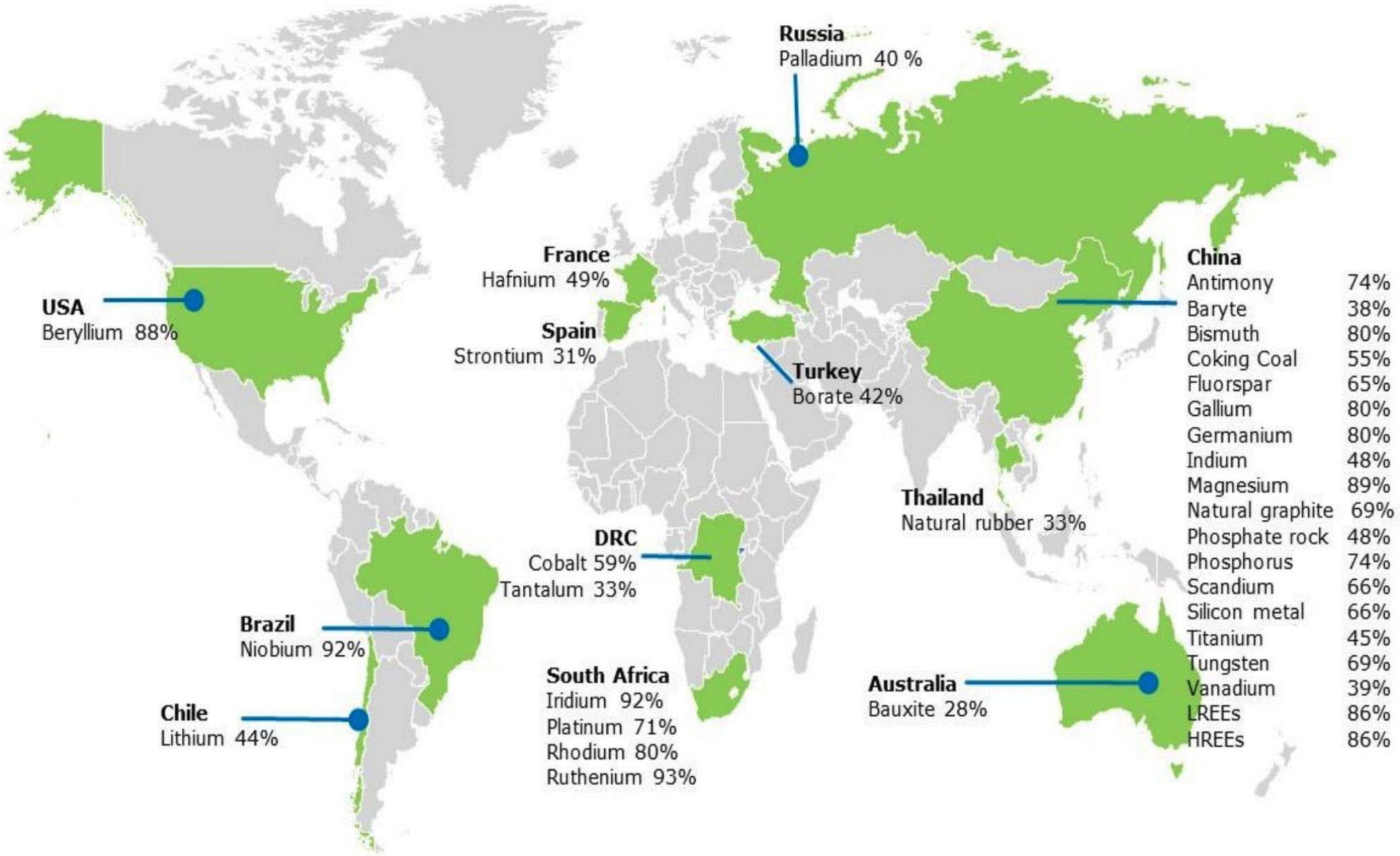
So where lies the problem ?

Human activity is taking elements from relatively concentrated ore deposits and distributing them so thinly across devices and gadgets that they are present in the environment in dilute forms, and no longer easily recoverable from wastes

DISTRIBUTION OF CRITICAL MINERAL RESOURCES IN THE WORLD

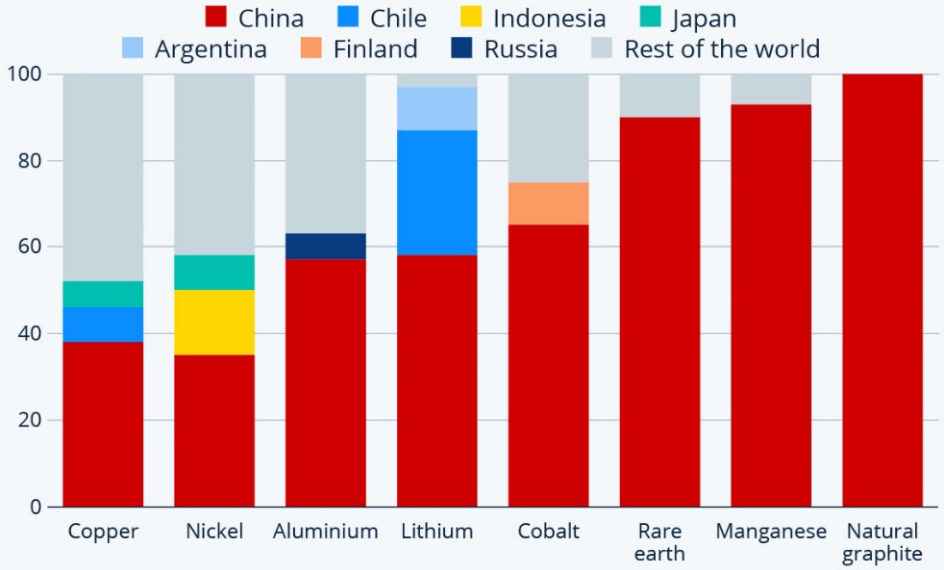


RISKS IN CRITICAL MINERAL SUPPLY CHAIN-2



China Leads Critical Minerals Production

Top countries by share in global processing of selected critical minerals in 2023 (in percent)



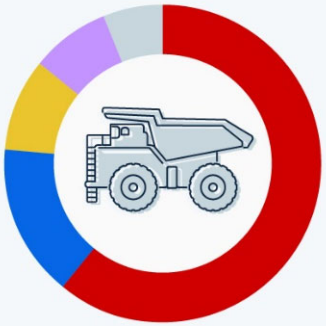
Sources: UNCTAD, OECD

statista

China Dominates the Rare Earth Market

Global rare earth reserves in 2021 (in million REO tons)*

Leading countries' share of global mine production in 2021



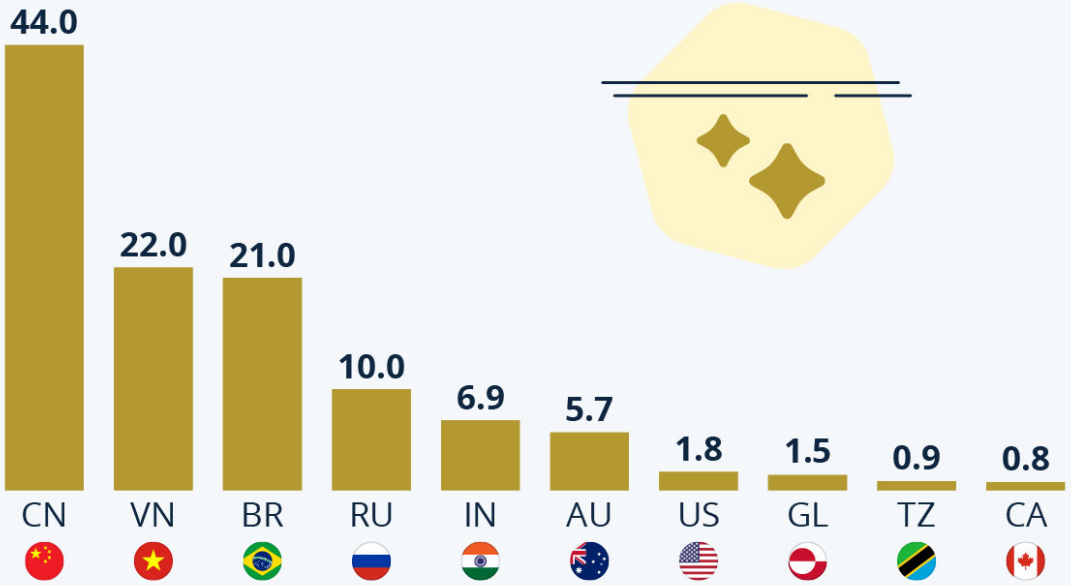
61.0% China
15.5% United States
9.4% Myanmar
8.0% Australia
6.1% Others

* REO=rare-earth oxides
Source: U.S. Geological Survey

statista

Where Are the World's Rare Earth Metals?

Top 10 countries with the greatest known reserves of rare earth elements in 2023 (in million tonnes of REO)*



* REO = Rare Earth Oxide

Source: USGS

China controls 90% of rare earths' refining capacity

▶Continued from Page 1

India has the fifth-largest deposits after China, Vietnam, Brazil and Russia, but China has a chokehold because it controls almost 90% of refining capacity. The disruption brought into focus tag-team efforts by US and India to overcome the Chinese monopoly even as Washington scours the globe — from Greenland to Ukraine — for deposits and refining capacity.

Earlier this year, in a bipartisan US effort, the Biden govt lifted decades-old sanctions on the state-owned Indian Rare Earths Ltd and the incoming Trump administration followed up by announcing during PM Modi's visit to Washington a US-India 'Strategic Mineral Recovery' to recover and process critical minerals.

"Recognising the strategic importance of critical minerals for emerging technologies and advanced manufacturing, India and the US will accelerate collaboration in research and development and promote investment across the entire critical mineral value chain, as well as through the Mineral Security Partnership, of which both the US and India are members," the two sides said in a statement.

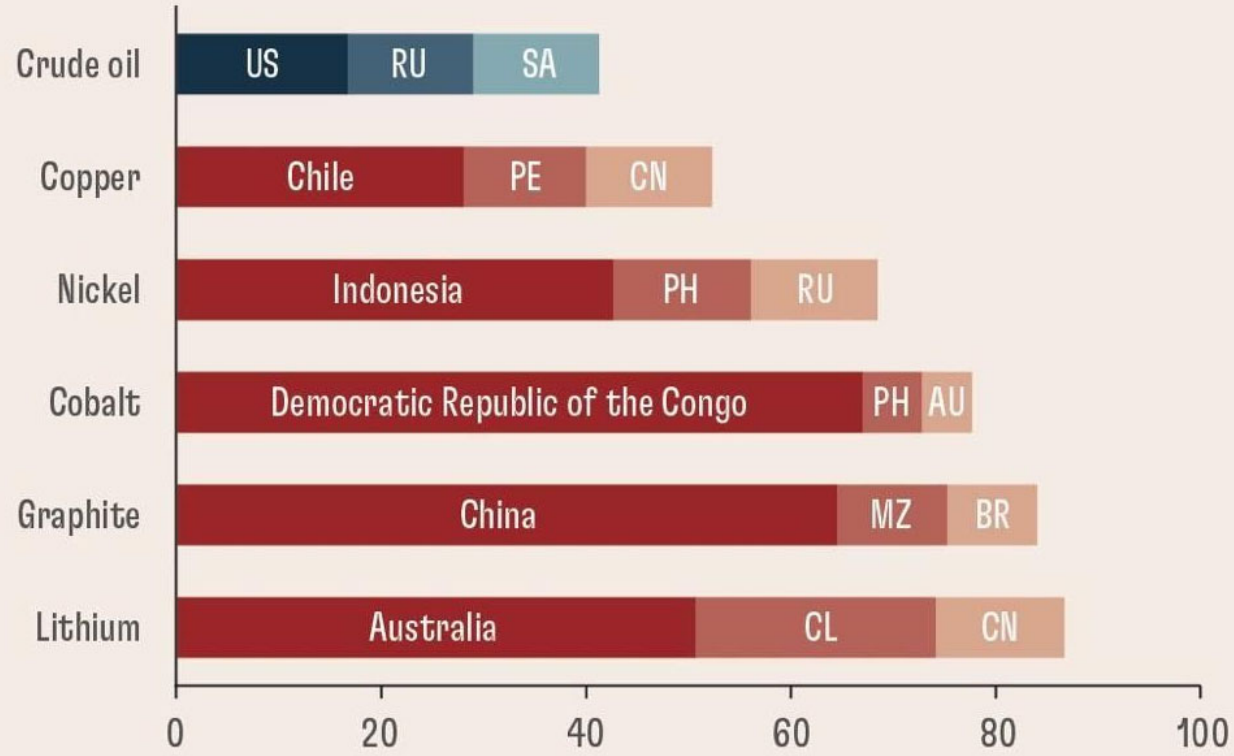
Industry experts say that's a start but nowhere near meeting the critical needs of US (and India), given the head-start China has in the field. In fact, even the Pentagon relies on Chinese-processed rare earth elements for components like permanent magnets in F-35 jets, laser targeting systems, and missile guidance systems — a shock realisation that has propelled the Trump White House to urgently look for other sourcing.

Elon Musk, who needs rare earths for a range of his tech products from EVs to rockets, was among those who reacted cautiously to China's squeeze. "Important to note that what matters is the ability to refine rare earth elements (which are NOT actually meaningfully rare) and manufacture magnets for use in electric motors. People understandably tend to think that rare earth mineral deposits are what's scarce, given the name. That is false. They're everywhere," Musk said in a post on X, conceding that as with lithium, what China has that others lack is the heavy industry of refining the minerals. In fact, even US-mined material is often sent to China for processing.

RISKS IN CRITICAL MINERAL SUPPLY CHAIN-2

The supply of critical minerals is more concentrated than that of crude oil and therefore more vulnerable to trade disruption.

Top three producers
(share of world production, percent)

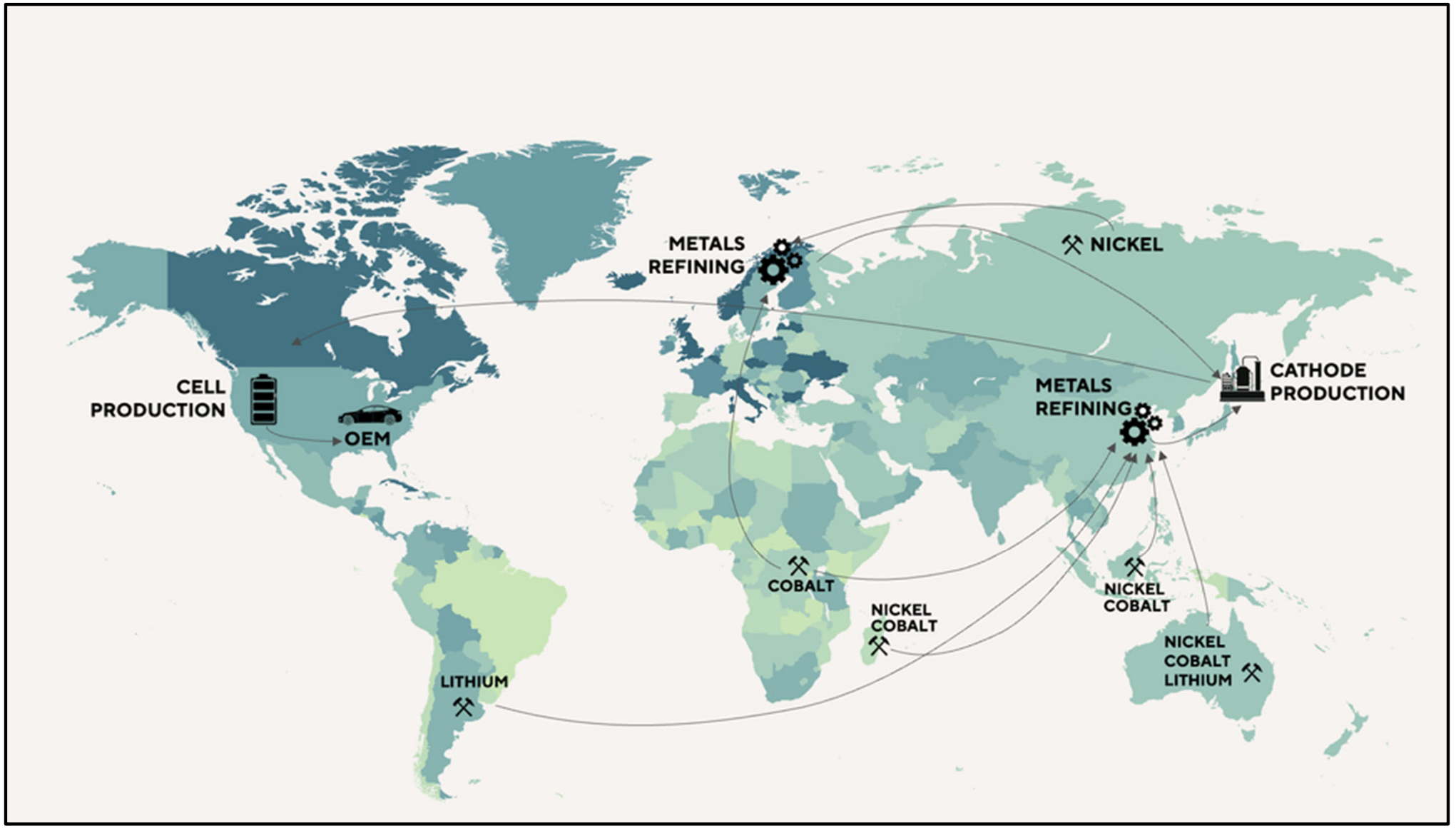


SOURCES: British Geological Survey; US Geological Survey; and IMF staff calculations.
NOTE: AU = Australia, BR = Brazil, CL = Chile, CN = China, MZ = Mozambique, PE = Peru, PH = Philippines, RU = Russia, SA = Saudi Arabia, US = United States.

Compared to oil, critical minerals are concentrated in few countries

RISKS IN CRITICAL MINERAL SUPPLY CHAIN-3

Critical minerals used in Li-ion batteries move large distances before making their way into a cell, posing enormous environmental, economic, and geopolitical risks

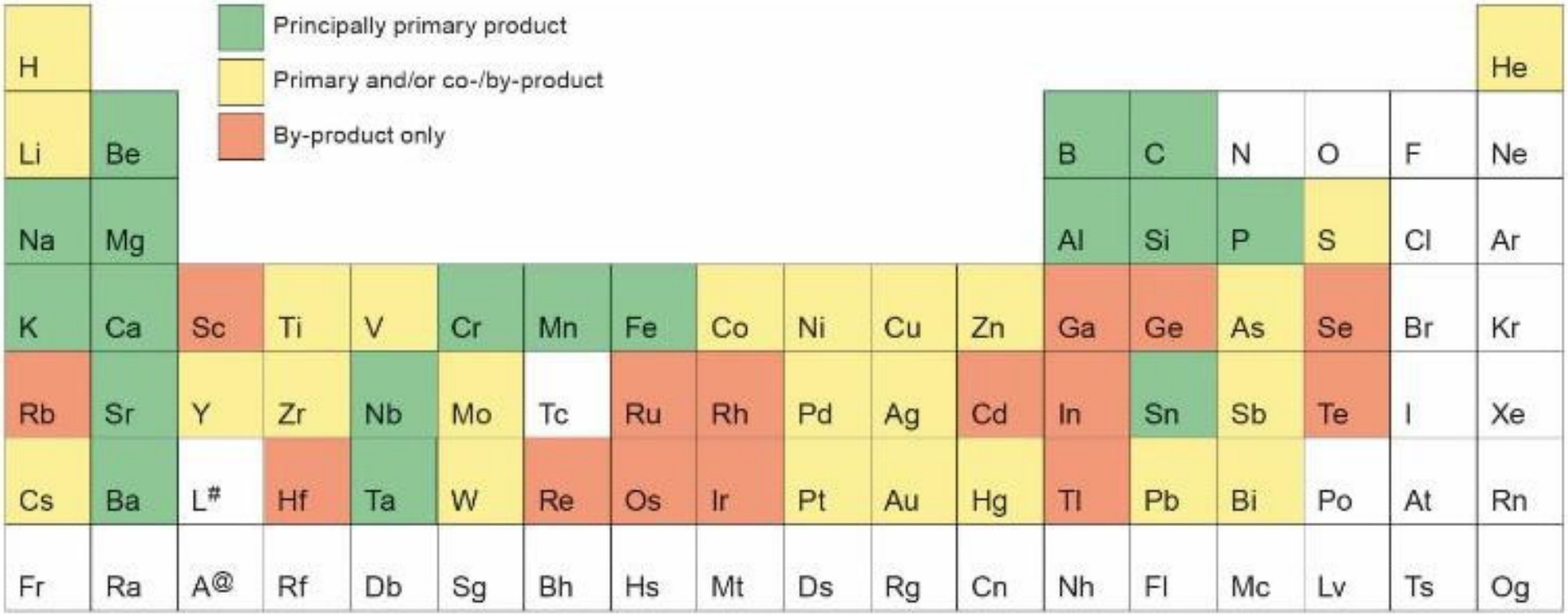


BY-PRODUCT SUPPLY CHAINS

- Reserves and resources are not relevant for by-products, since they *cannot* be extracted independently from the main-products

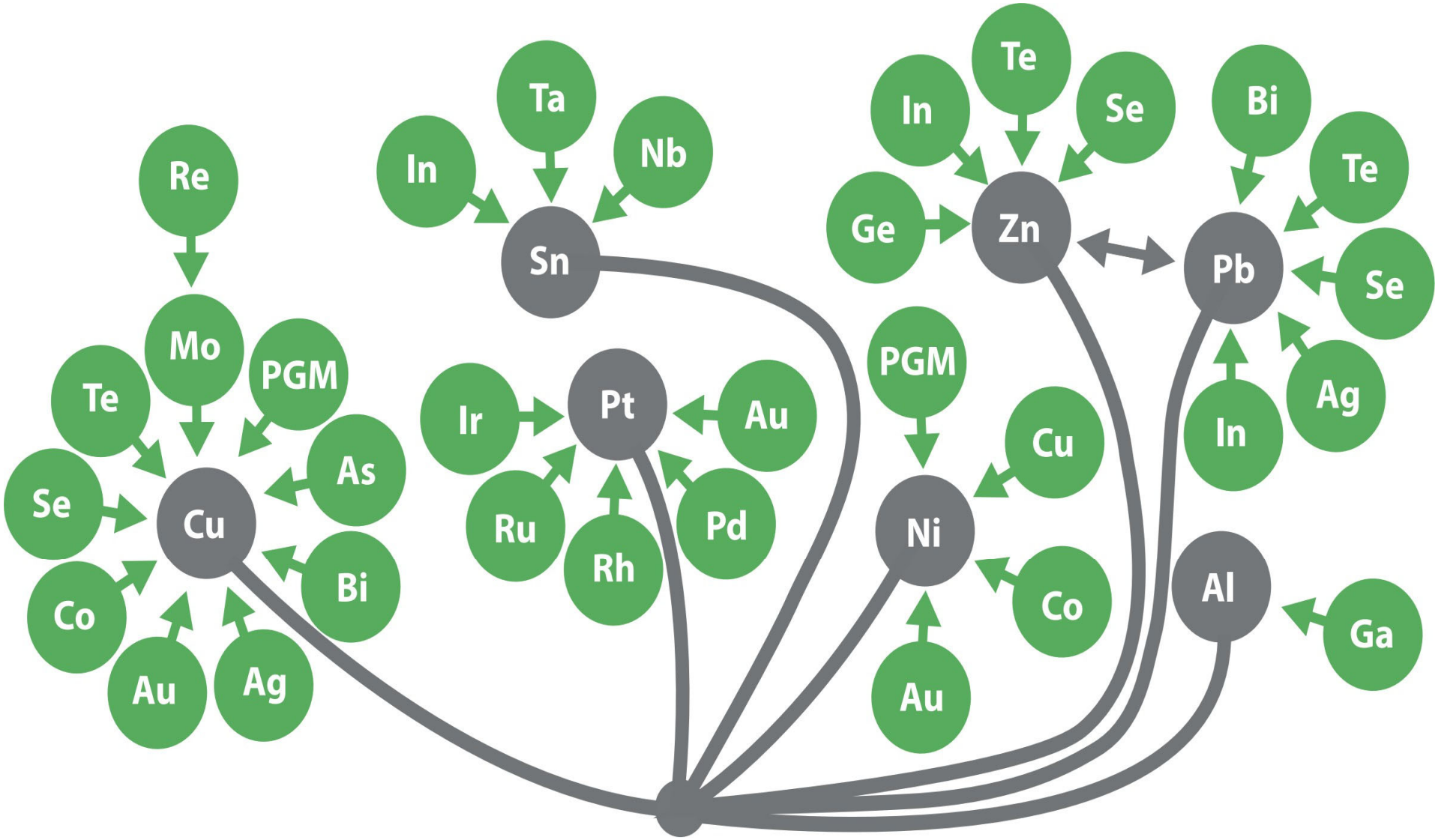
- The supply potential of a by-product is defined as that amount which is economically extractable from its host materials per year *under current market conditions (i.e. technology and price)*

PRIMARY, CO- / BY-PRODUCT ONLY STATUS OF ELEMENTS



Nassar, et.al, 2015; British Geological Services

CO-DEPENDENCY OF MINED METALS



Source: Hagelüken and Meskers (2010).

THANK YOU

If you do not change direction, you may end up where we are heading: Lao Tzu