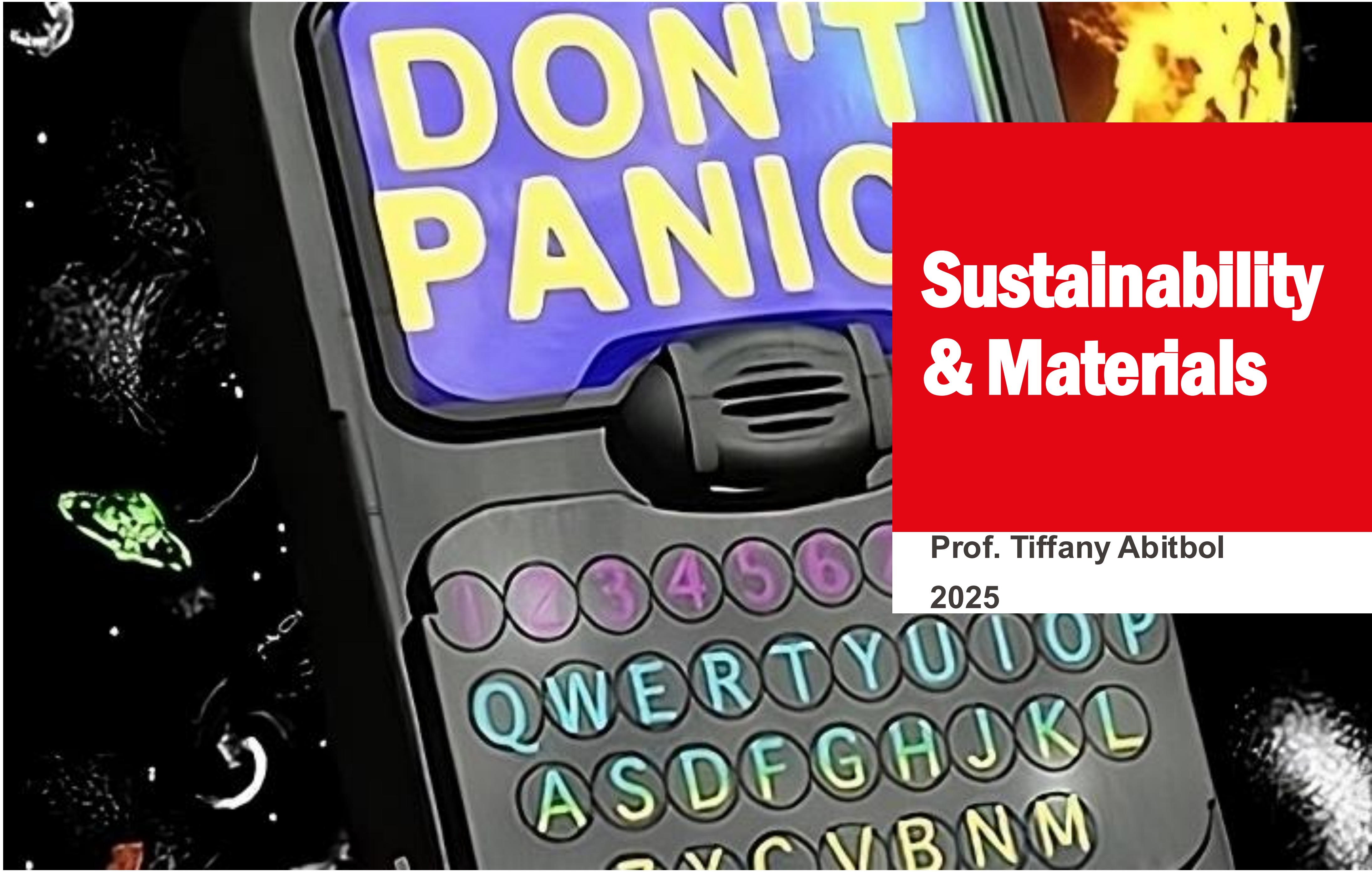
EPFL

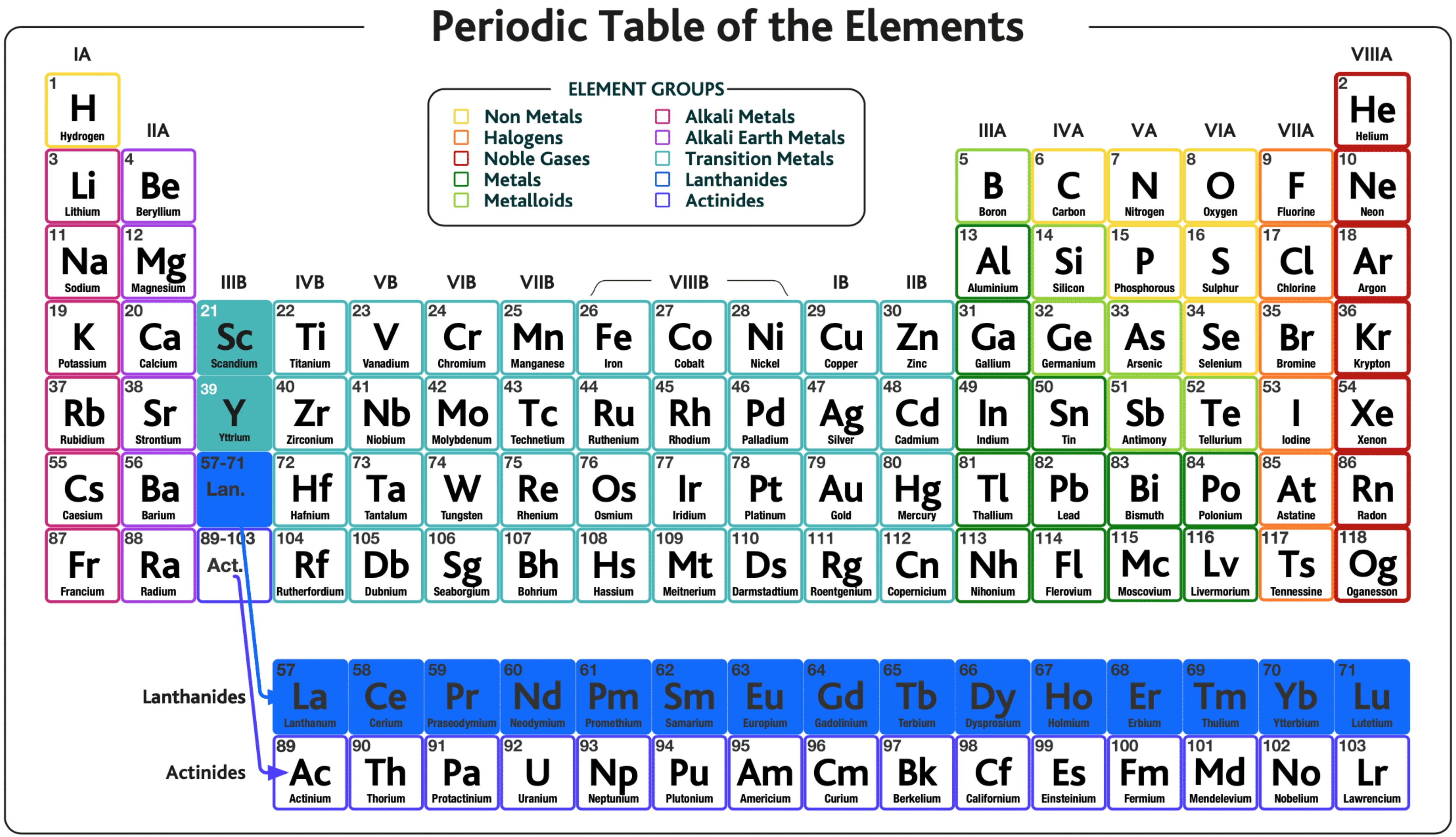


Sustainability & Materials

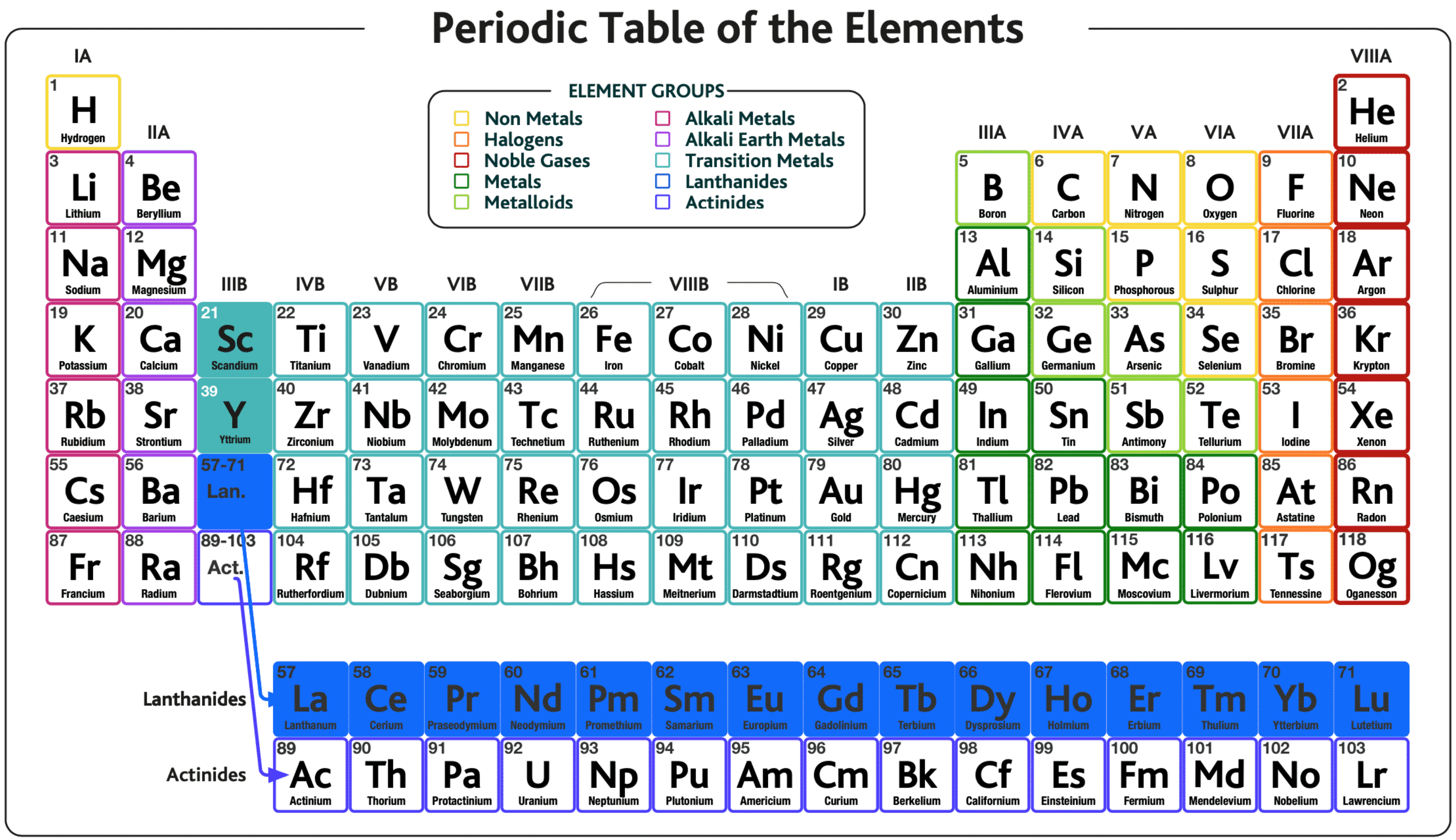
Prof. Tiffany Abitbol

2025

Rare earth elements (REE)



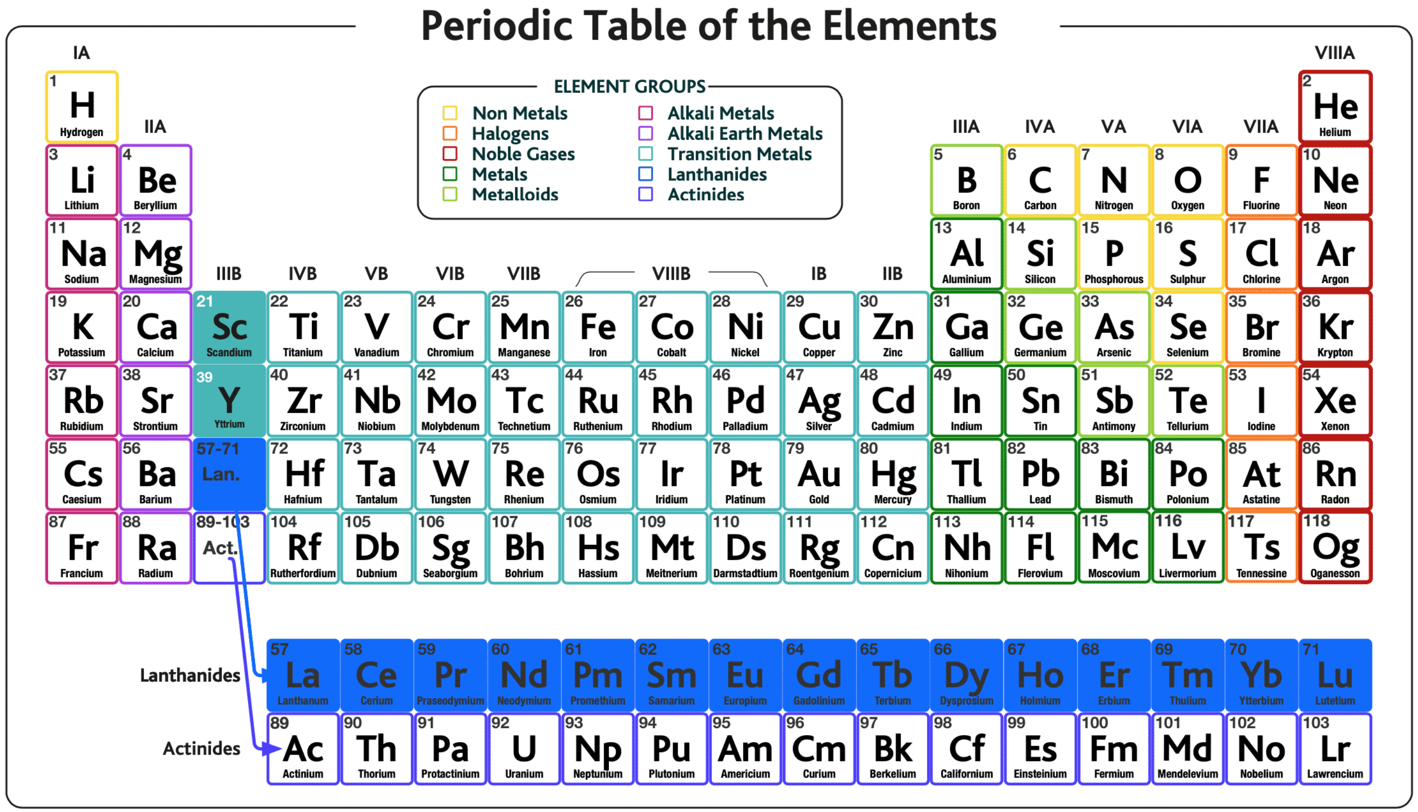
Rare earth elements (REE)



The 4f electrons in rare earth elements (REEs) are crucial for their unique properties due to their shielding and localization:

- Magnetic properties
- Optical properties
- Chemical reactivity

REE electron configuration



Generic: $[Xe]4f^{1\text{-}14}5d^{0\text{-}1}6s^2$

La (Z=57): [Xe] $5d^1 6s^2$
Ce (Z=58): [Xe] $4f^1 5d^1 6s^2$
Pr (Z=59): [Xe] $4f^3 6s^2$
Nd (Z=60): [Xe] $4f^4 6s^2$
Pm (Z=61): [Xe] $4f^5 6s^2$
Sm (Z=62): [Xe] $4f^6 6s^2$
Eu (Z=63): [Xe] $4f^7 6s^2$

Light (LREE)

Gd (Z=64): [Xe] $4f^7 5d^1 6s^2$
Tb (Z=65): [Xe] $4f^9 6s^2$
Dy (Z=66): [Xe] $4f^{10} 6s^2$
Ho (Z=67): [Xe] $4f^{11} 6s^2$
Er (Z=68): [Xe] $4f^{12} 6s^2$
Tm (Z=69): [Xe] $4f^{13}\ 6s^2$
Yb (Z=70): [Xe] $4f^{14} 6s^2$
Ho (Z=71): [Xe] $4f^{14} 5d^1 6s^2$

Heavy (HREE)

Reference: Electron configurations of lanthanides

REE oxidation states

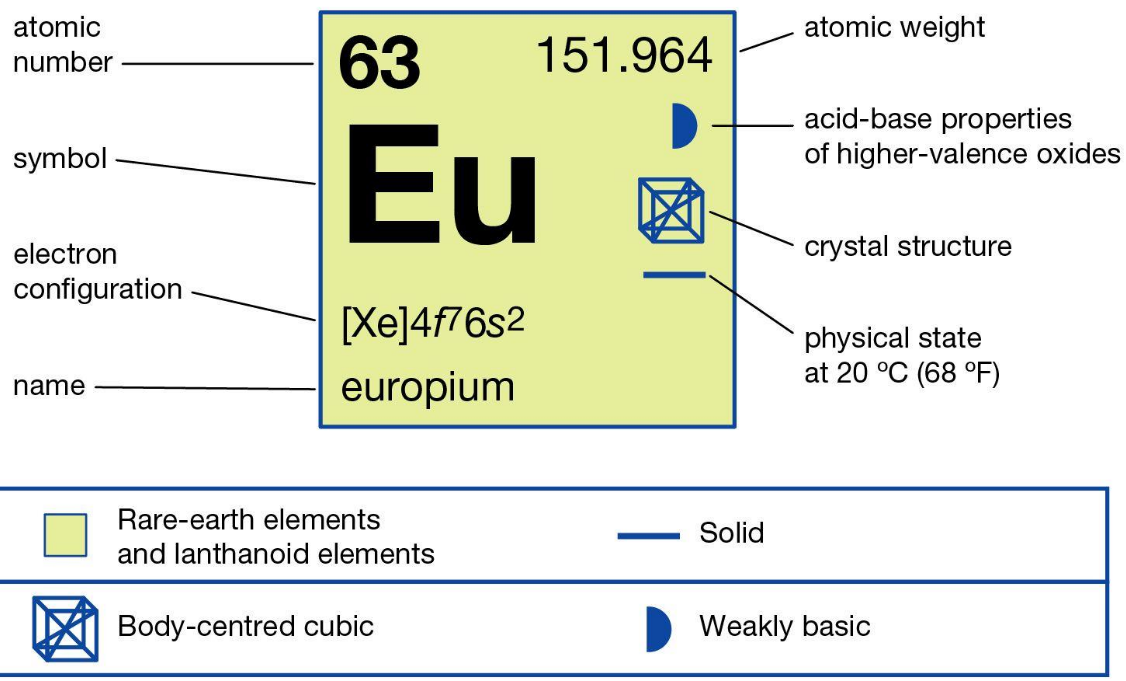
MAIN PROPERTIES of REEs:
1. *Luminescent*
2. *Magnetic*
3. *Electrical*
4. *Catalytic*

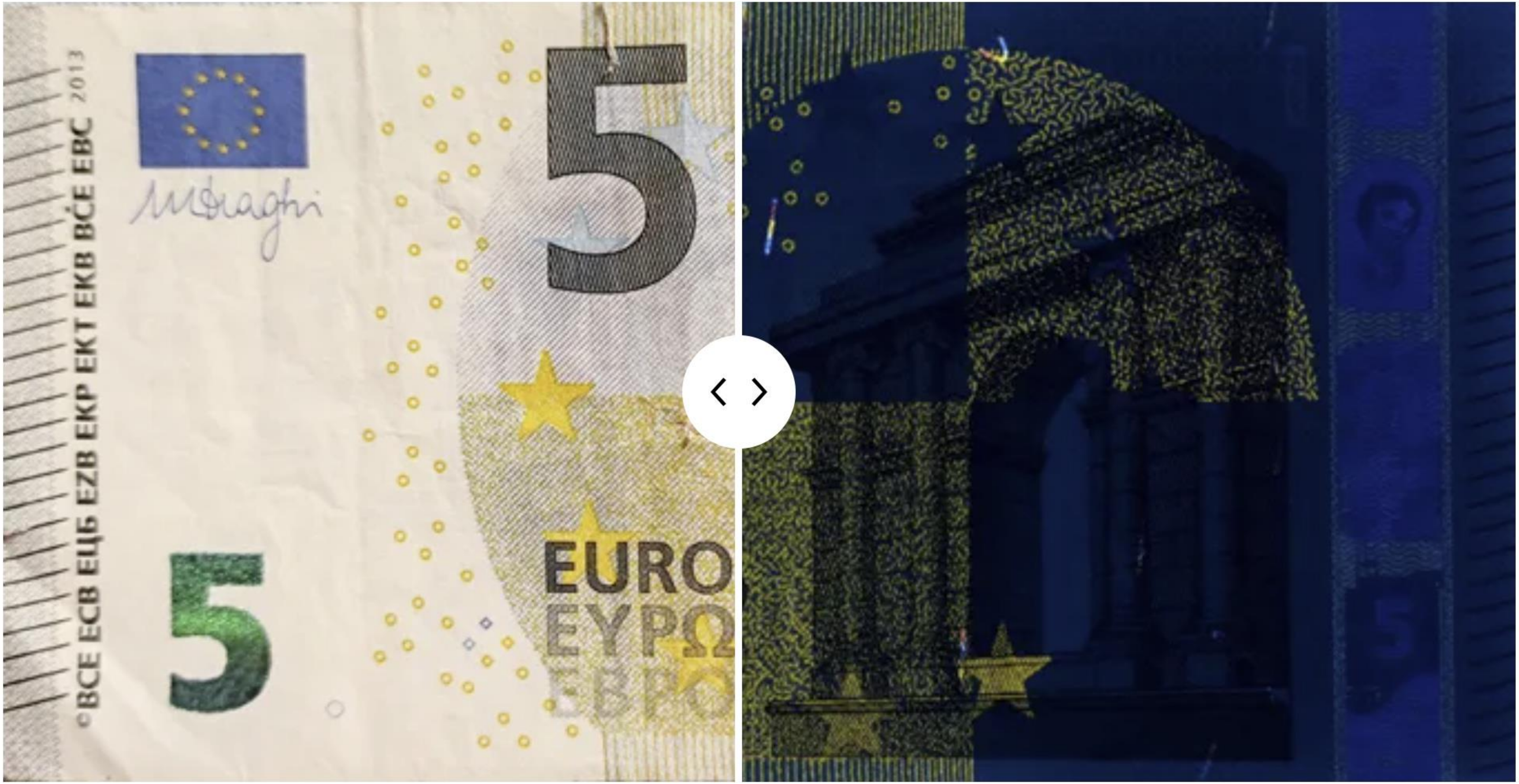
- Variable
- +3 oxidation state is most common
- +2, +4 also occur

- Example: Europium (Z = 63)
  - Eu: [Xe] $4f^7 6s^2$
  - Eu(III): [Xe] $4f^6$
  - Eu(II): [Xe] $4f^7$

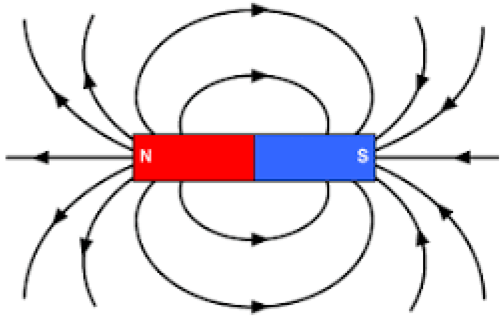
- Unpaired f-orbital electrons give rise to unique properties of lanthanides (electrons in f-orbitals shielded between nucleus and valence shell)

Europium

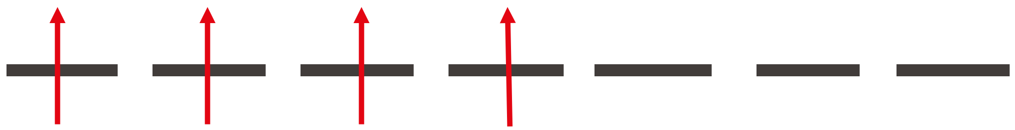



©BCE ECB ЕЦБ EZB EKP EKT EKB BĊE EBC 2013
5
5
EURO
ΕΥΡΩ
5

Magnetic properties



- f-orbitals, unpaired electrons of same spin
- For example, Nd = [Xe] $4f^4 6s^2$

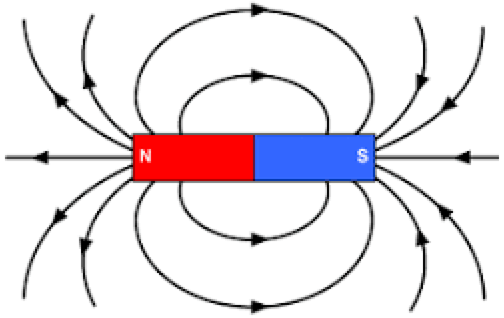


4f orbitals, with 4 unpaired electrons

- Spin direction creates N/S poles needed for magnetism
- f-electrons shielded from demagnetizing forces (heat, other magnets) by valence electron shell – excellent for **permanent** magnets
- However, pure Nd, readily corrodes and fractures, so alloyed, e.g., **NdFeB magnets** (>95% of permanent magnets):

REE technology

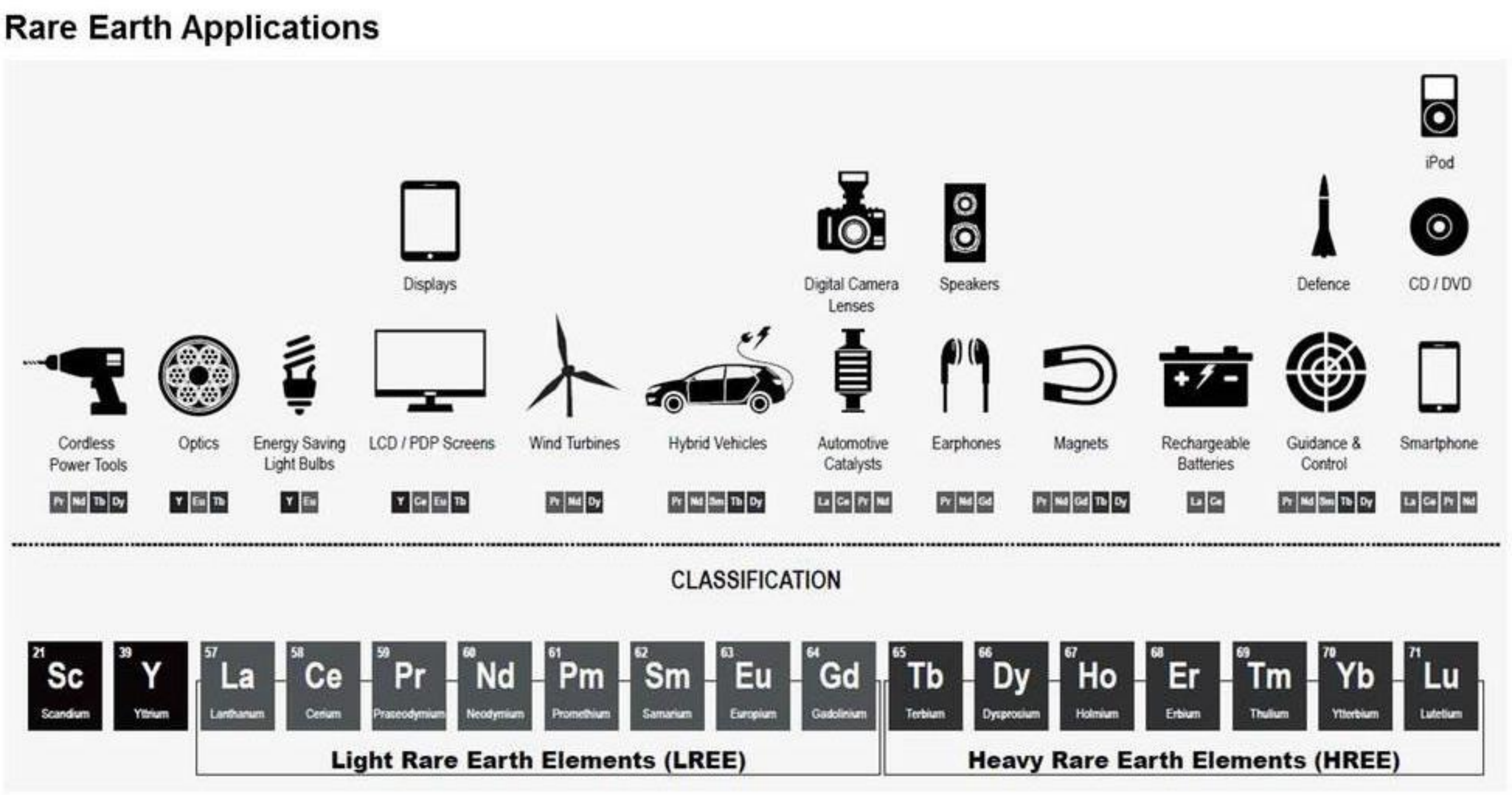
REE magnets



- NdFeB pack more "magnetism" per volume, so they can be smaller than other magnets with the same field strength
- Largest global use for REEs; 43% of 2021 total demand
- Used in smartphones, earbuds and headphones, R/W data on hard disk drives, MRIs, wind turbines (increase power generation, reduce maintenance), EV batteries, power steering
- Samarium-cobalt (Sm-Co), less strong, more heat and corrosion resistant; used in high-speed motors, generators, speed sensors in vehicles, moving parts of heat sensing missiles

[REE technology]

REE in the green transition



From magnets, lasers, GPS satellites, photoluminescence, computer components, lighting, and electronics…

NATO report

EU ban on the sale of new petrol and diesel cars from 2035 explained

All new cars and vans sold in the EU as of 2035 should not produce any CO_2 emissions. What does this mean in practice? Check out our FAQ to find out.

Published: 03-11-2022

Last updated: 30-06-2023 - 13:11

5 min read

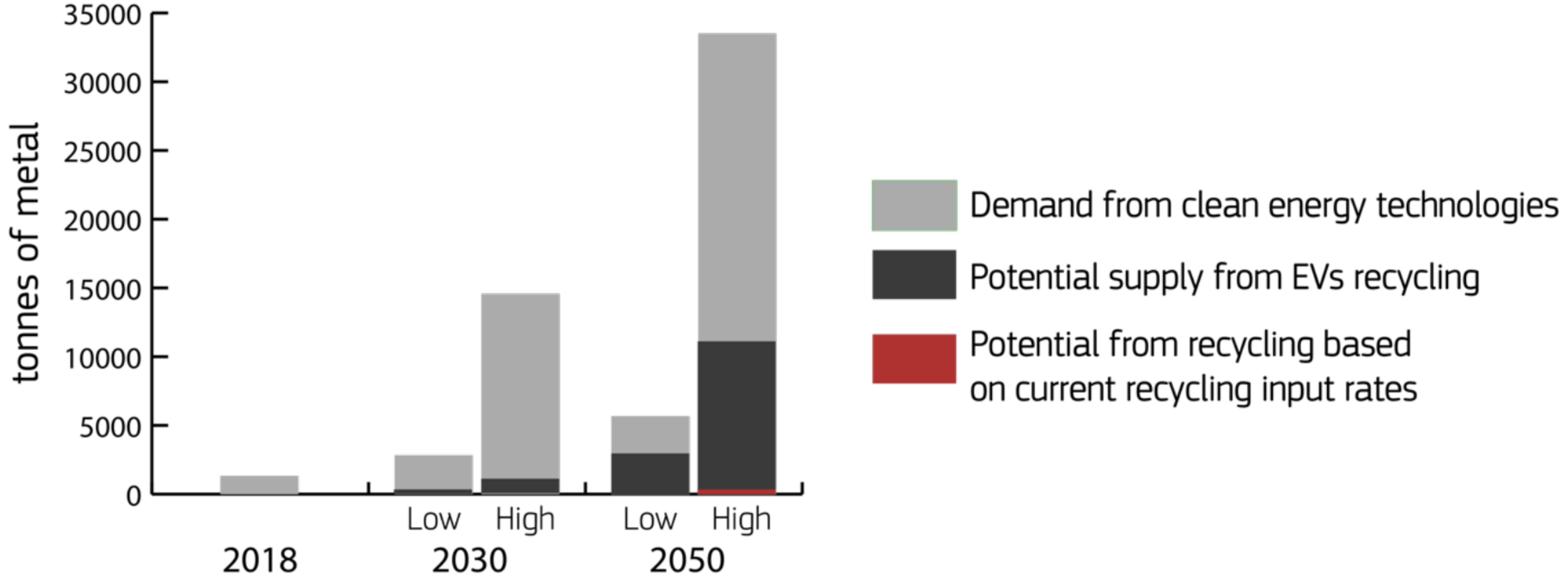
https://www.europarl.europa.eu/topics/en/article/20221019STO44572/eu-ban-on-sale-of-new-petrol-and-diesel-cars-from-2035-explained

Approximately how many kg's of REE in a full hybrid EV with a Li-ion battery?

A. 0.5 kg
B. 1 kg
C. 2 kg
D. 4.5 kg

REE in EV batteries

Figure 3: Projected demand for neodymium, praseodymium and dysprosium for clean energy technologies compared with the potential supply from recycling of rare earths from electric vehicles (EVs) (EU-27 and the United Kingdom)



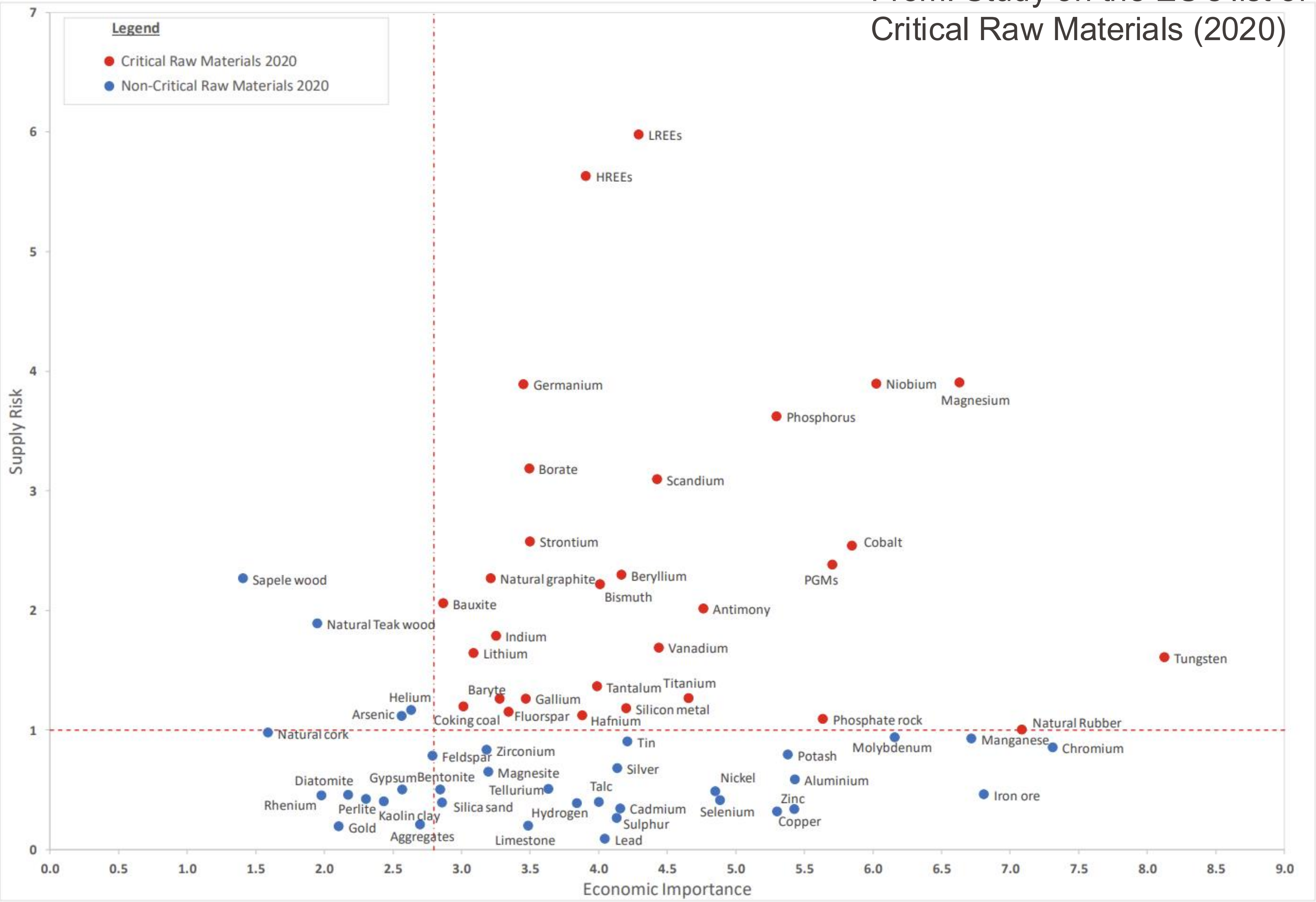
Source: JRC.

European Commission Report: THE ROLE OF RARE EARTH ELEMENTS IN WIND ENERGY AND ELECTRIC MOBILITY

EPFL

Figure 6: Criticality assessment results (individual materials and groups)

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

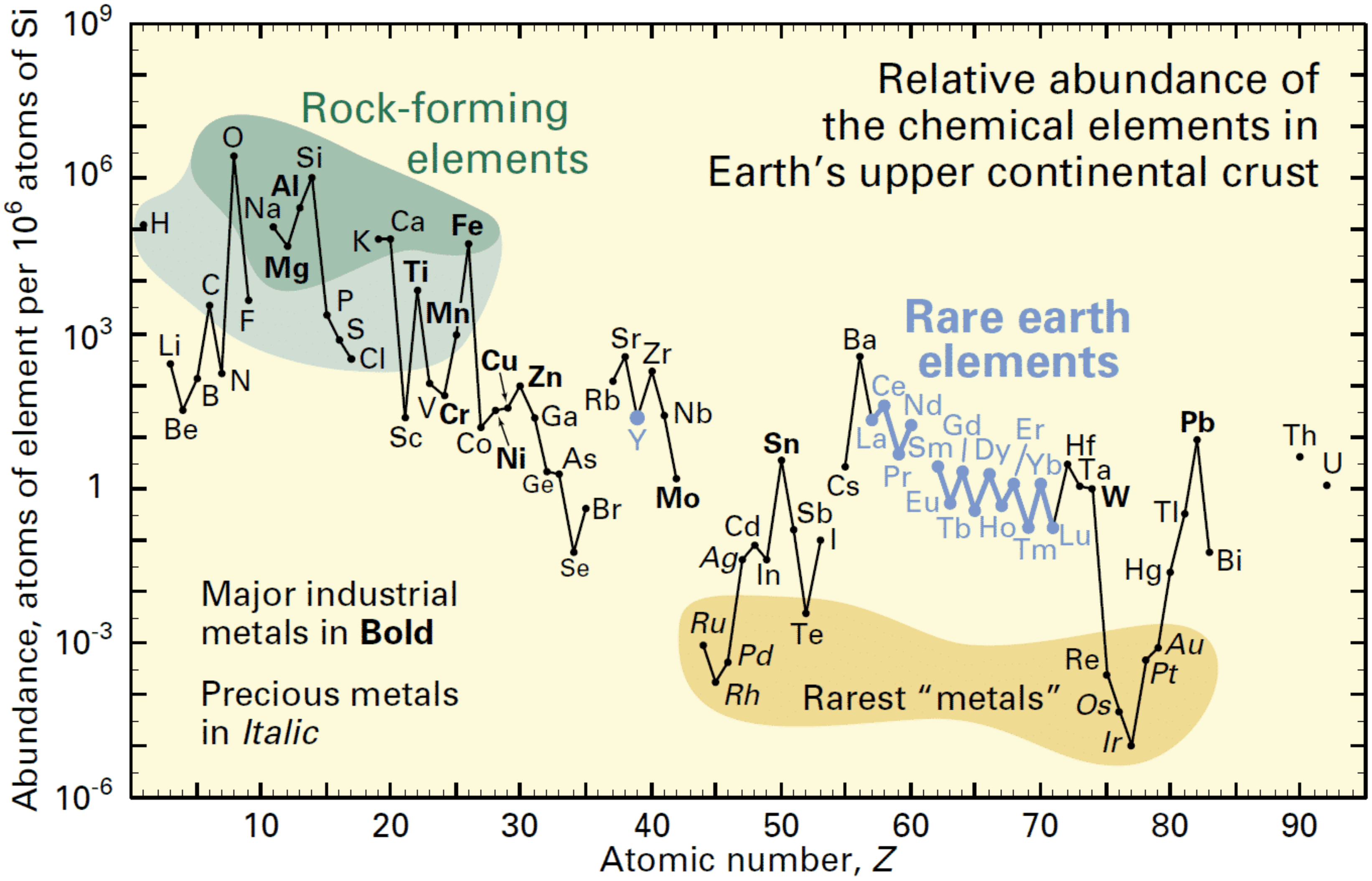


Are rare earth elements actually rare?

A. True

B. False

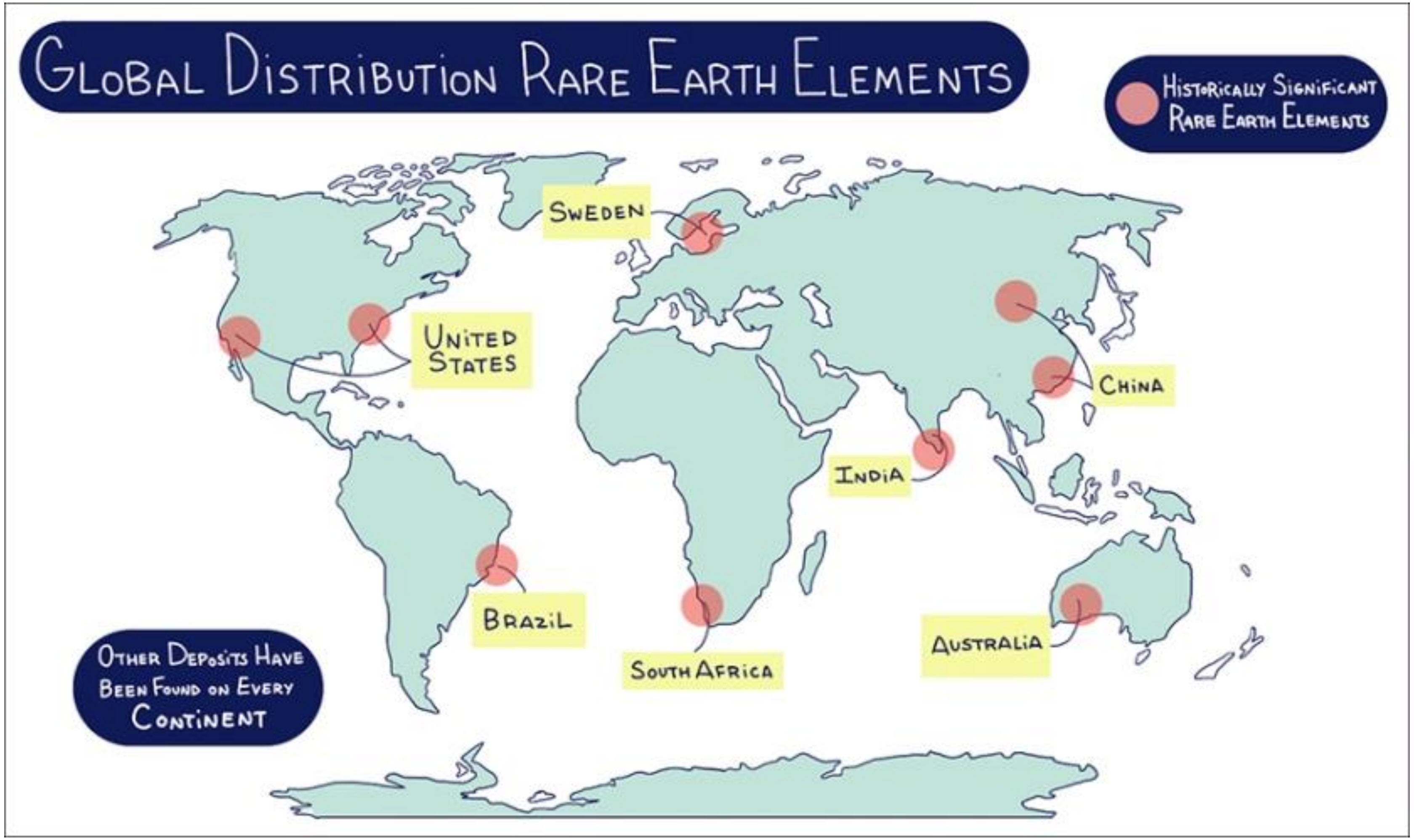
Abundance of REE in Earth's crust



- "rare" is a misnomer
- Similar crustal concentrations to common metals (Cr, Ni, Cu, Zn, Mb, Sn, W, Pb)

Figure ref

So not rare, but low in concentration

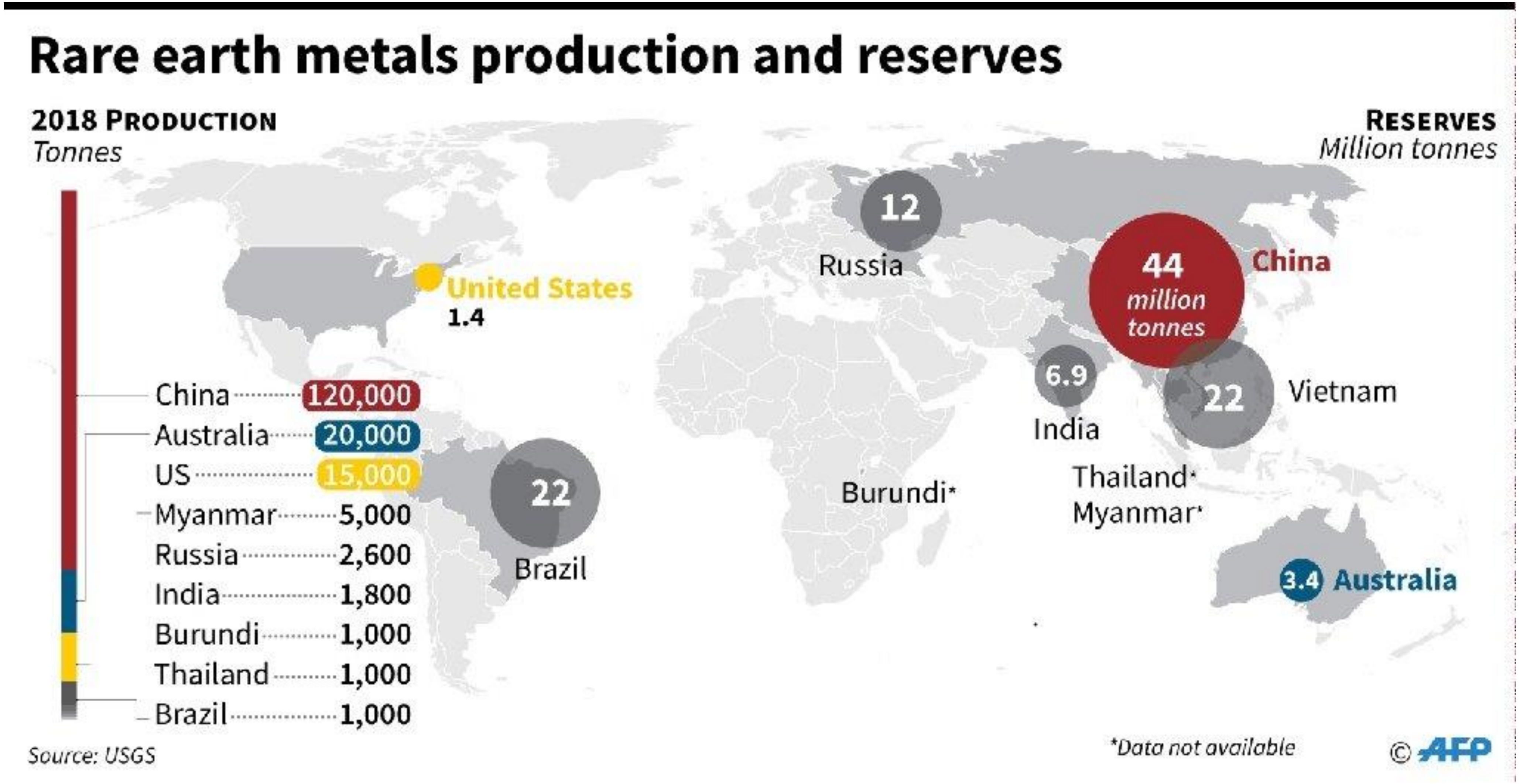


- Finding ores that contain significant concentrations to make their mining economically feasible

Global dist REE image
Material and Energy Requirement for Rare Earth Production

REE production and reserves

USGS



% REE global mined production in China in 2022?

A. 23
B. 45
C. 70
D. 90

REE in Canada

EPFL

Environmental impacts of REE in China (main producer)

1 tonne LREE used to make NdFeB magnets →

- 60,000 m^3 waste gases
- 200 m^3 acidified water
- 1-1.4 tonnes of radioactive waste
- 200 m^2 destroyed vegetation
- 300 m^2 destroyed topsoil
- 2000 m^3 of tailings

- Some REEs are found with naturally occurring radioactive elements such as uranium and thorium
- When REE ores are extracted from the ground and processed, these radioactive elements can be brought to the surface along with the REEs.

Report: Can China continue to fuel our global clean smart future?

How is China addressing environmental risk?

Big issues:

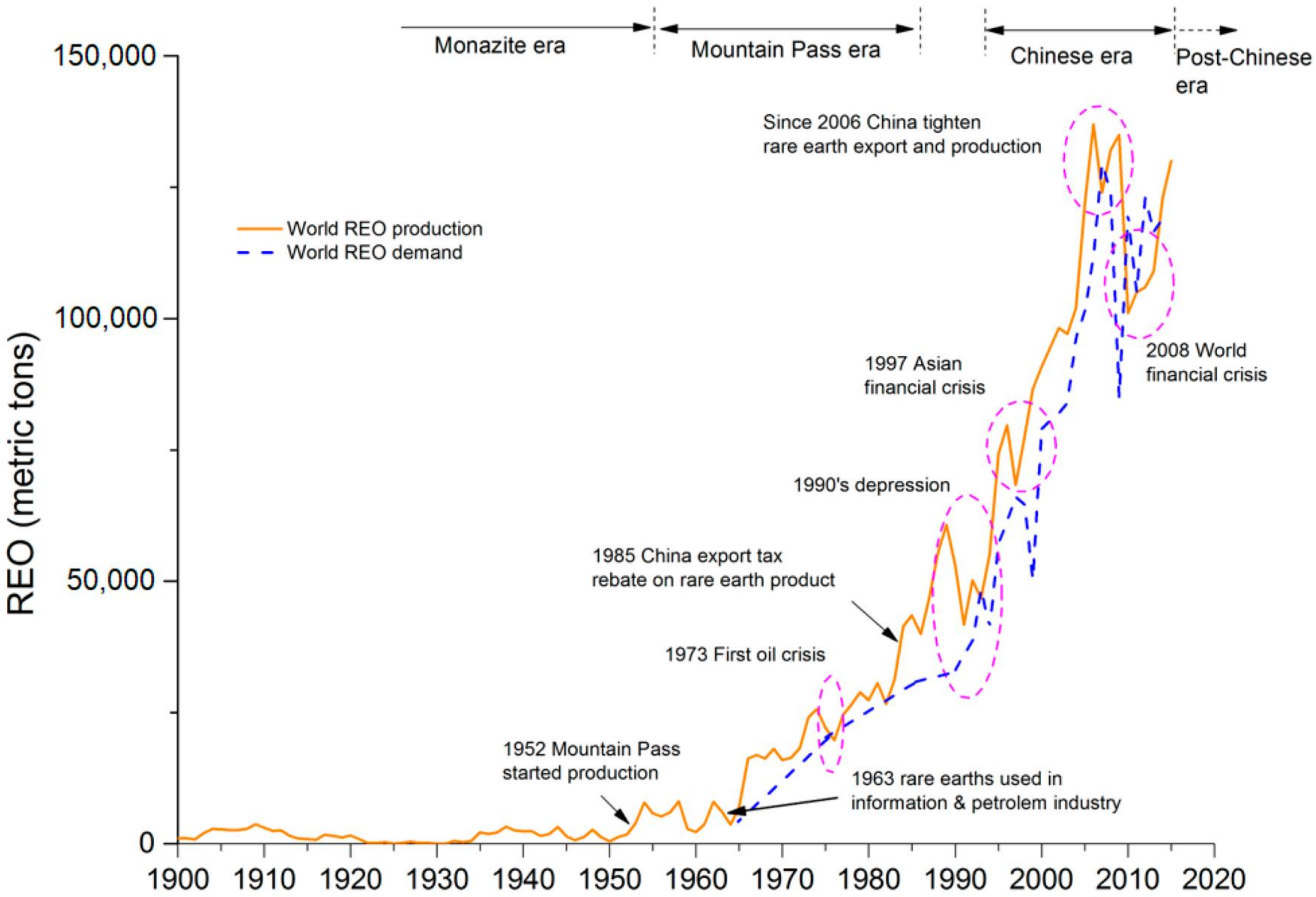
- Illegal mining operations
- Cancer villages
- Contaminated water… Yellow River

Mitigation strategies:

- Consolidate all mining operations into 6 state-owned companies
- Buying African reserves in exchange of infrastructure projects
- Cleaning up dirty sites
- Recycling REEs
- Research into cleaner technologies

Report: Can China continue to fuel our global clean smart future?

When one country holds the resources , production and refining processes… what happened in 2010…



In 2010:

- Export quota
- Spike in price
- Demand increase

https://www.mdpi.com/2075-163X/7/11/203

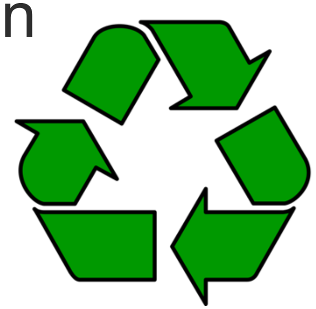
What happened in 2010…

- Dispute between China and Japan concerning a group of islands in the East China Sea (Senkaku Islands – Japan / Diaoyu Islands – China)
- Islands are of strategic importance – thought to be rich in oil and gas reserves, close to shipping lanes
- In Sept 2010, Chinese sea captain was arrested by Japanese coast guard
- China responded by cutting off REE exports to Japan (accounting for 50% of Japan's REE imports)
- This caused a global shortage of REEs, leading to higher costs and worries about supply chain vulnerability
- Globally this has spurred action toward supply chain diversification

NY Times 2010

REE recycling?

- Majority of current REE recycling is from permanent magnets (large ones)
- Difficult to recycle from waste electrical and electronic equipment (WEEE) due to small size and high potential to contaminate recycle streams (cell phones, hard disks)
- **Hydrometallurgical recovery techniques** - Magnets are dissolved in acids before the REE are precipitated out of solution.
- **Pyrometallurgical recovery techniques** - REE alloys are remelted & separated, exact approach used depends on the nature of the REE alloys within the magnets.
- **Gas phase extraction methods** where the REE are transferred to a volatile chloride phase and are separated based on differences in volatility.



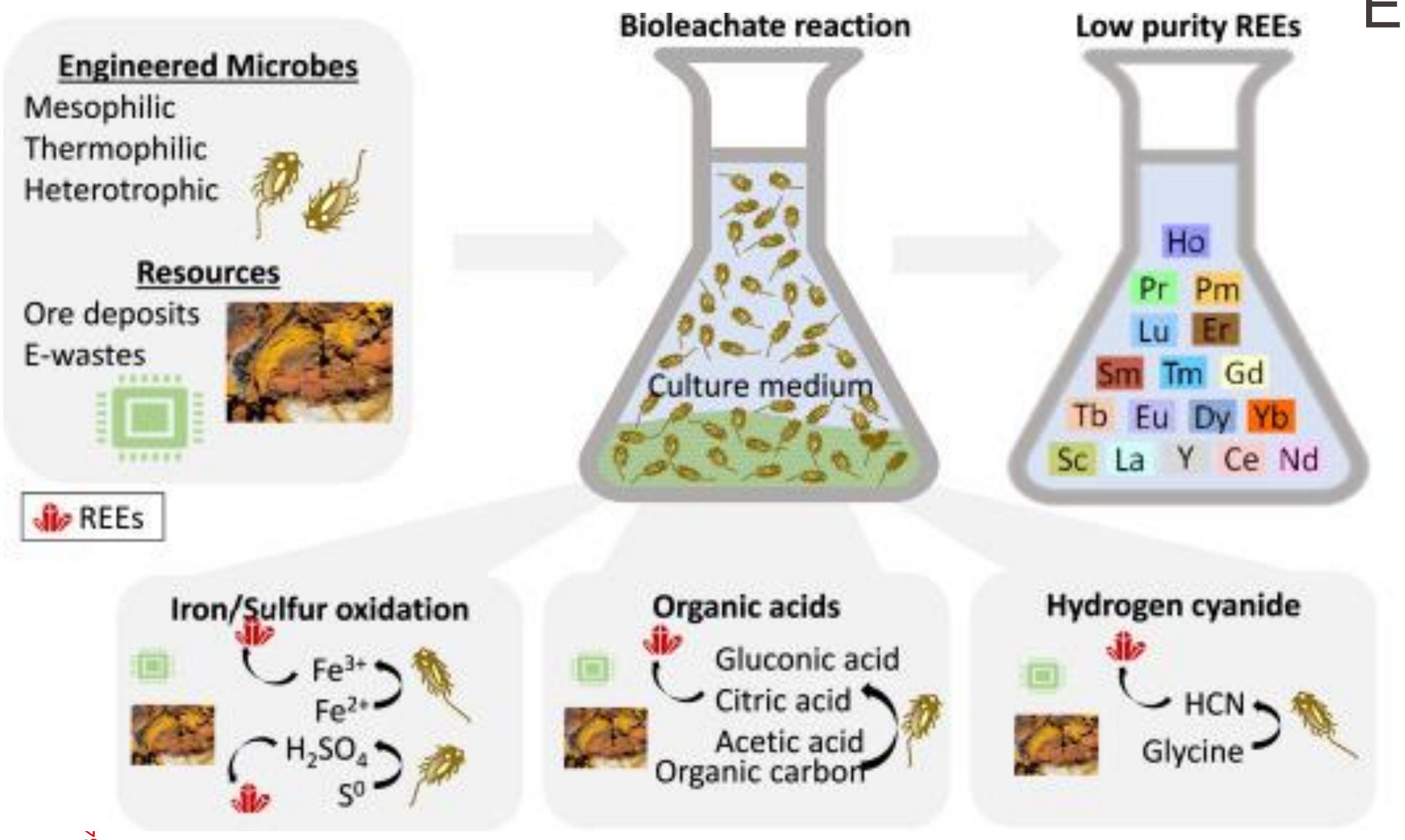
Recycling REEs

Tesla and REEs

[Tesla REE Reuters Article]

- 2024 Investor Day – Tesla announced that it will eliminate the use of REEs in its next gen EVs
- Already reduced REEs by 25%

New tech – bacteria that extract REEs? (ELMs!)



E.g.,"bioleaching" REEs with microbes

Current nature-based biological practices for rare earth elements extraction and recovery: Bioleaching and biosorption, Renewable and Sustainable Energy Reviews, Volume 173, 2023, 113099, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2022.113099.

Key takeaways…

- REE's unique properties derive from their electronic configurations
- REE's are important to many key technologies, including our transition to green energy/decarbonisation (especially as magnets!)
- REE's in green energy applications (EVs, green energy) must be balanced with the environmental costs of their production
- The supply chain for REE's is risky, since it is mainly controlled by one country (although this is changing…)
- Diversification of the supply chain, alternative technologies (ferrite magnets), and REE recycling are all important to mitigate the risk

EPFL

Textiles

- Materials made from fibers that are natural, synthetic, semi-synthetic or a mix of both
- Umbrella term that covers fibers, yarns, filaments, threads, different fabric types (woven/non-woven)

Textile Wikipedia

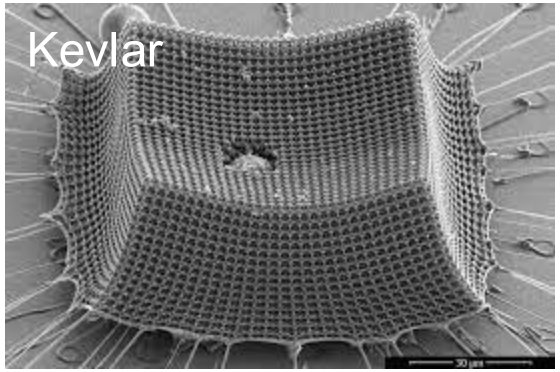
Textiles – fiber-based materials

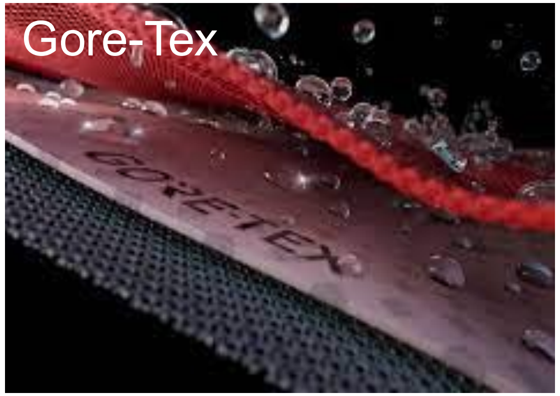
CONSUMER

Natural:
plant or animal

Semi-Synthetic
or Synthetic

TECHNICAL



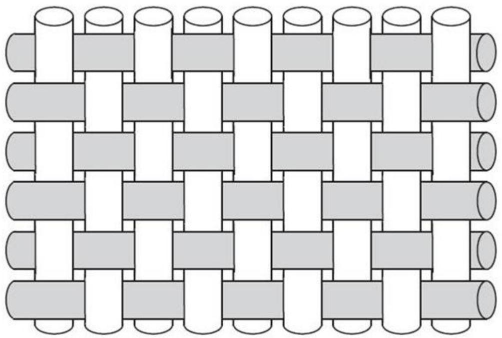


Synthetic

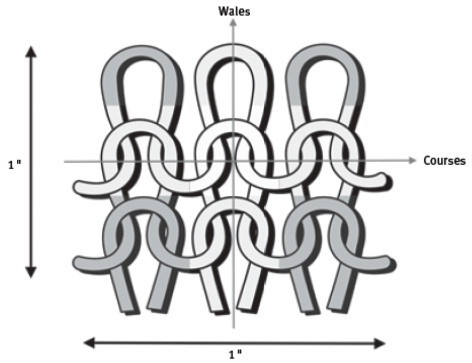
Woven; most common approaches

- Woven – fibers/threads are interlaced, like **weaving, knitting, crochet**

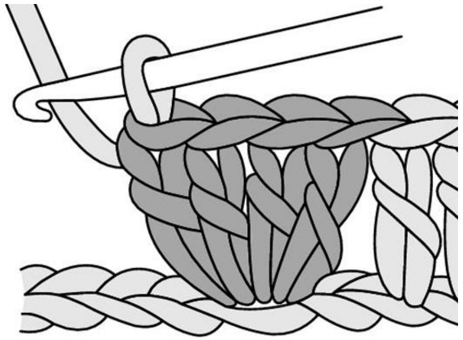
Weaving



Knitting



Crocheting



Industrial loom

Knitting machines

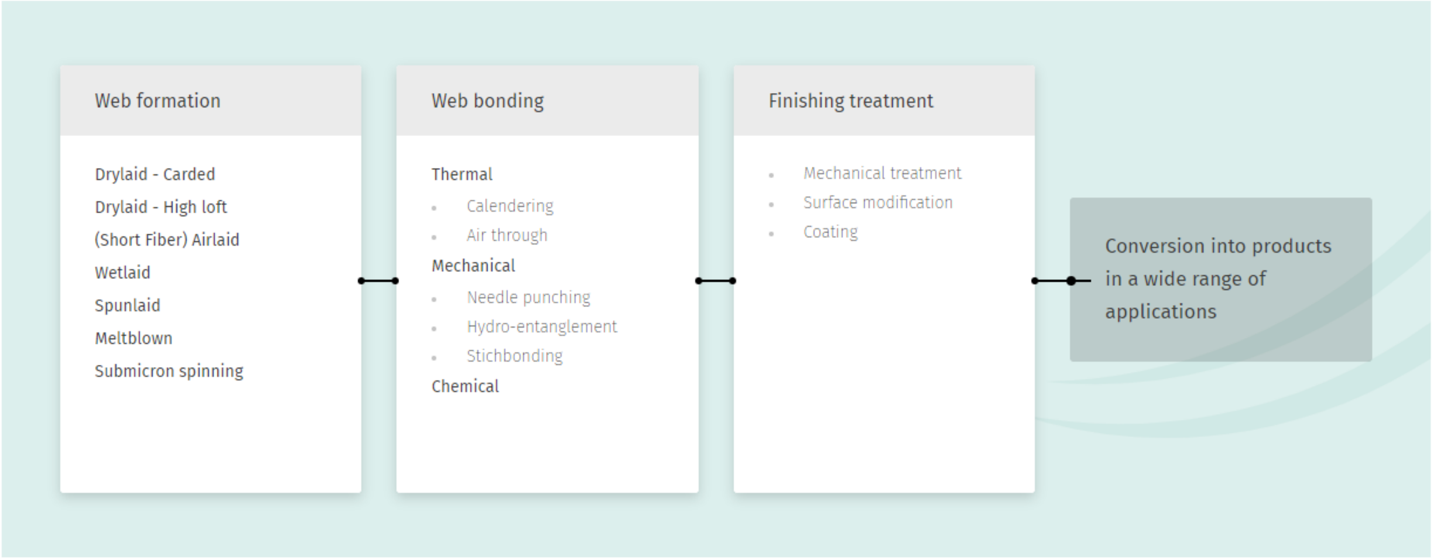
Woven and non-woven

Woven; Additive Manufacturing

Non-wovens

- Non-woven – short fibers/threads (staple fiber) bonded together by heat chemical, mechanical, or solvent treatments
- Distinct methods depending on end-use requirements like softness, strength, absorbency, and barrier protection
- Generally 3 steps: web formation, web-bonding, finishing

Woven and non-woven
Nonwovens (highly recommended website for level of detail)



Examples of non-wovens

Wool felt

Bandages

Cleaning cloths

Shoe covers

Masks

Tea bags

Vacuum bags

Generalized process for making a fashion textile

“Producing 1 kg of cotton in India consumes 22,500 litres of water, on average, according to research done by the Water Footprint Network.”

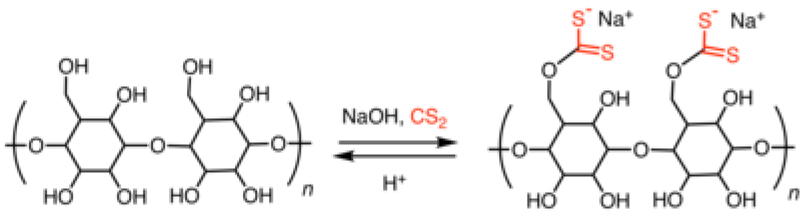
Step 1: Fiber

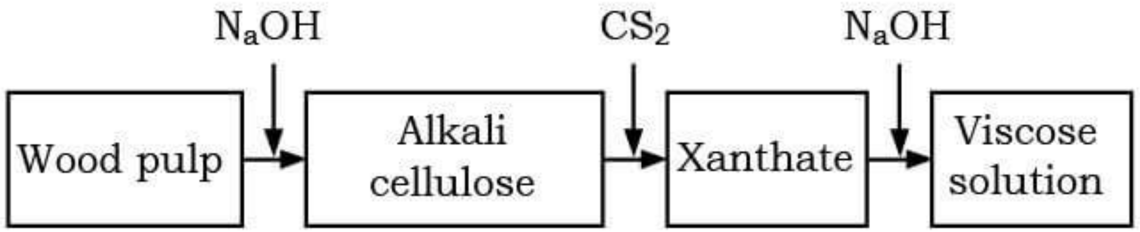
- Plant fibers – water, pesticides, insecticides, fertilizers (cotton)
- Animal fibers – pesticides, insecticides, chemicals (wool, silk)
- Semi-synthetic – acids, bases, process chemicals (viscose, lyocell)
- Synthetic – fossil oil feedstocks (polymerization), dyes, pigments, catalysts, etc.,
- Blended, e.g., polycotton (!!!)

Textile Guide

Cotton

Viscose process – semi-synthetic fibers from wood





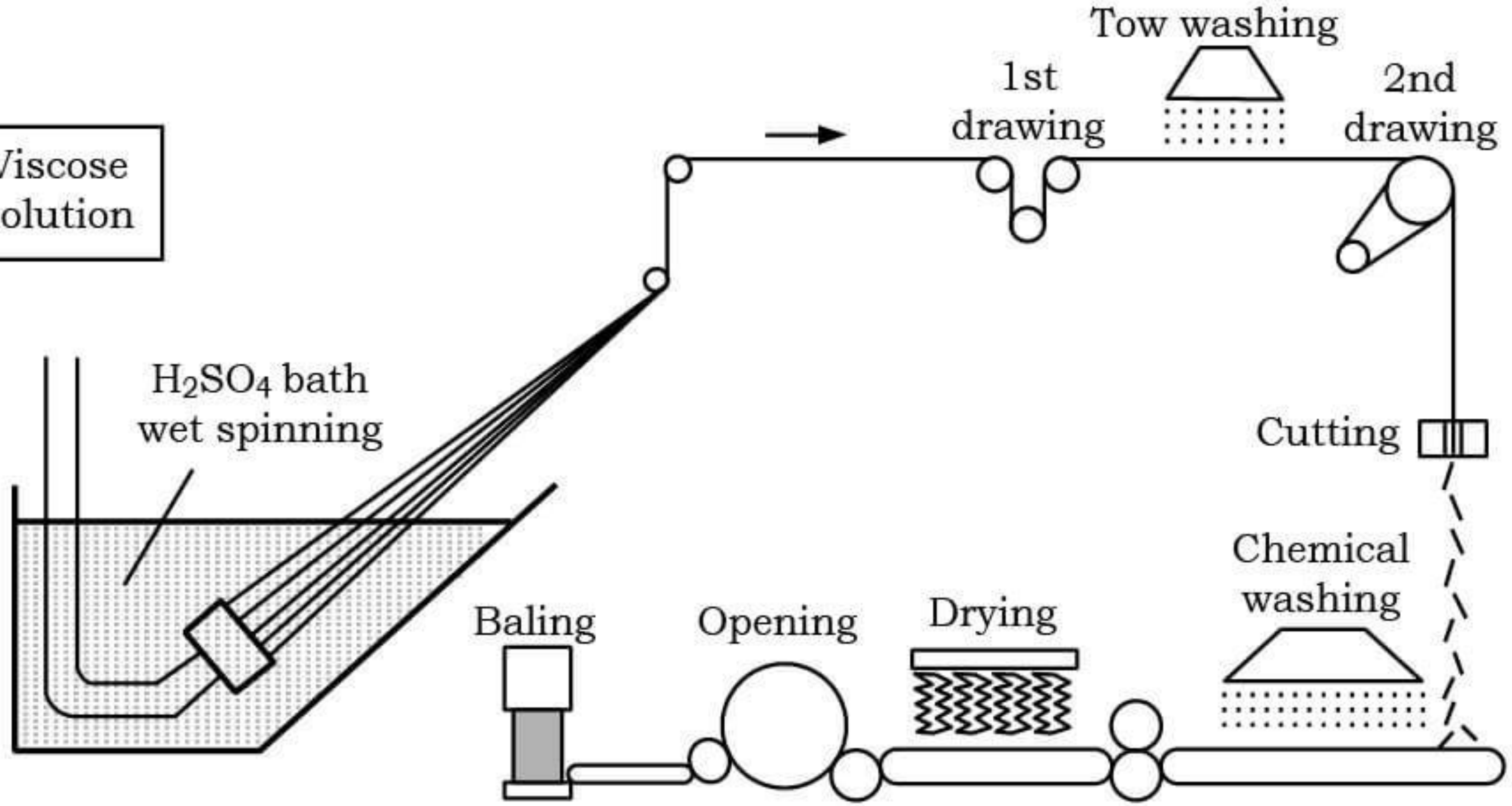


Fig: Schematic of rayon fiber production

https://www.deniminnovation.com/2019/02/09/viscose-manufacturing-process/

Generalized process for making a fashion textile

Step 2: Yarn

- Fibers are spun into a yarn
- Mechanical process
- Uses spinning oils to modify fiber properties, like pliability

Textile Guide

Generalized process for making a fashion textile

Step 3: Fabric

- Woven or non-woven
- Sizing chemicals and lubricant are added to strengthen and prevent breakage during processing
- Exact chemical inputs depend on whether woven or non-woven

Textile Guide

EPFL

Generalized process for making a fashion textile

Step 4: Pretreatment

- Washing (detergents, solvents)
- Desizing (enzymes)
- Bleaching (facilitates dying, makes fibers more absorbent)
- Mercerization (swell and strengthen cellulose fibers; NaOH)
- Carbonisation (remove impurities from wool; acid)

Textile Guide

Generalized process for making a fashion textile

Step 5: Dyeing & Printing

- Hazardous chemical, dyes and pigments
- Washing (detergents, water)

Textile Guide

Generalized process for making a fashion textile

Step 6: Finishing

- Handle modification (softeners)
- Anti-wrinkle
- Anti-static
- Anti-piling
- Anti-bacterial
- Wet repellant
- Oil repellent
- Flame retardant
- Etc…

Textile Guide

Resources and pollution

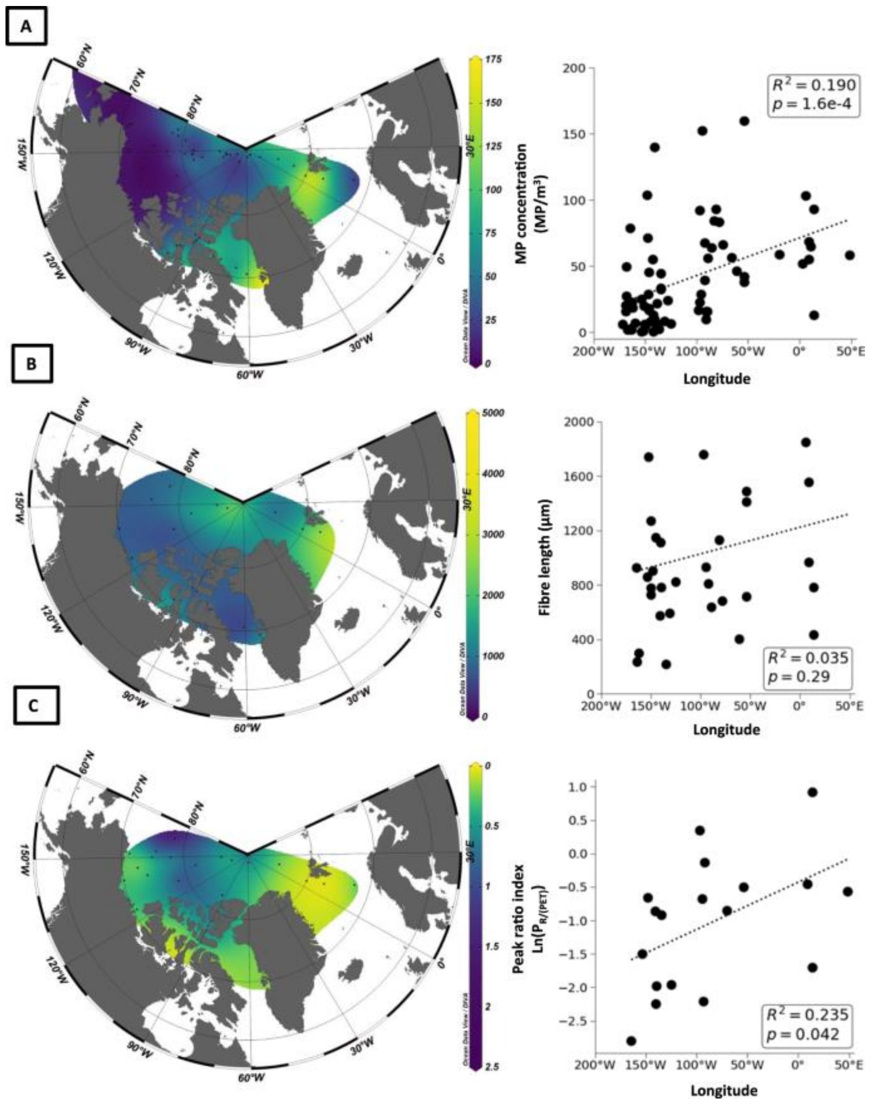
- 79 trillion liters of water consumed/year
- Up to 8% of global CO_2 equivalent emissions (2.9-4 Gt of CO_2 equivalent)
- Carbon footprint derived from high energy use, depends on location (e.g., China's textile production uses coal-based energy)
- Energy use and CO_2 emission highest in fiber extraction/production; 160 kWh/kg polyamide
- 20% of industrial water pollution
- Toxic chemicals – cotton accounts for 24% of global sales of insecticides and 11% of pesticides
- >92 million tonnes of textile waste/year (80% of clothing produced ends up landfilled or incinerated, only 20% recycled)
- 35% of oceanic primary plastic pollution (190,000 tonnes/year)

Nat Rev Earth Environ **1**, 189–200 (2020).
https://doi.org/10.1038/s43017-020-0039-9

Source: WWF report

Microplastics

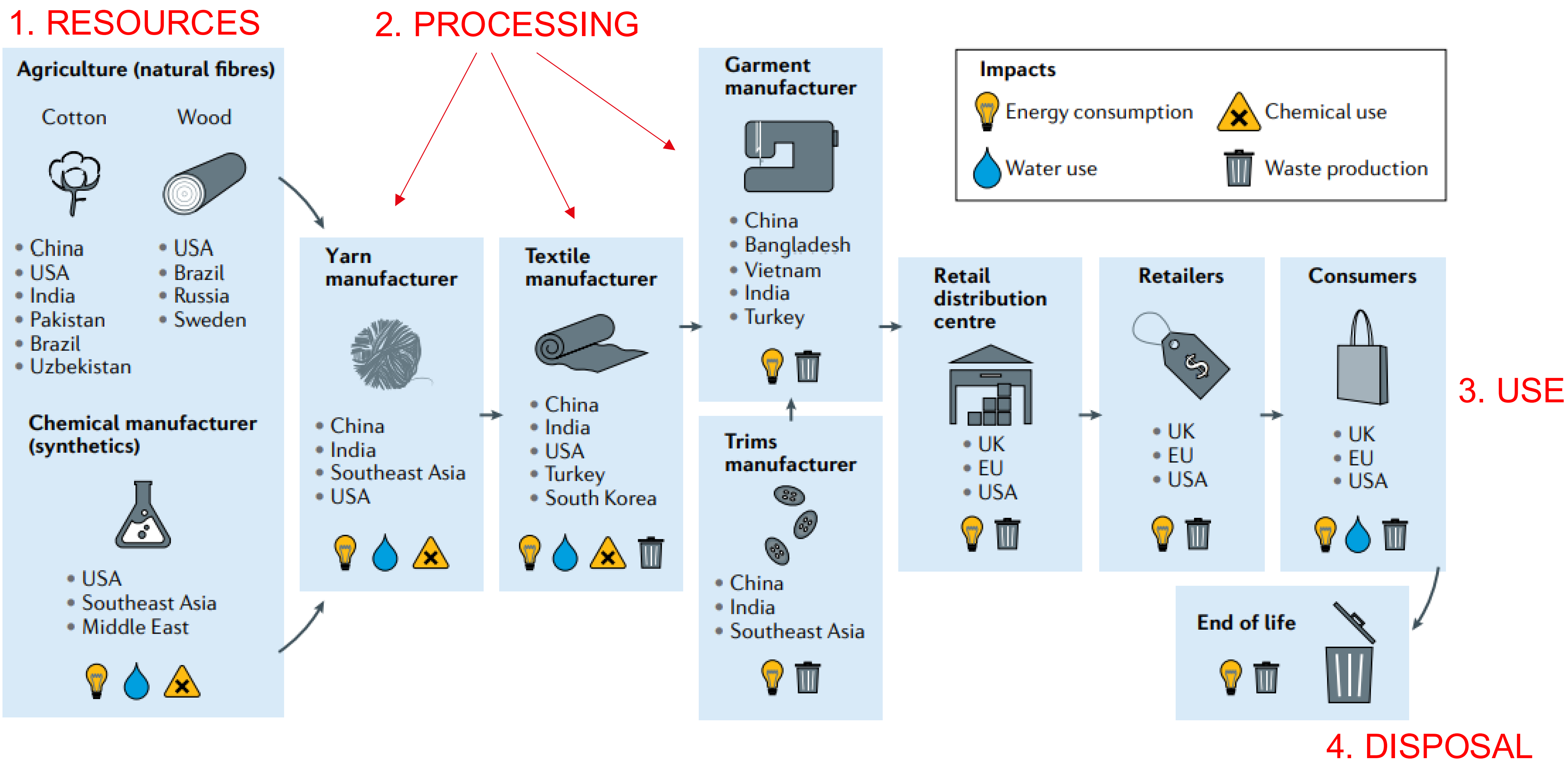
- Released by mismanaged plastic and textile waste
- 14 million tonnes of microplastics on the ocean floor
- 18% of European microplastics released to oceans from synthetic textiles (globally 16-35%)
- **Majority released in first few washes**



Pervasive distribution of polyester fibres in the Arctic Ocean is driven by Atlantic inputs. *Nat Commun* **12**, 106 (2021).

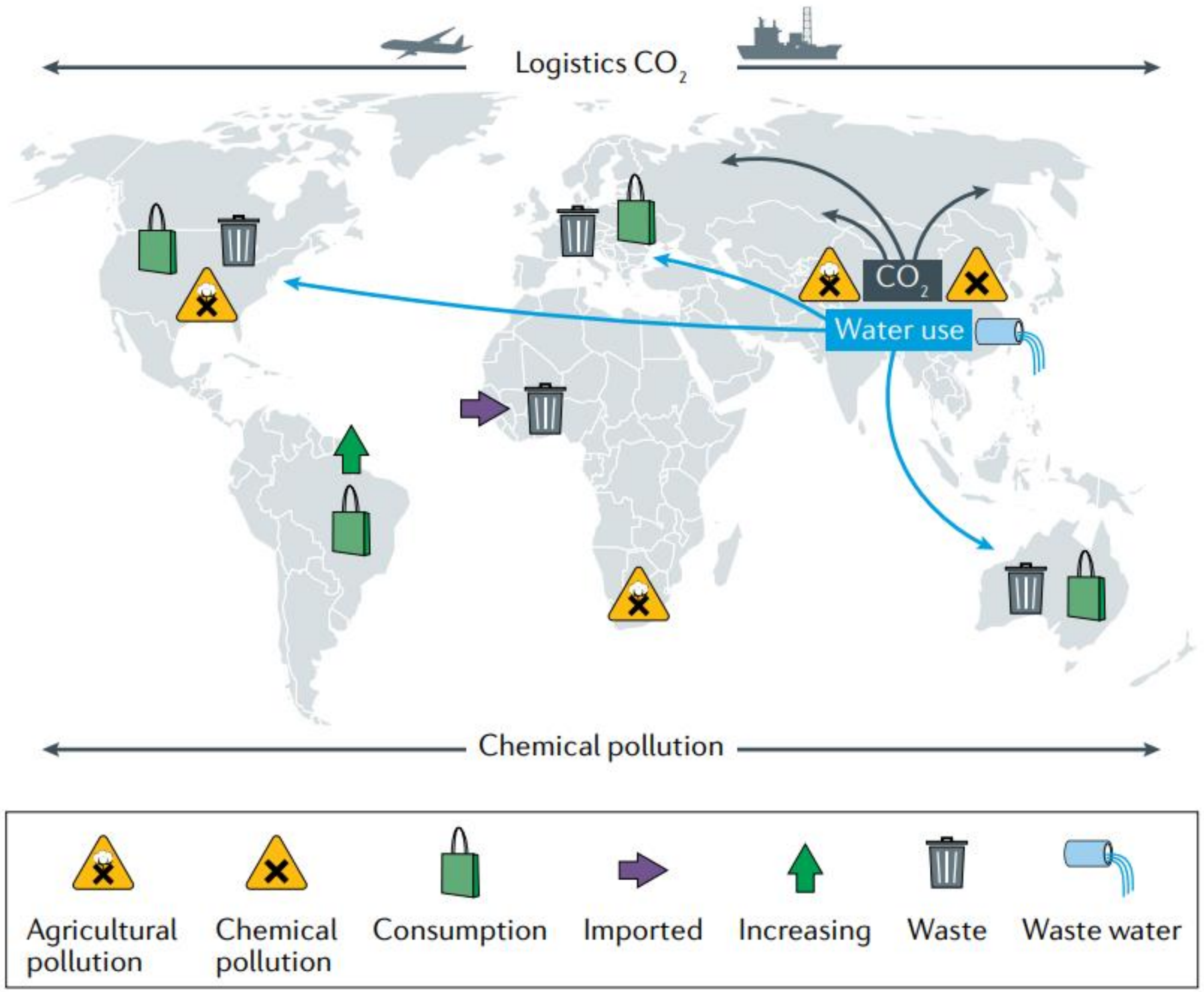
https://www.eea.europa.eu/

Hot spots in the life cycle of a fashion textile



The environmental price of fast fashion. *Nat Rev Earth Environ* **1**, 189–200 (2020). https://doi.org/10.1038/s43017-020-0039-9

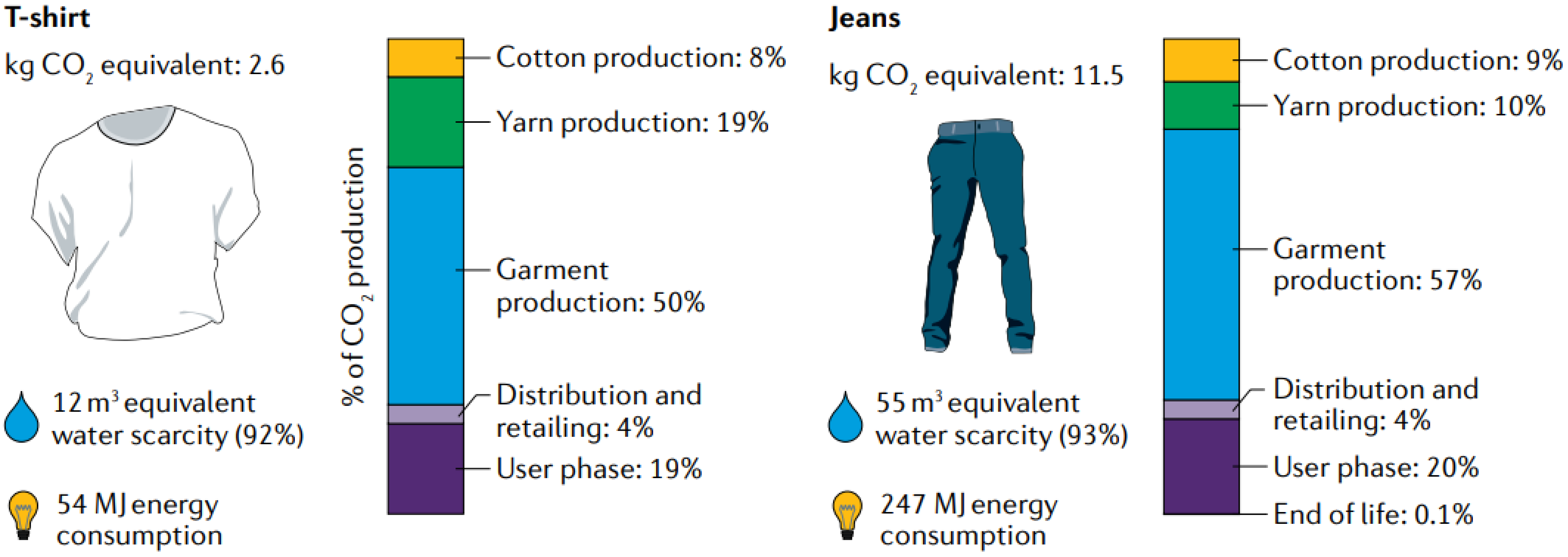
Geographic impacts across the value chain



- Chemical pollution most significant in countries where cotton is cultivated (India, China) and where water from processing is not properly purified
- Waste in production and consumption, disposed of locally or exported (countries in Africa for example)

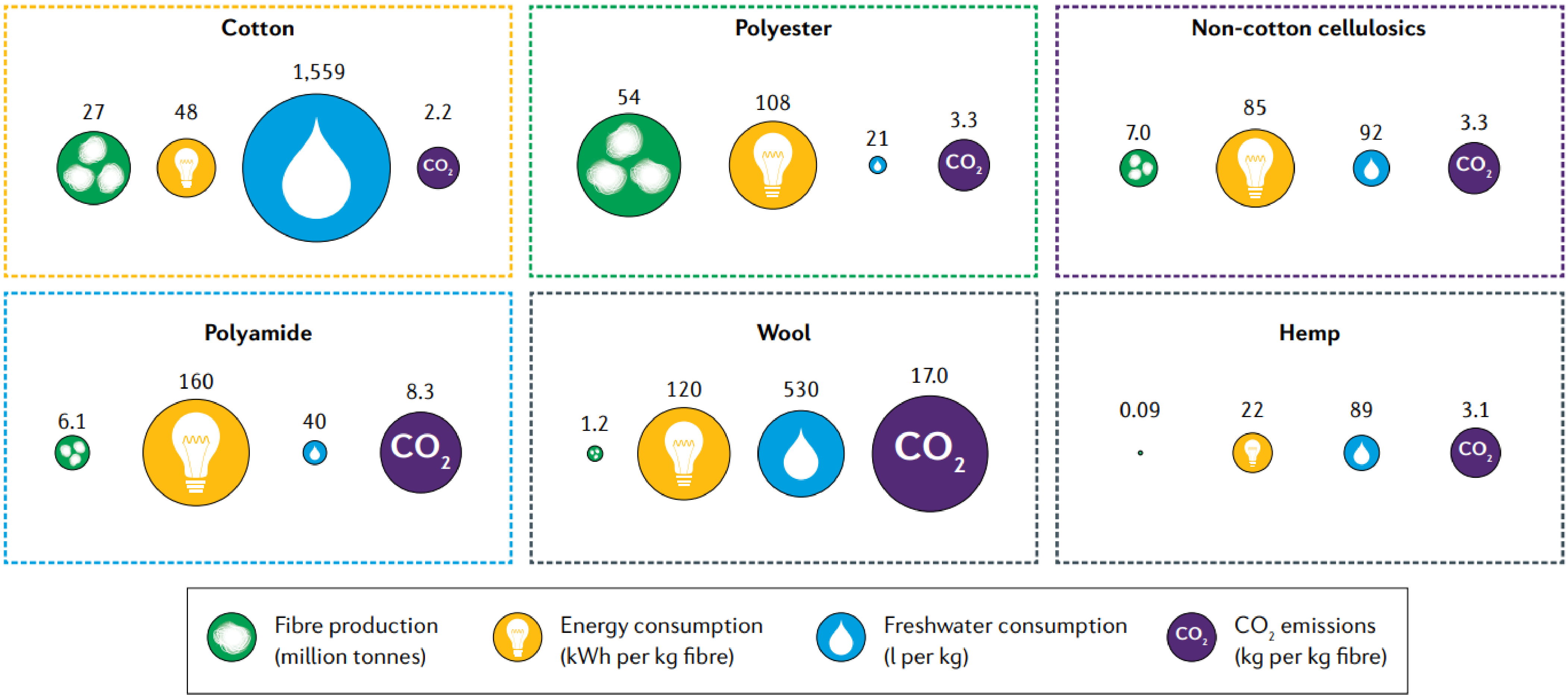
The environmental price of fast fashion. *Nat Rev Earth Environ* **1**, 189–200 (2020). https://doi.org/10.1038/s43017-020-0039-9

A t-shirt and a pair of jeans

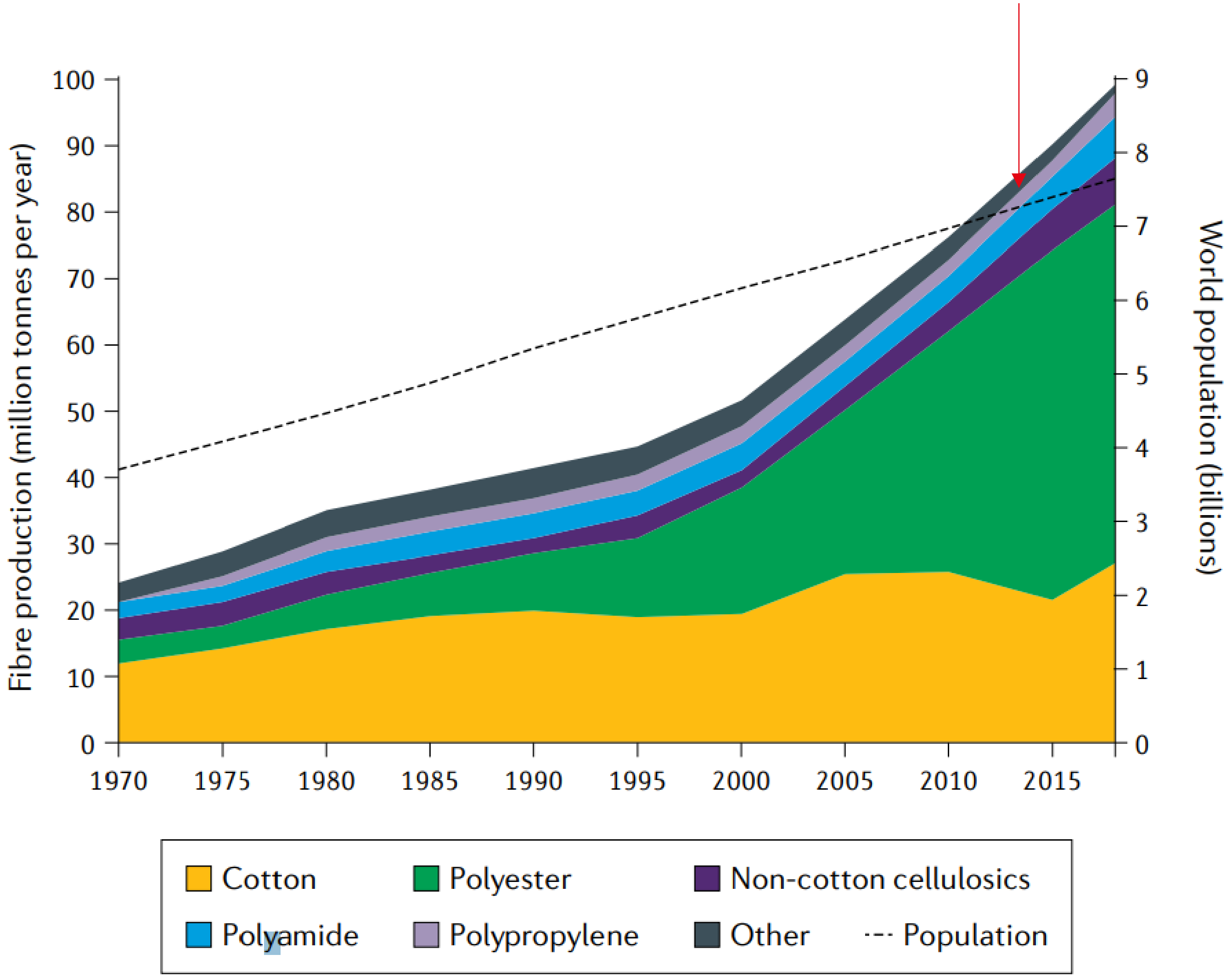


The environmental price of fast fashion. *Nat Rev Earth Environ* **1**, 189–200 (2020). https://doi.org/10.1038/s43017-020-0039-9

Environmental impacts of 6 different fibers



The environmental price of fast fashion. *Nat Rev Earth Environ* **1**, 189–200 (2020). https://doi.org/10.1038/s43017-020-0039-9



- *In 2010's: rate of textile production > rate of pop growth*
- *Brands now producing almost 2× more than before 2000*
- *Driven by cheap manufacture costs, fast fashion, increasing consumerism*

The environmental price of fast fashion. *Nat Rev Earth Environ* **1**, 189–200 (2020). https://doi.org/10.1038/s43017-020-0039-9

EPFL

EU 27 textile consumption in 2020
Per person
In kilograms

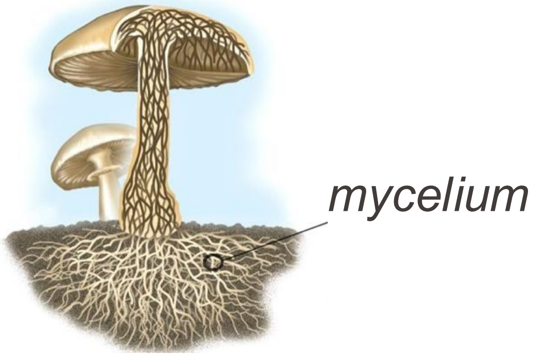
EU 27 textiles

Greener ways to produce textile fibers

It is assessed vs conventional viscose process to enable reduction of ***at least* 33 percent energy, *at least* 80 percent lower water usage, and *at least* 70 percent less chemicals**. Compared to market average cotton, it would mean **significantly lower water consumption, and no use of pesticides, herbicides, or fertilizers**. TreeToTextile is still refining its process and with the help of the demonstration plant, **the intent is to further optimize the environmental performance and minimize energy and chemical use.**

https://treetotextile.com/sustainability

Artificial leathers grown from mycelium



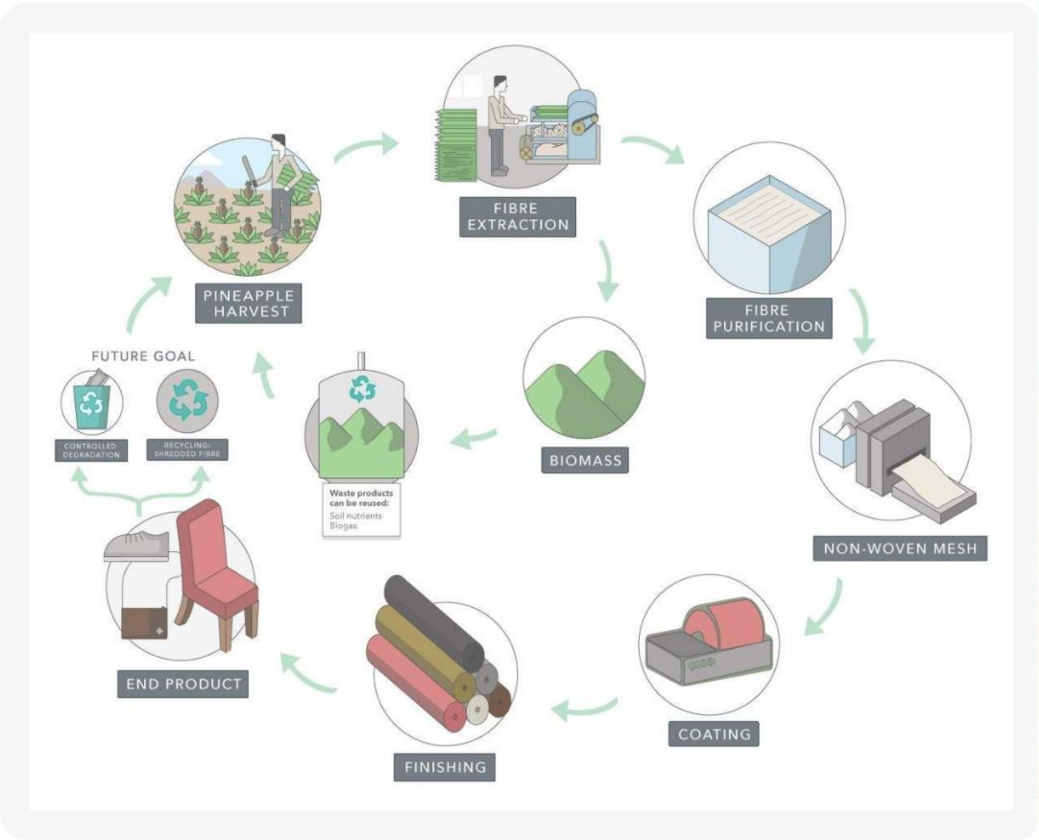
Haneef, M. *et al.*
Sci. Rep. 7, (2017).

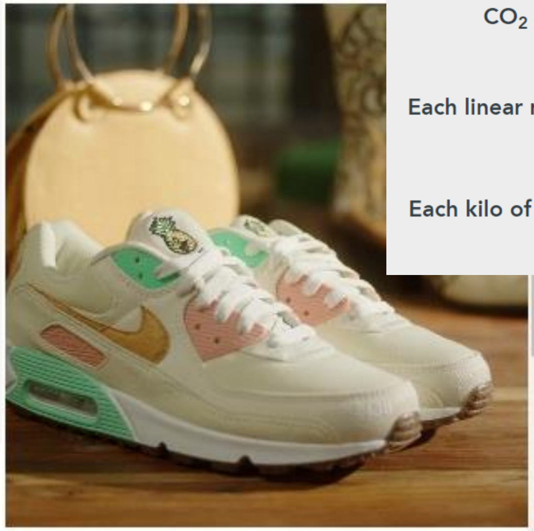
https://www.madewithreishi.com/

https://boltthreads.com/technology/mylo/

Food waste to fabric and leather – pineapple leaf yarns, fabrics, leathers

THE LIFE CYCLE OF PIÑATEX





/ Environmental Impact

The pineapple leaf fibres used to create our products are an agricultural waste product, which means that no extra land, water or pesticides are required to produce the raw material. Through waste valorisation, Ananas Anam reduces the amount of pineapple leaves being burnt which reduces CO_2 emissions from being released into the atmosphere.

Each linear meter of Piñatex prevents the equivalent of 12kg CO_2 from being emitted.

Each kilo of Piñayarn prevents the equivalent of up to 6kg of CO_2 from being emitted.

https://www.ananas-anam.com/

CNC – cellulose nanocrystals (some of my research)

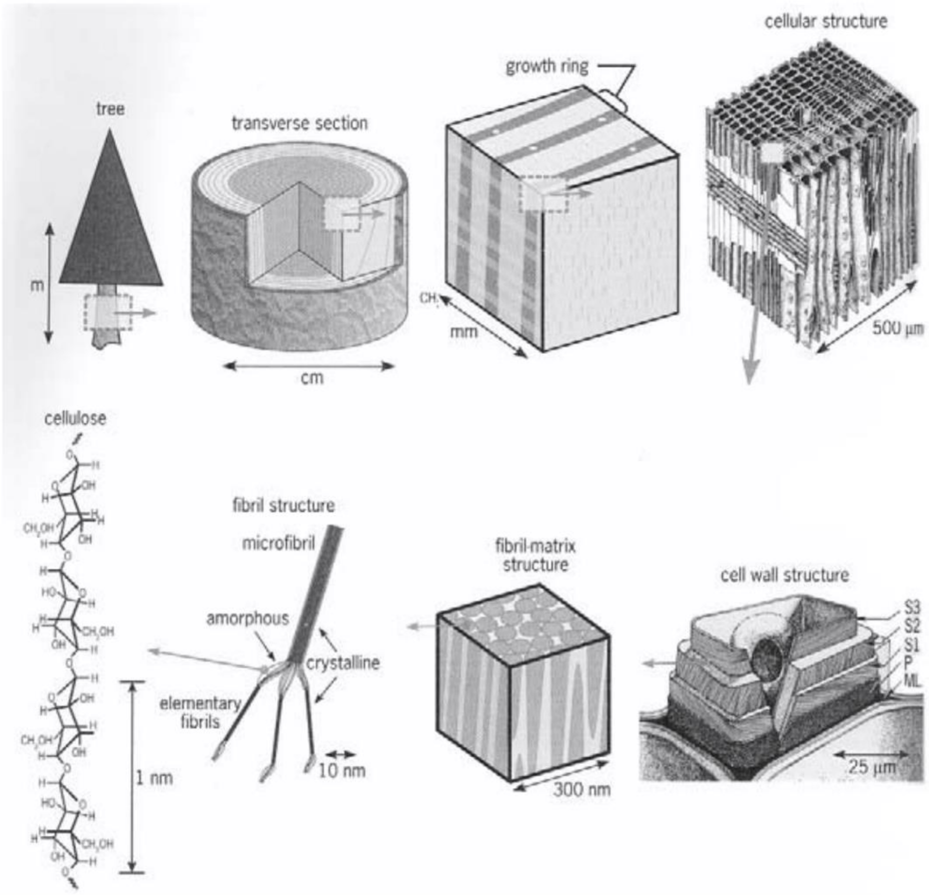
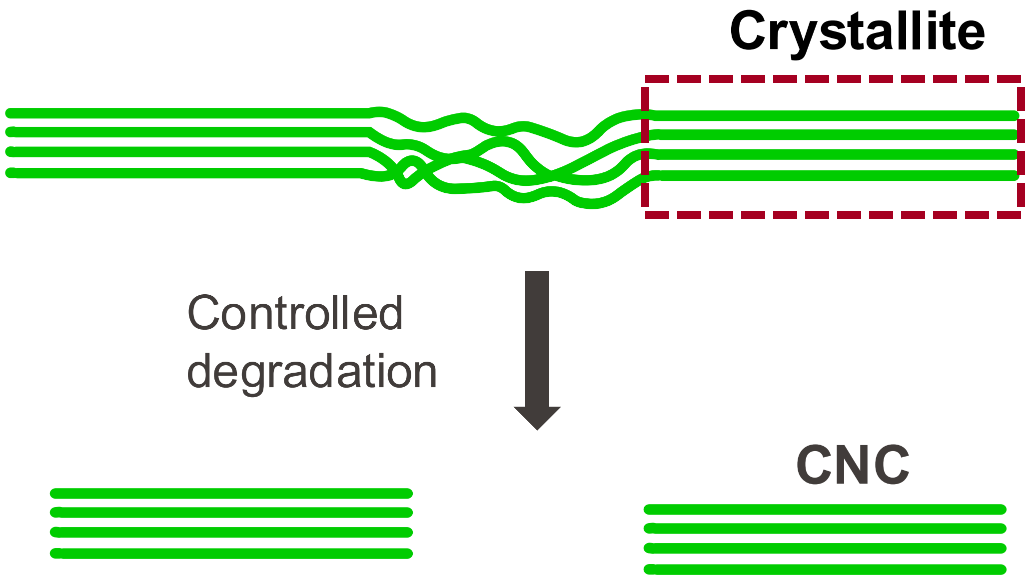
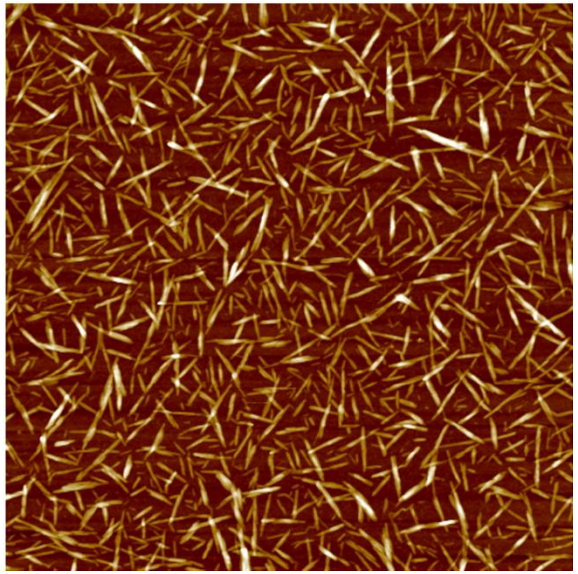


Fig. 1. Hierarchical structure of wood, showing the size scale of each structural feature within wood. The linear polymer chains of cellulose (30% of wood by weight) arrange to form cellulose fibrils, which are the base strengthening component within wood. *(Adapted from R. J. Moon, C. R. Frihart, and T. Wegner, Nanotechnology applications in the forest products industry, Forest Prod. J., 56(5):4–10, 2006)*



Can be made from waste derived sources of cellulose

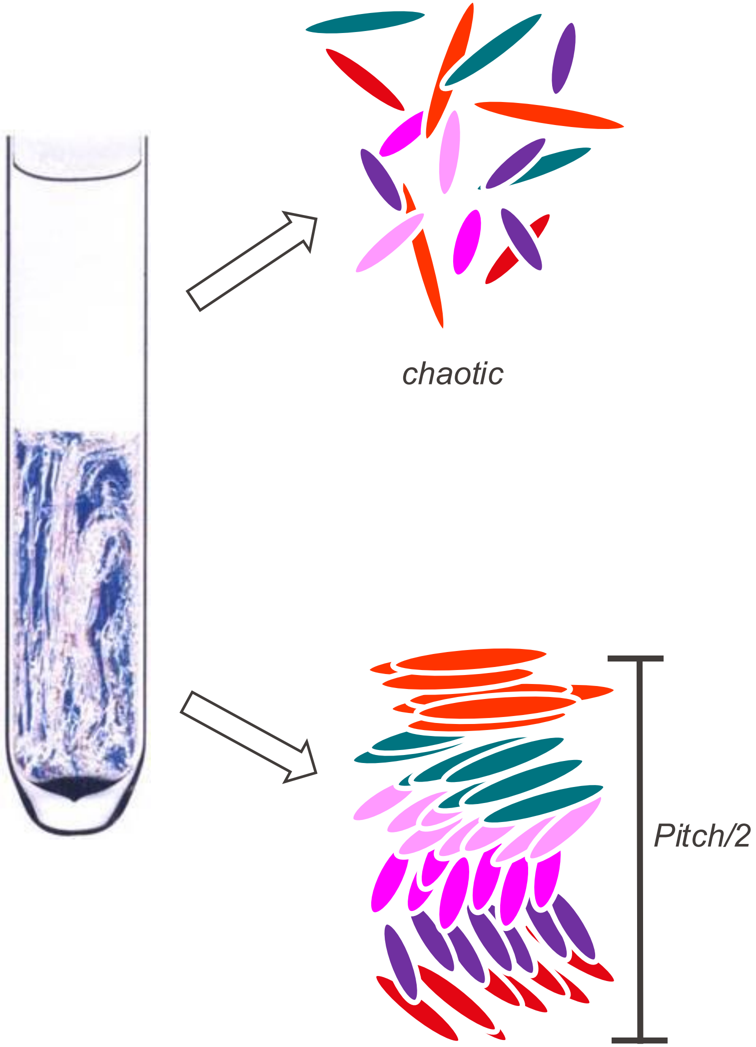


CNC, 28

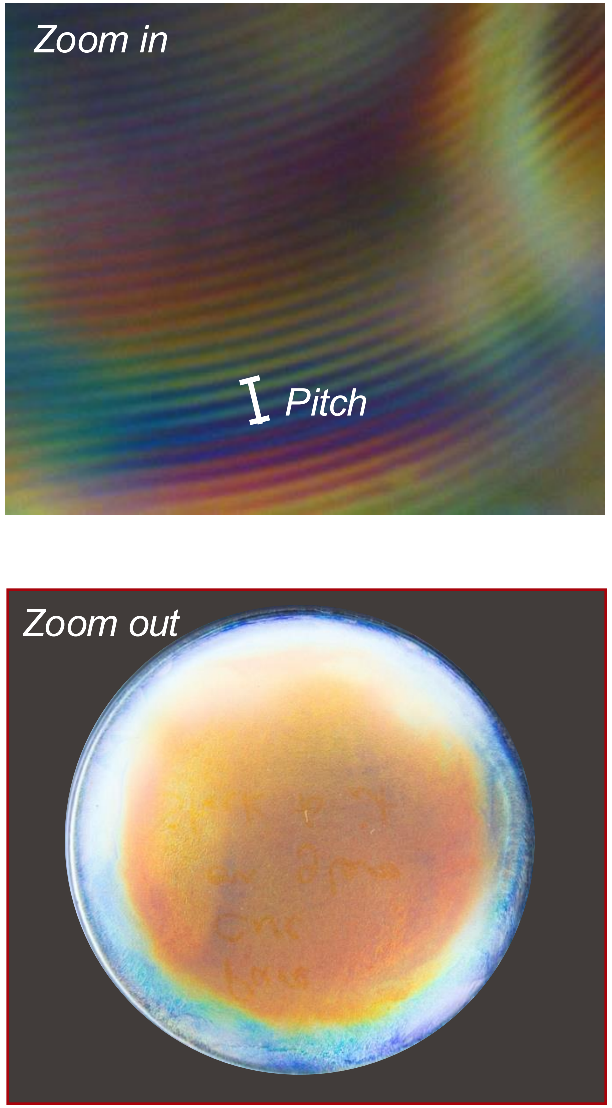
1 km away

I am super strong and love water so much! Depending on my mood and how much water is around, I can be random and chaotic or highly self-organized, especially when I feel crowded. If I become dehydrated, I start to feel crunchy but I become colorful and glittery. Weird, I know.

In water



All dried out



100% cellulose sequins

https://www.lvmh.com/news-documents/news/stella-mccartney-revolutionizes-fashion-with-worlds-first-sustainable-biosequins-material/

Key take aways (of the semester)

- I had a lot of information I wanted to share with you ☺
- Materials are intertwined with humanity's successes
- On the flip side, many of our current environmental challenges are closely tied to how we resource (Distribution? Quantities? Access? Renewable?), process (Energy! Water! Emissions!), use, and dispose of materials
- We can't just stop using materials (duh!), but we can use them more responsibly
- It's complicated – we rely on materials for a wide variety of function, from very simple to high performing, no one size fits all answer
- Use less, use for longer/re-use, simplify composition where possible, modular, repairable, diversity of materials where possible (alternatives, especially if needed for key technologies), diversity of materials sources where possible, investment in end-of life strategies, investment in the material-enabled technologies that can alleviate environmental impacts (e.g., renewable energy, DAC)
- Thank you!