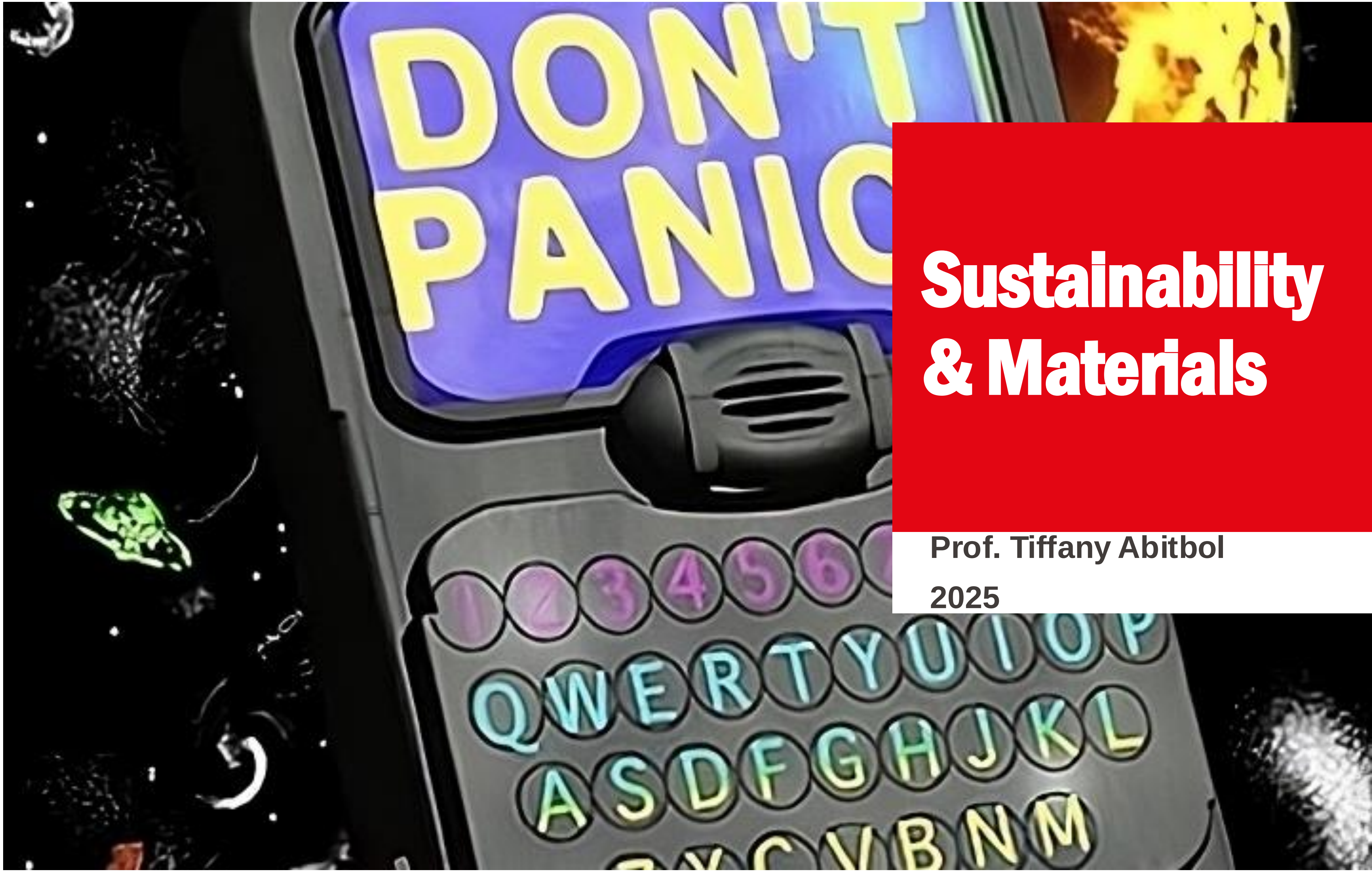
Sustainability & Materials

Prof. Tiffany Abitbol

2025



Updates

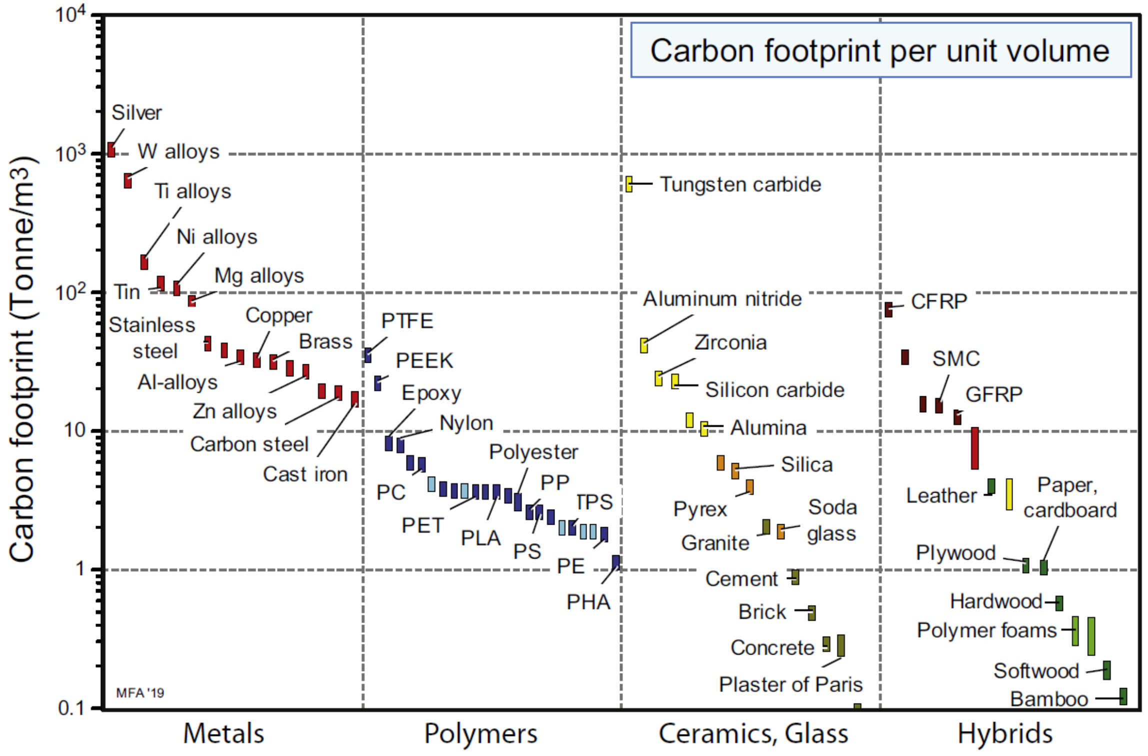
- **New:** Assignment due Mar 24 at 17
- **Next week guest lecture:** Dr. Edoardo Chiarrotti of the Enterprise for Society (E4S) Center will teach us about carbon and biodiversity credits, from 10-11 AM (Please prioritize attendance in person)
- **9:15-10 AM: Project time**
- **In two weeks:** Biomaterials focus, with guest lecture from Dr. Wolfram Bruck (me: finishing materials classes, possible all 3 class slots will be used)
- **In three weeks:** Midterm
- **After midterm:** moving on from the very general content thus far

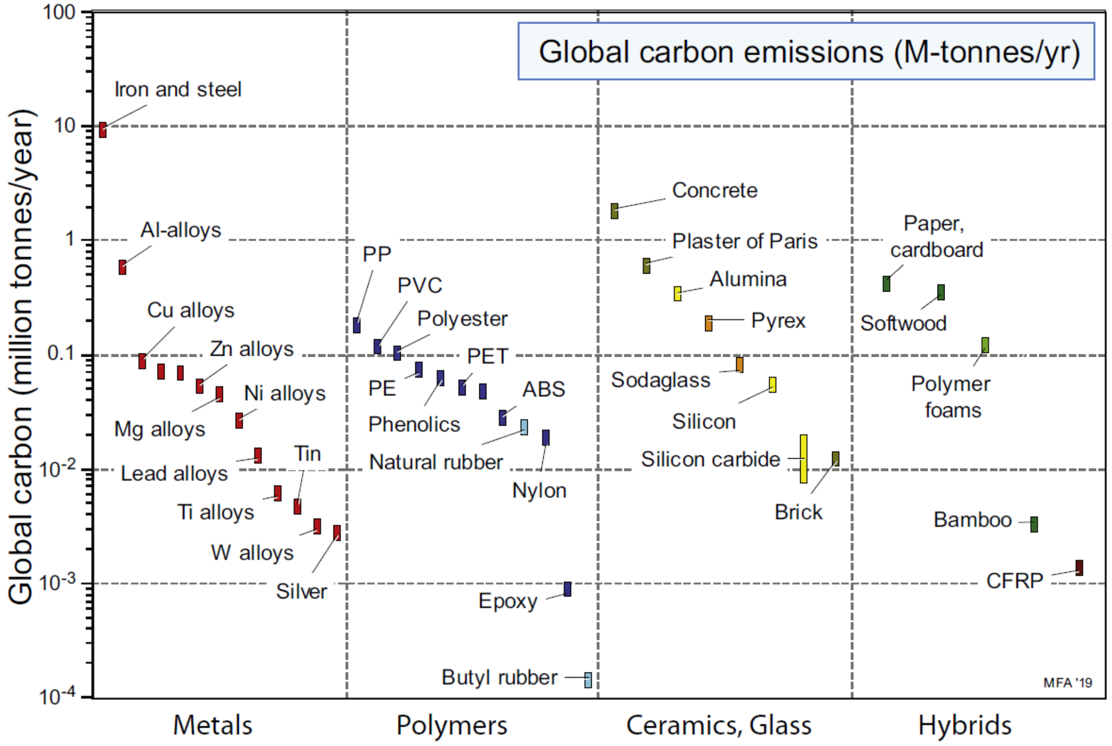
Recap

- Last week we discussed some metrics for circularity and the concept of LCA
- We saw that carbon footprint when measured per kg or volume of a material does not always translate to an accurate picture, **global carbon is better**
- We saw the general concept of LCA: it's not straightforward, for example you need to be able to describe your material product or service in terms of a functional unit and this is not always possible!
- Eco-audits or more simplified metrics are not only more accessible but can be more appropriate

Recap: Carbon footprint vs. global carbon

- Concrete has a low carbon footprint but a high global impact





- Unit does not consider how much of the material is produced

- More accurate since it accounts how much material is produced

Recap: LCA

- Can you imagine situations where it's just not possible to do an LCA?

Four phases:

1. Goal and scope: It can be non-trivial to describe a functional unit
2. Inventory: It can be non-trivial to have access to all data and to reliable data
3. Impact: data normalization and weighting is not without challenges
4. Assessment: how to best assess and use the results of these studies depends on many factors

Real-life example: my research

WOODCELL

WOOD RESIDUES DERIVED MICROCRYSTALLINE CELLULOSE FOR SUSTAINABLE MATERIALS

Circular Bio-based Europe Joint Undertaking

- New grade of microcrystalline cellulose (MCC)
- We know that it can be produced from waste and is produced more efficiently and with fewer emissions than its counterparts (traditional MCC, nanocellulose)
- The project partly involves figuring out where we can use this material and there will likely be a few different functions
- How will we do an LCA for a material whose function is not yet defined and with multiple functions? What is a fair comparison?

Woodcell

Elaborating weighting of impact in LCA

- Last week, we discussed impact normalization and weighting to enable comparison between different impact categories
- A bit more on how this is done, not perfect but not as arbitrary as implied

Weighting

https://doi.org/10.1016/j.scitotenv.2023.169599

Table 1
Previous MCDA studies addressing sustainability and safety of chemicals or materials.

Authors (Year)	Purpose	Chemical/Material	Life cycle stages	Environmental assessment	Safety assessment	Other assessments	Normali-zation	MCDA method	Weighting
(Abdel-Basset et al., 2021)	Comparison of hydrogen production options	Hydrogen	Production	Contaminants emission, land requirements, rigid waste generation (Qualitative assessments from experts)	Influence in public health (Qualitative assessments from experts)	Economic, technical, and social (Qualitative assessments from experts)	N/A	Analytic Hierarchy Process (AHP)-COPRAS-EDAS	Weights provided by experts
(Acar et al., 2018)	Comparison of alternative hydrogen production options	Hydrogen	Production	GHG emissions, land use, water discharge quality, and solid waste (Qualitative assessments from experts)	Impact on public health (Qualitative assessments from experts)	Economic, technical, availability and other social (Qualitative assessments from experts)	N/A	hesitant fuzzy AHP	Weights provided by three experts from hydrogen production industry
(Acar et al., 2022)	Comparison of fuel cells	polymer electrolyte membrane, alkaline, phosphoric acid, molten carbonate, and solid oxide fuel cells	Not explicit	GHG, Land use, water discharge quality, solid waste generation (Qualitative and comparative assessments from three experts)	Human Health Impact (Qualitative and comparative assessments from three experts)	Economic, technical, and social	N/A	AHP (fuzzy variant)	Weights provided by experts
(Alkhatib et al., 2021)	Comparison of Hybrid Solvents for acid gas removal	mixtures of chemical solvents	Cradle to grate	LCA indicators (Cumulative energy demand, GWP, Eco-indicator 99) - assessment method FineChem Tool	Health and safety hazards	Relevant physicochemical solvent properties - using Polar soft-SAFT	N/A	Single-criterion rankings are compared, without an overall aggregation	N/A
(Banimostafa et al., 2012)	Comparison of chemical routes during early process design	4-(2-methoxyethyl)-phenol (MEP) and methyl methacrylate (MMA)	Not explicit	CED (Ecoinvent)	Risks (toxicity, safety, etc)	–	Internal (max-min normalization and other)	principal component analysis (PCA) based	Driven by the PCA
(Crivellari et al., 2021)	Comparison of alternative processes for synthetic methanol synthesis	Methanol	Production	Technological performance (energy efficiency) Env. Performance (Levelized GHG Emissions- the averaged emission over the lifetime of the process scheme)	Safety (Inherent hazard of the production unit with respect to humans)	Economic performance	Between zero (undesired) and 1 (desired) comparing the actual indicator with respect to a given target value	AHP	Four perspectives: Individualist, Egalitarian, Hierarchist, and Equal weighting
(Dinh et al., 2009)	Comparison of biodiesel production alternatives	Biodiesel from 5 different feedstocks	All	LCIA (GHG, water, land use),	methanol ratio, flash point	Economic and technical	N/A	AHP	Weights defined by the authors
(Iranfar et al., 2023)	Comparison of construction materials	Eight traditional and new construction materials	Production	Water, Energy, Recyclability, Sustainability (qualitative assessments)	Safety for workers (qualitative assessment)	Resource availability and technical	Internal (division by vector norm)	AHP (fuzzy), TOPSIS, VIKOR, WASPAS	Weights defined by the authors
(Janošovský et al., 2022a, 2022b)	Comparison of hydrogen production processes	Hydrogen	Not explicit	Environmental Impact (C factor, Eco-Indicator 99)	Process Safety (Process Route Index, Comprehensive Inherent Safety Index)	Economic, Material and energy utilization	Internal (max-min normalization)	AHP	Weights defined by the authors
(Jia et al., 2016)	Comparison of chemical processes	chemicals in general, example for ethanol	Production	Environmental (global warming potential (GWP), photochemical oxidation potential (PCOP), ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), human toxicity potential by ingestion	Safety (inherent safety, process safety)	Economic	Integer 1–5 scores	Analytic Hierarchy Process (AHP)	Weighs provided by decision makers and domain experts

2024 review

- Experts
- Authors
- PCA driven

Possible weighting approaches

- **Distance to policy target**, e.g., if the national goal is to reduce SO_2 emission by 50% and SO_2 by 20%, the carbon footprint will be weighted higher
- **Distance to scientific target**, e.g., if scientific consensus is 350 ppm atmospheric CO_2, the further away the current situation is from the target, the greater the weight
- **Monetization**, e.g., greater weight to impact categories that are expensive to prevent or repair, or how much people are willing to pay to prevent a certain impact
- **Panel**, e.g., ask a panel to rank the impacts

On the subject of weighting...

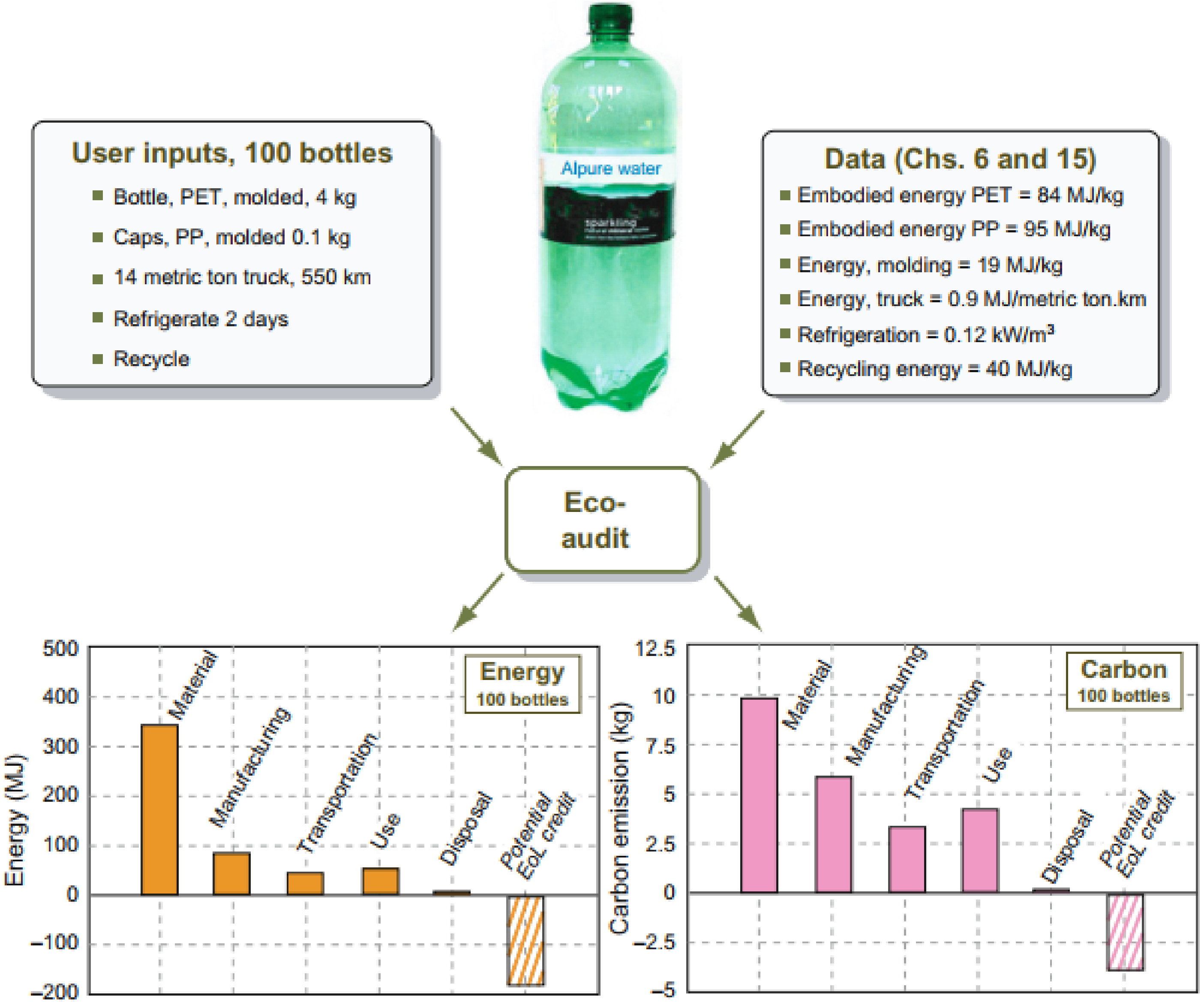


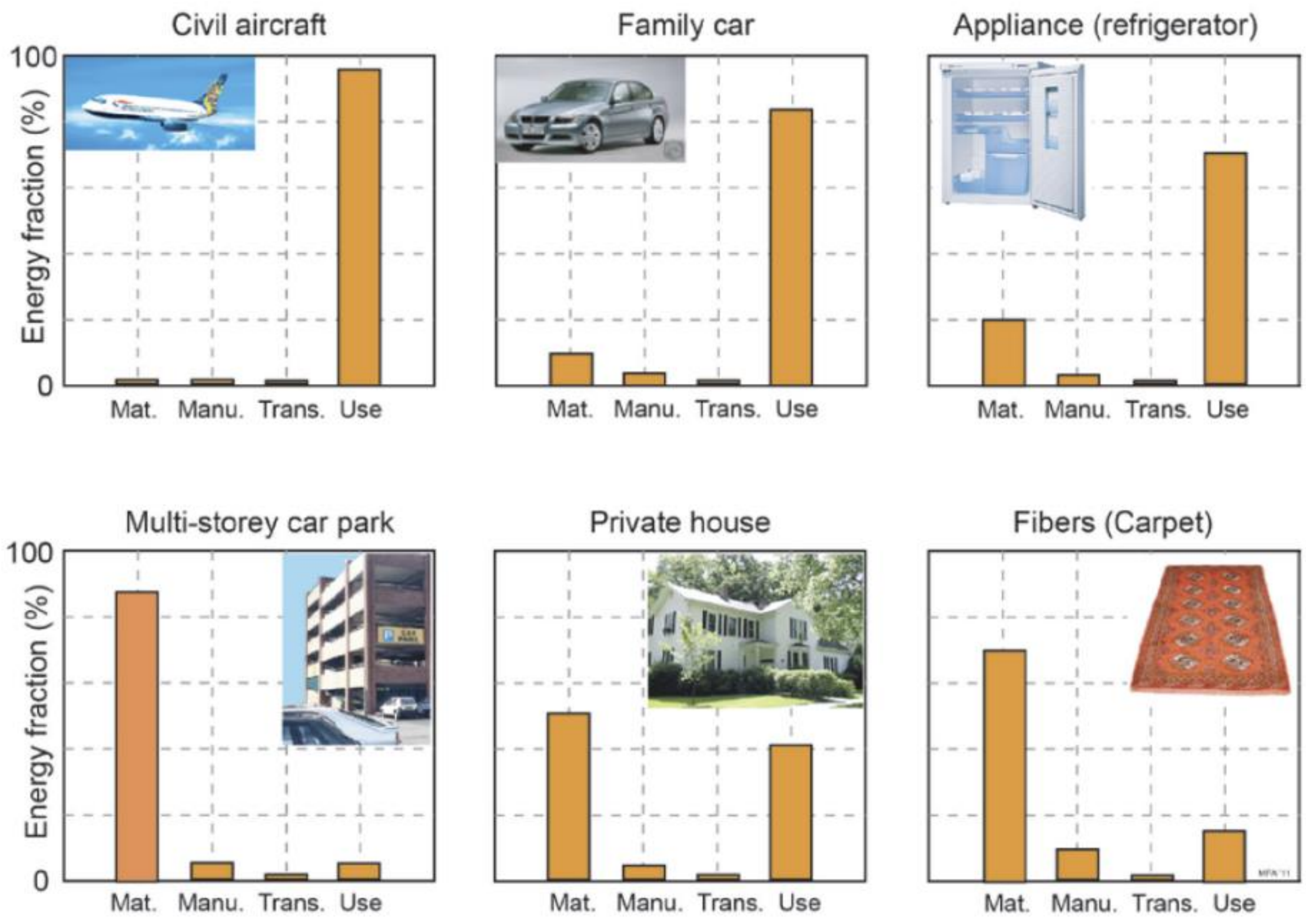
FIGURE 7.2 *The eco-audit of a 1-liter PET water bottle, filled in France, trucked to England, and refrigerated for 2 days*

From: Materials and the Environment, Michael F. Ashby, Copyright 2021 Elsevier, chapter 7.

EoL potential

- This approach is great for identifying hotspots & where we should best focus efforts/ decisions, e.g., maybe paper vs. plastic is secondary to transport (last week's example)?

Hotspots

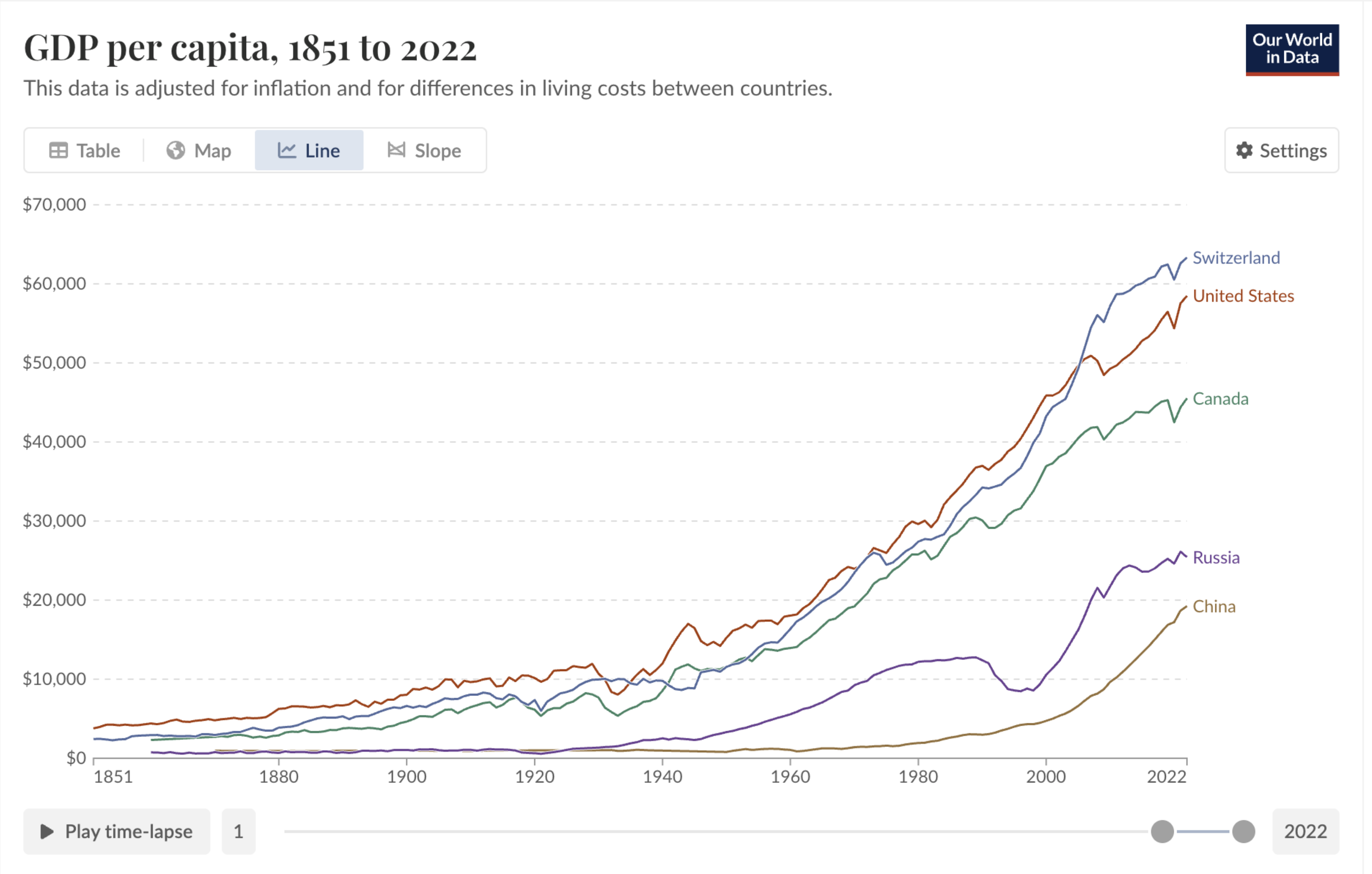


- Highly dependent on entire lifecycle
- Use can be increasingly important in ”active” materials

Eco Audit tool White Paper

Moving on:

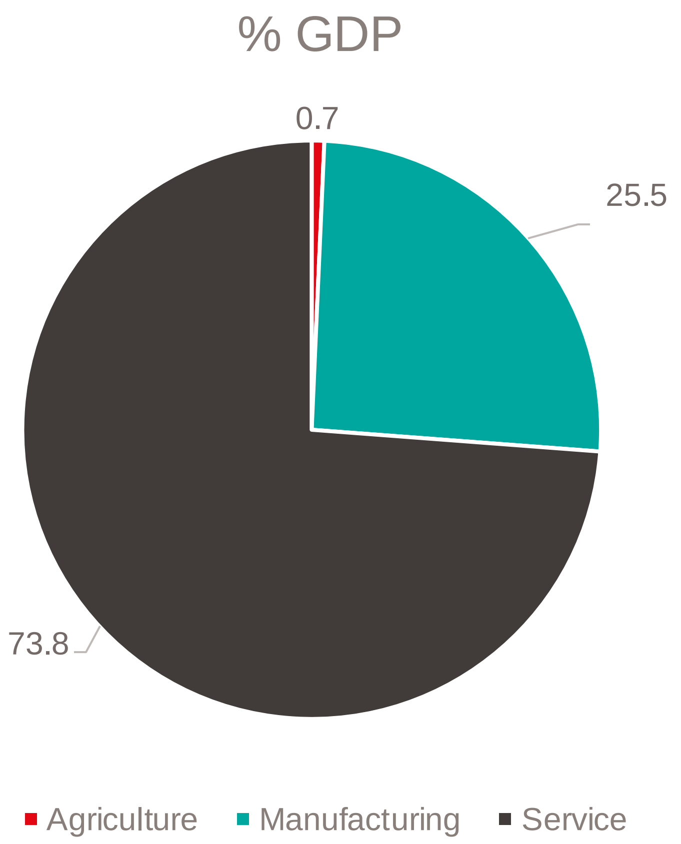
- Snapshot of the Swiss economy (recall, less than 7% circular) – why? Economy tracks with carbon footprint
- Two important periodic tables, leading into a discussion of CRMs, 3TG
- Maybe the most “materials” class we will have in the semester, where we look at the main material classes, with the aim of understanding sustainability hotspots
- Why? Through this lens, we can start to see what critical technologies or material alternatives are needed to reduce impact

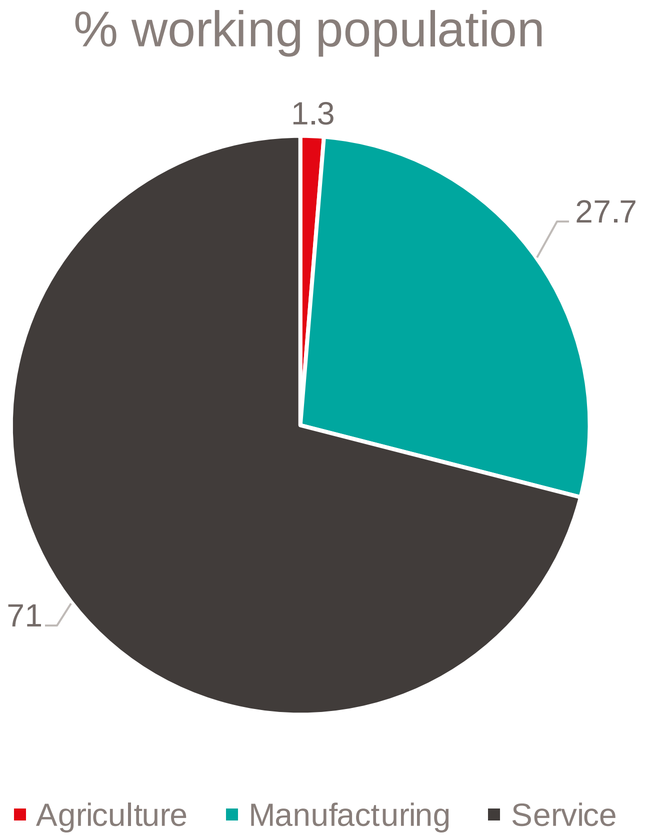


[GDP per capita](#)

Gross domestic product (GDP) is the standard measure of the value added created through the production of goods and services in a country during a certain period.

Snapshot of Swiss economy

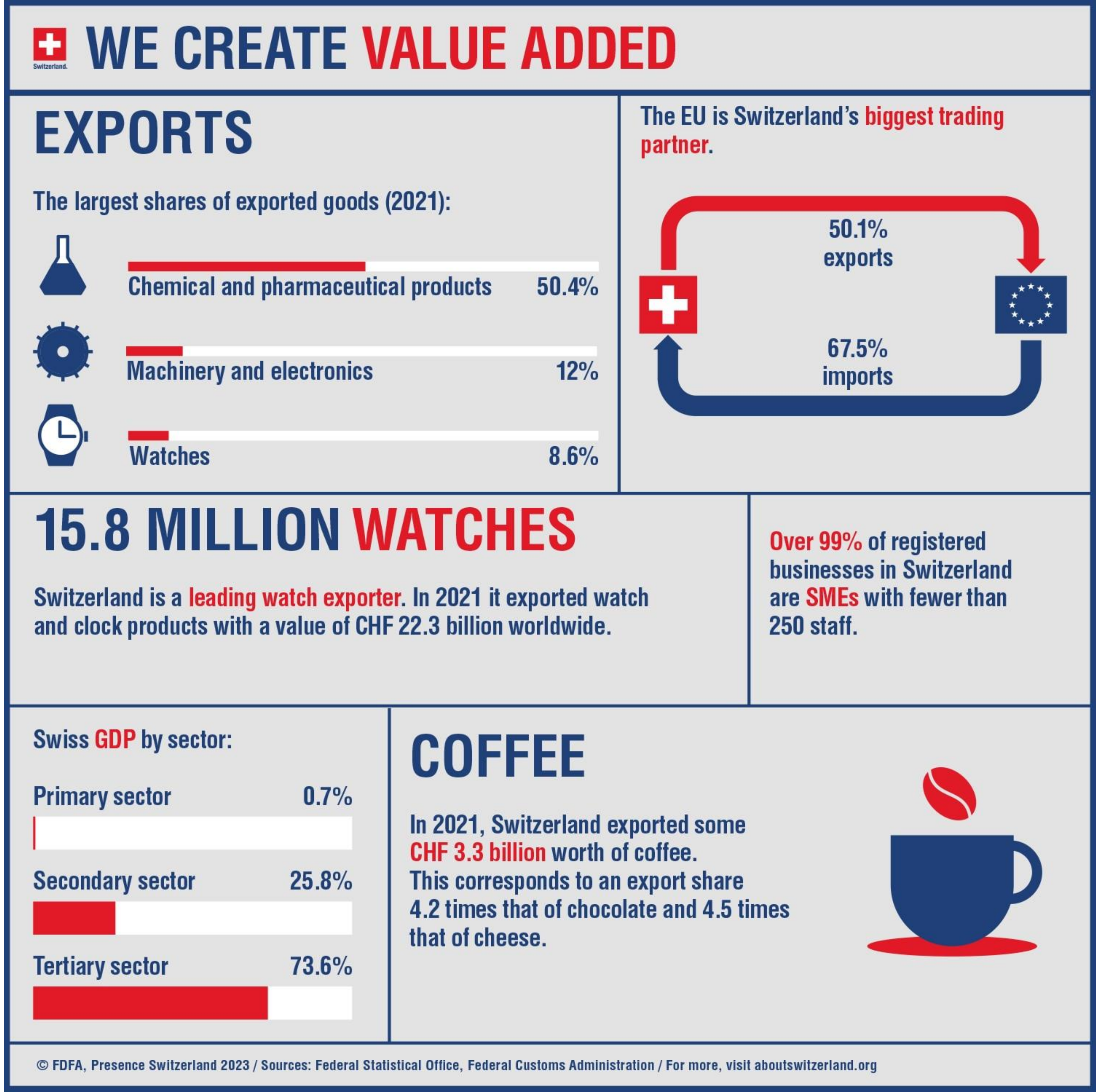




Service = banking, tourism, insurance, more

Pop of 8.7 million (2021)

https://en.wikipedia.org/wiki/Economy_of_Switzerland
Aboutswitzerland (2021 data on GDP)



[Swiss economy facts and figures]

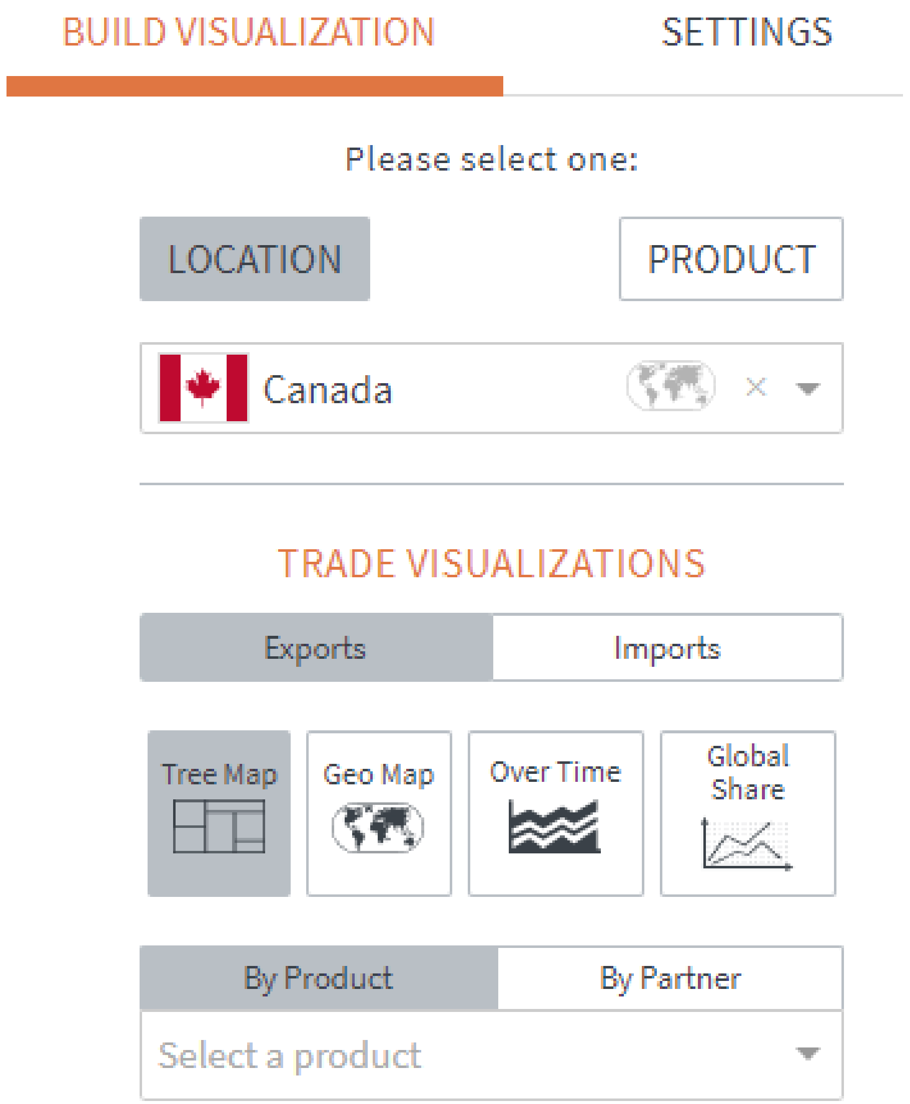
- GDP per capita – 92,000 USD (2022)

Primary sector – agriculture, raw materials

Secondary sector – manufacture

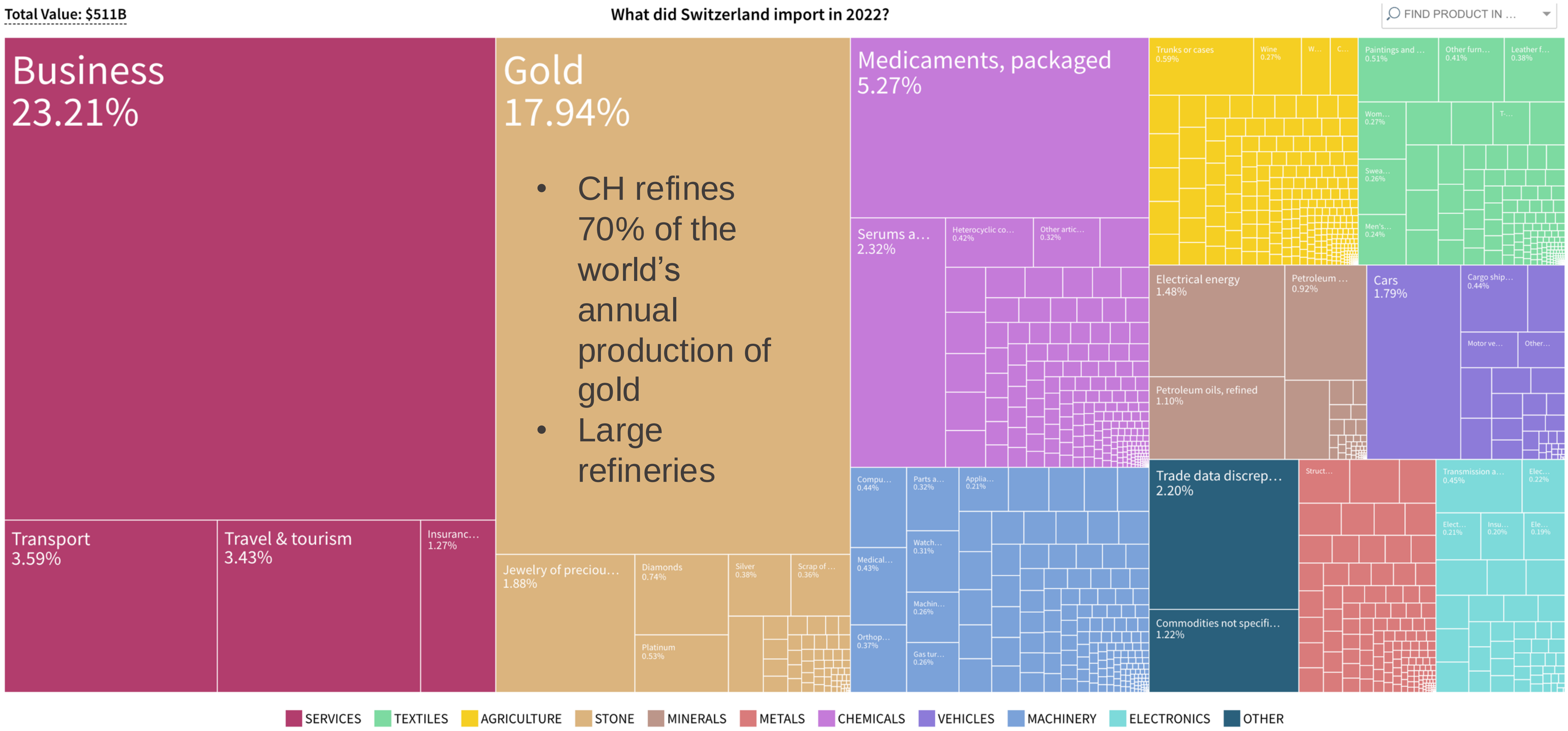
Tertiary sector – service, including distribution and sale of goods from secondary sector

Atlas of Economic Complexity



Imports in Switzerland

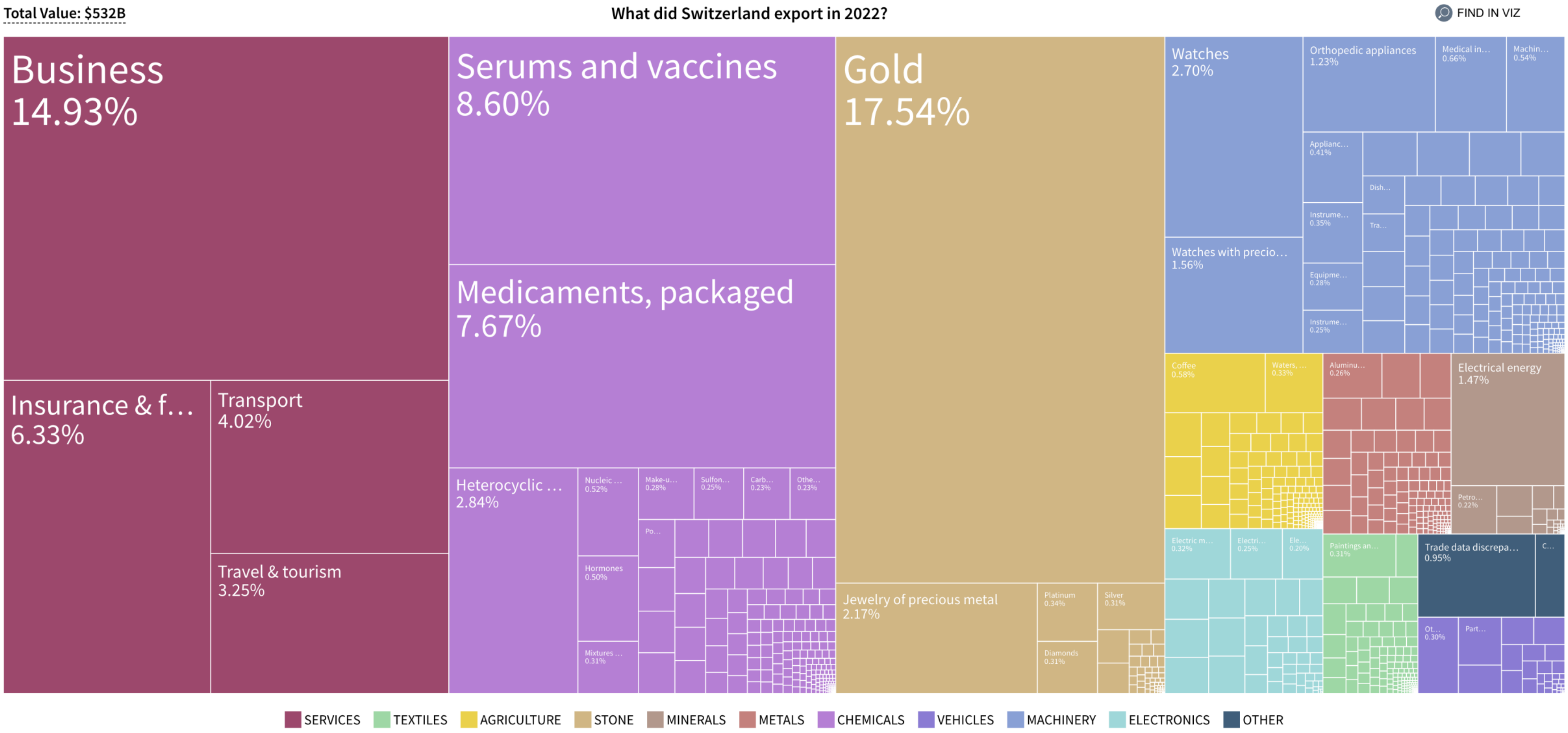
$511B



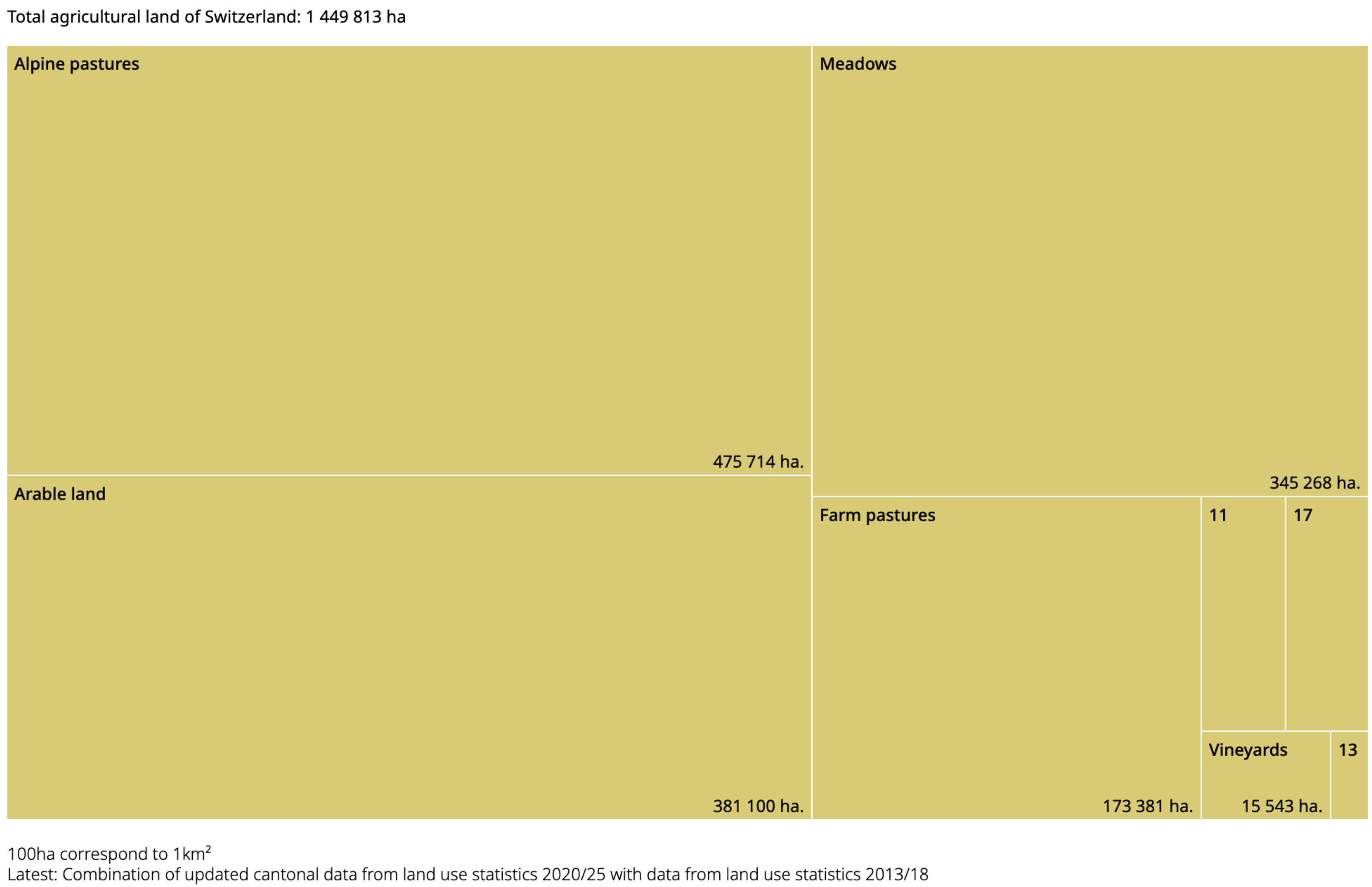
- CH refines 70% of the world's annual production of gold
- Large refineries

Exports in Switzerland

$532B



Agricultural land

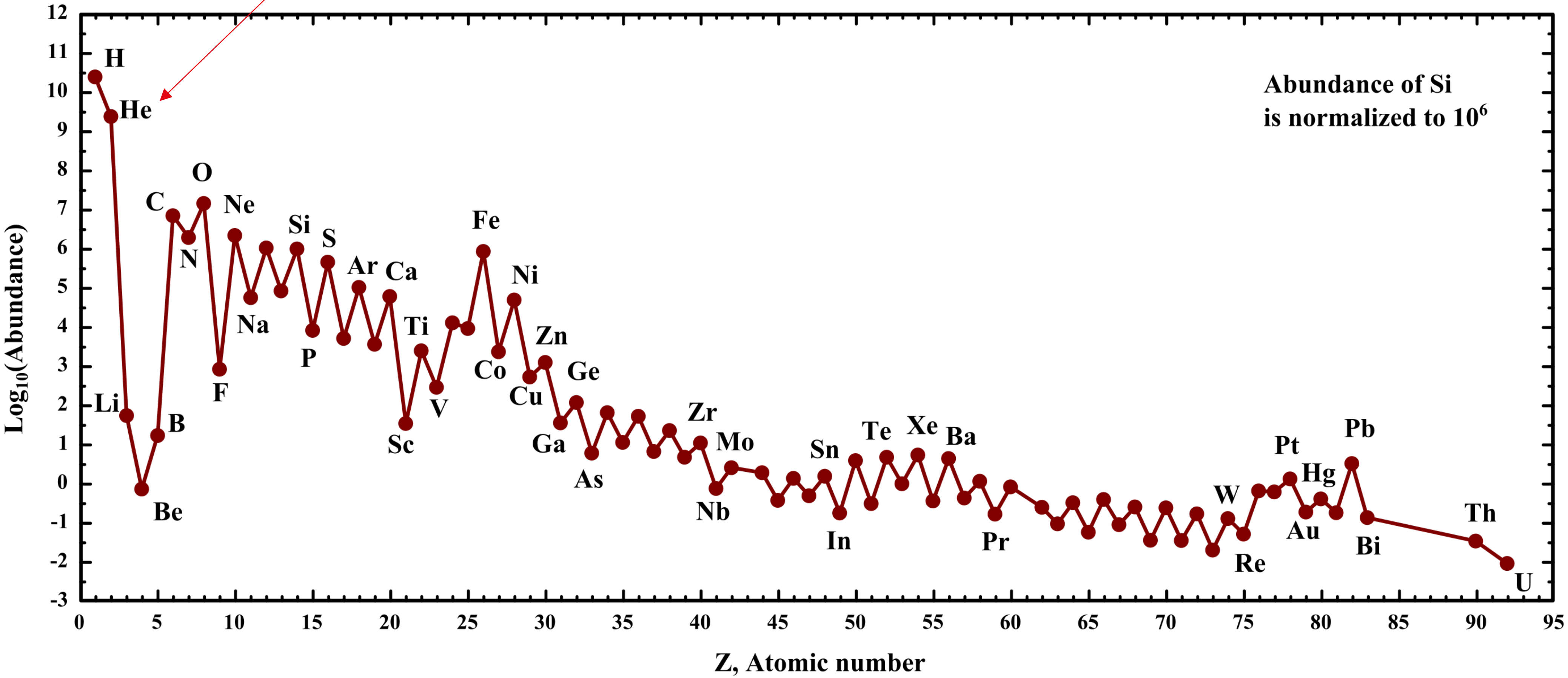


- Total area: 41 291 km^2
- About 1% of GDP in agriculture, and 1/3 of total land
- Agriculture land is lost more and more to new settlements in the lower altitudes and to forests in the mountains

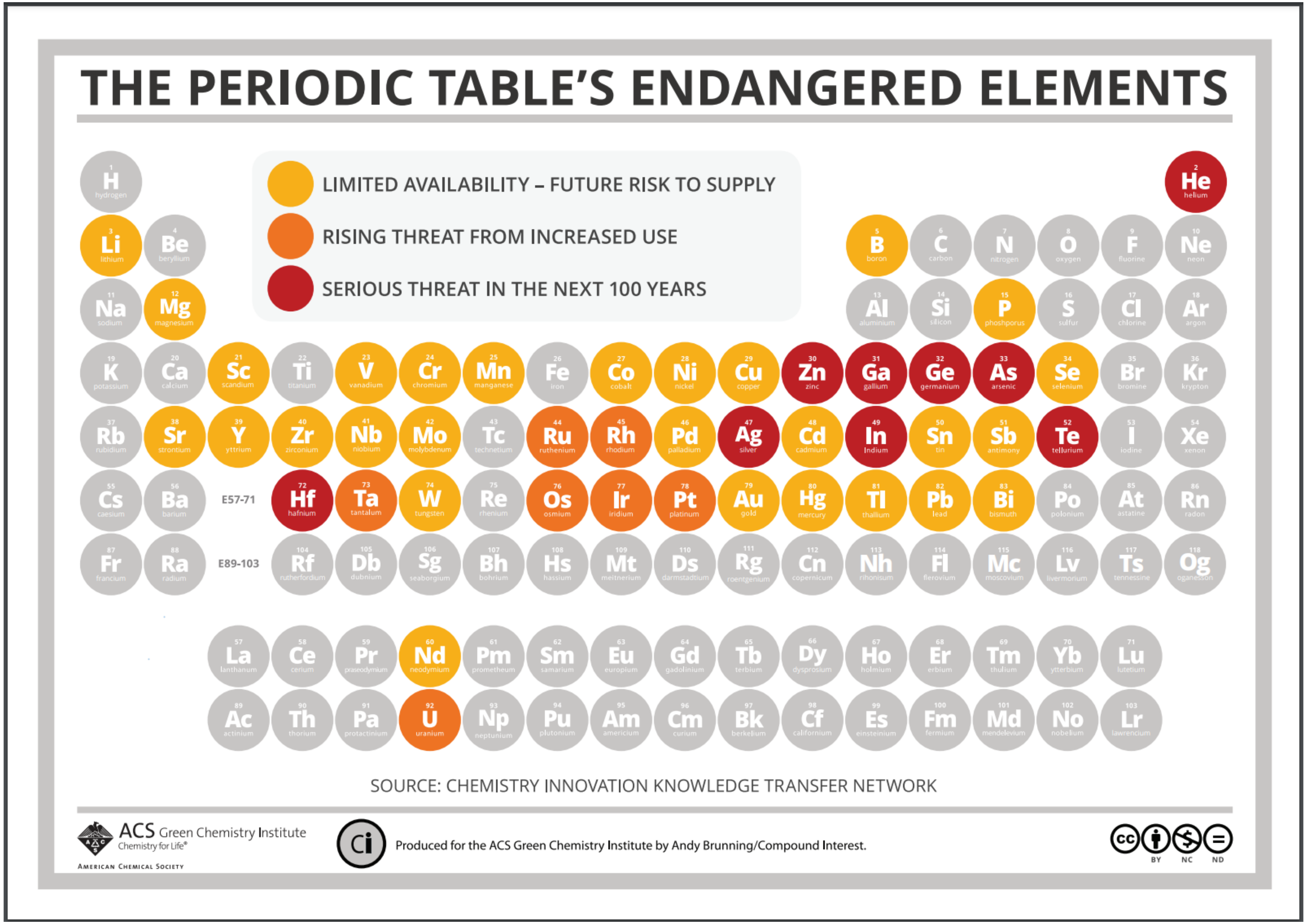
[Swiss agriculture]

Abundance in universe

2nd most abundant



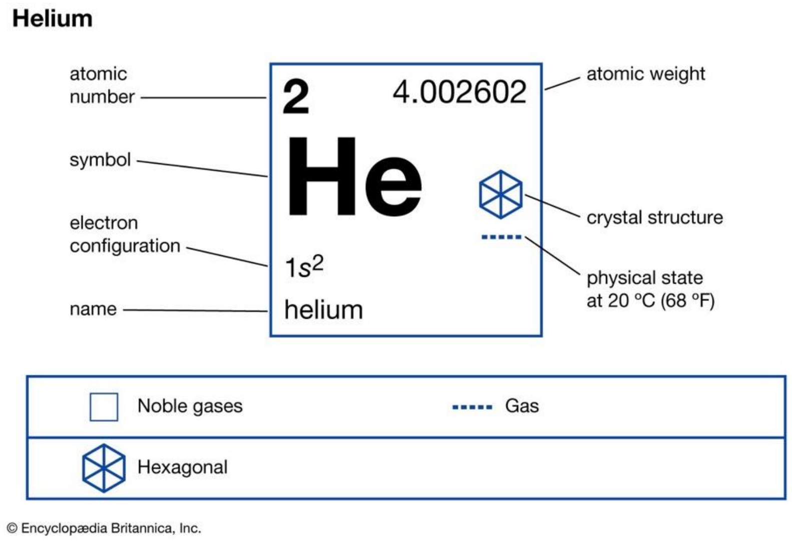
Abundance in universe

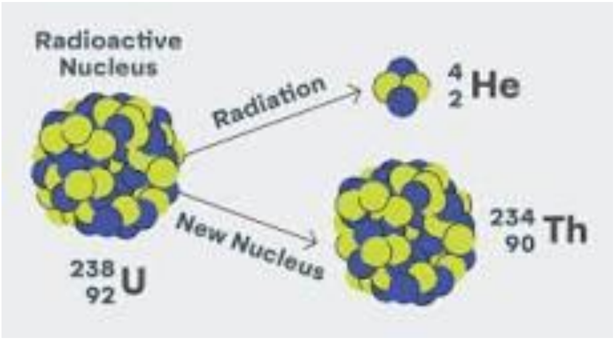


What's up with helium?

Up, up, and away…

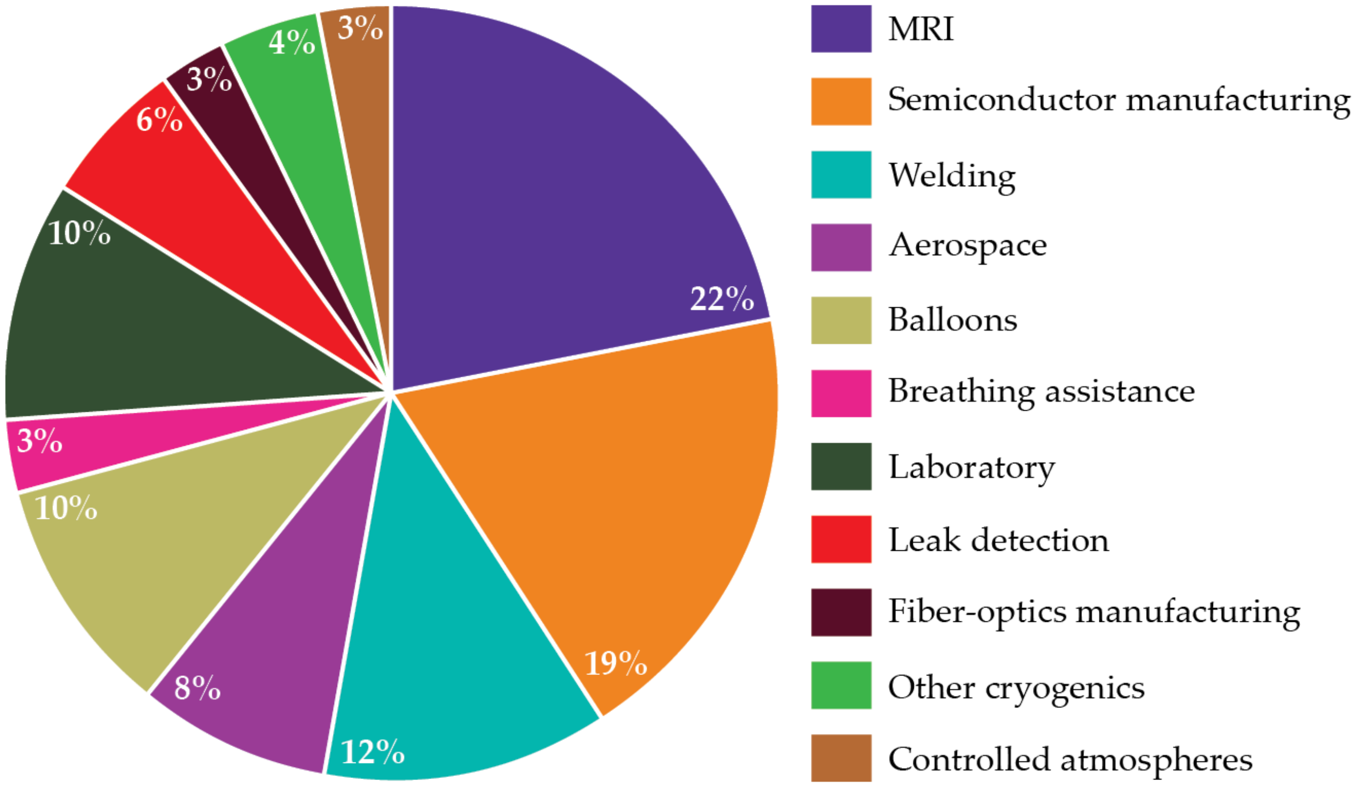
Helium





- Colorless, odorless, tasteless, nontoxic, inert
- 1st noble gas in the periodic table
- 2 protons, 2 electrons, 2 neutrons
- 2nd lightest and 2nd most abundant element in universe (after hydrogen), relatively rare on earth at 5.2 ppm in atmosphere
- Extracted from natural gas deposits, slowly produced by radioactive decay
- Non-renewable – once released into the atmosphere it escapes into space (lighter than air!)
- Low boiling point of -269 °C (lowest of any element)
- Used as a coolant in cryogenics, MRI scanners, superconducting magnets, etc.,
- Same old story: Rate of consumption bigger than rate of production

Helium uses



"Helium is critical to low-temperature physics, chemistry, and life-sciences experiments, yet laboratory usage accounts for just 10% of helium consumption worldwide, well below medical MRI and semiconductor manufacturing."

Physics Today_2023

Helium uses - MRI

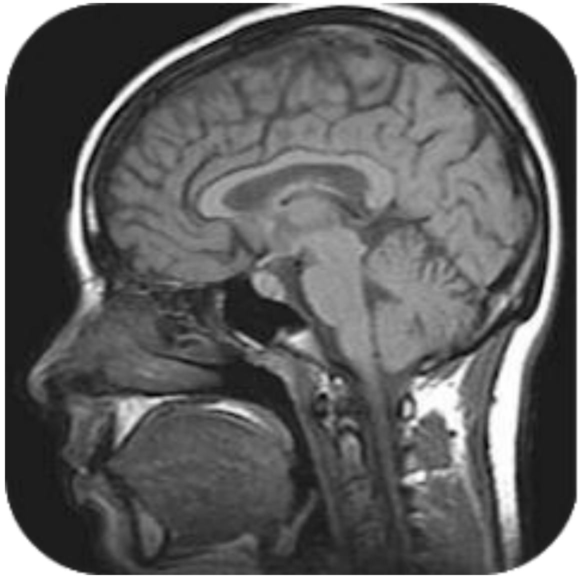
- Current carrying wires used in superconducting magnets typically contain *niobium-titanium* alloy microfilaments embedded within a copper core

- The critical temperature (Tc) for superconductivity for NbTi is 9.4 K (needs to be below 9.4 K)

- Cooling to these ultra-low temperatures is achieved in most modern MRI scanners by bathing the superconducting wire in liquid helium

- Because of its very low boiling point of 4.2 K, helium is a necessary component of these systems

- A typical MRI scanner operates with ~1500–2000 liters of liquid helium and uses up to 10,000 liters over its nearly 13-year lifetime



Environmental Sustainability and MRI: Challenges, Opportunities, and a Call for Action

Helium shortages

- Helium is needed for important applications
- Consumed at a rate that exceeds its natural production
- Helium extraction is only viable from reserves that contain a sufficiently high concentration
- Cost of helium to run laboratory equipment (e.g., NMR) has doubled or more in recent years for various reasons, including slow downs at helium enrichment plants
- Good news – high costs and limited supplies have led to efforts to capture & recycle liquid helium

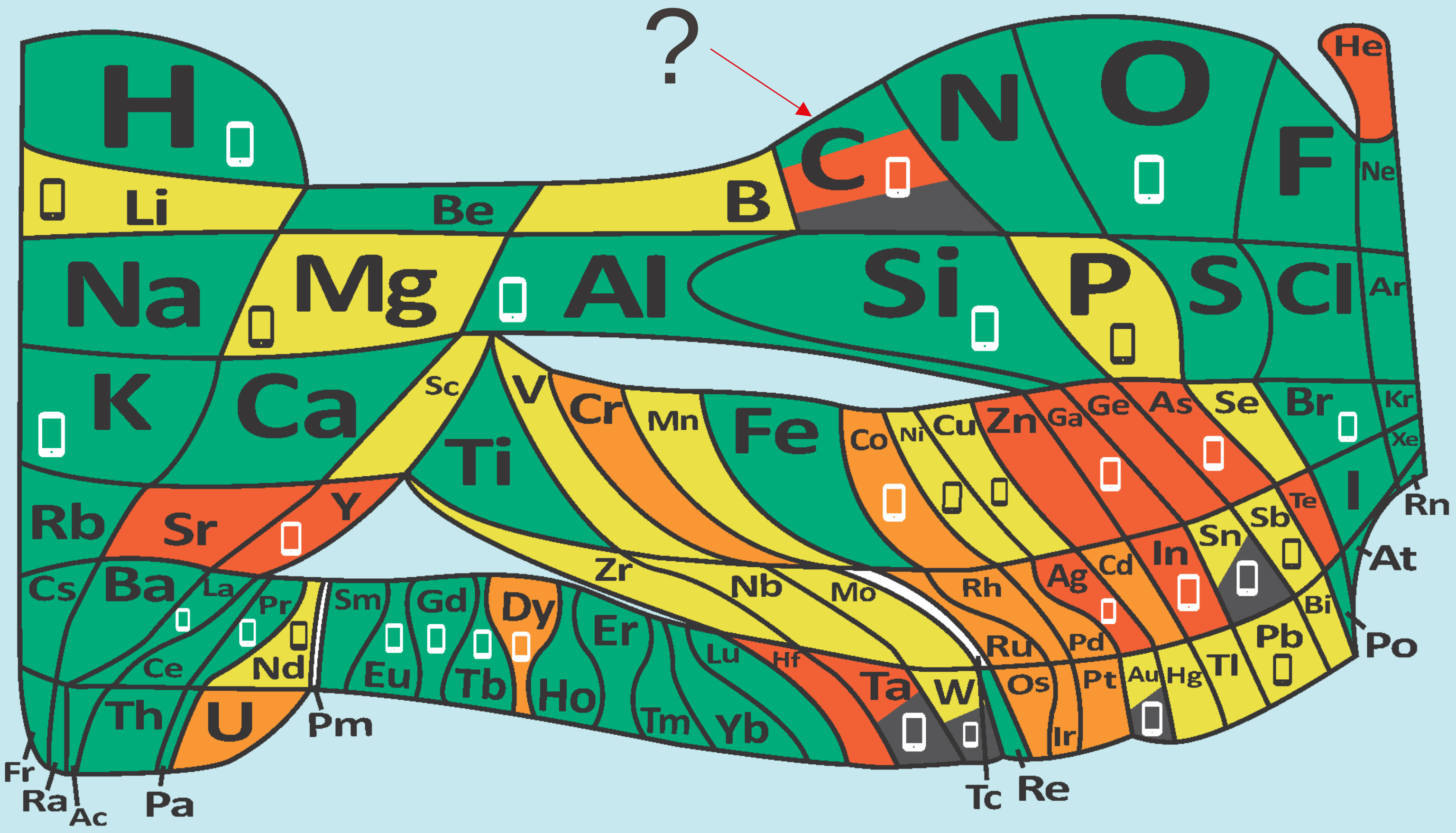
Google's quantum computer

Helium short supply_2022

Physics Today_2023

The 90 natural elements that make up everything

How much is there? Is that enough? Is it sustainable?



- Serious threat in the next 100 years
- Rising threat from increased use
- Limited availability, future risk to supply
- Plentiful Supply
- Synthetic
- From conflict resources
- Elements used in a smart phone

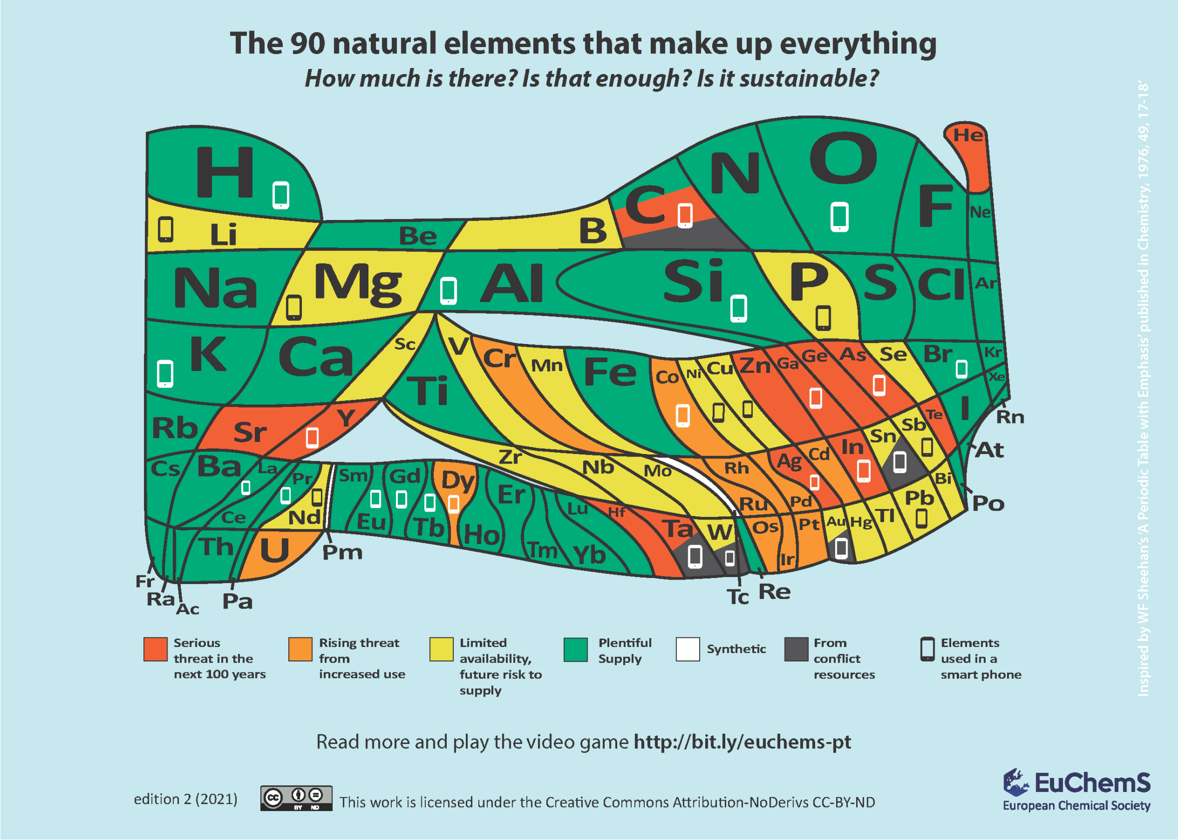
Inspired by WF Sheehan's 'A Periodic Table with Emphasis' published in Chemistry, 1976, 49, 17-18'

Read more and play the video game **http://bit.ly/euchems-pt**

edition 2 (2021)

EuChemS European Chemical Society

Why is carbon green, red, and grey?



Plentiful supply, serious threat, and from conflict resources?
What's going on here?

EuChemS Carbon

Let's break it down:

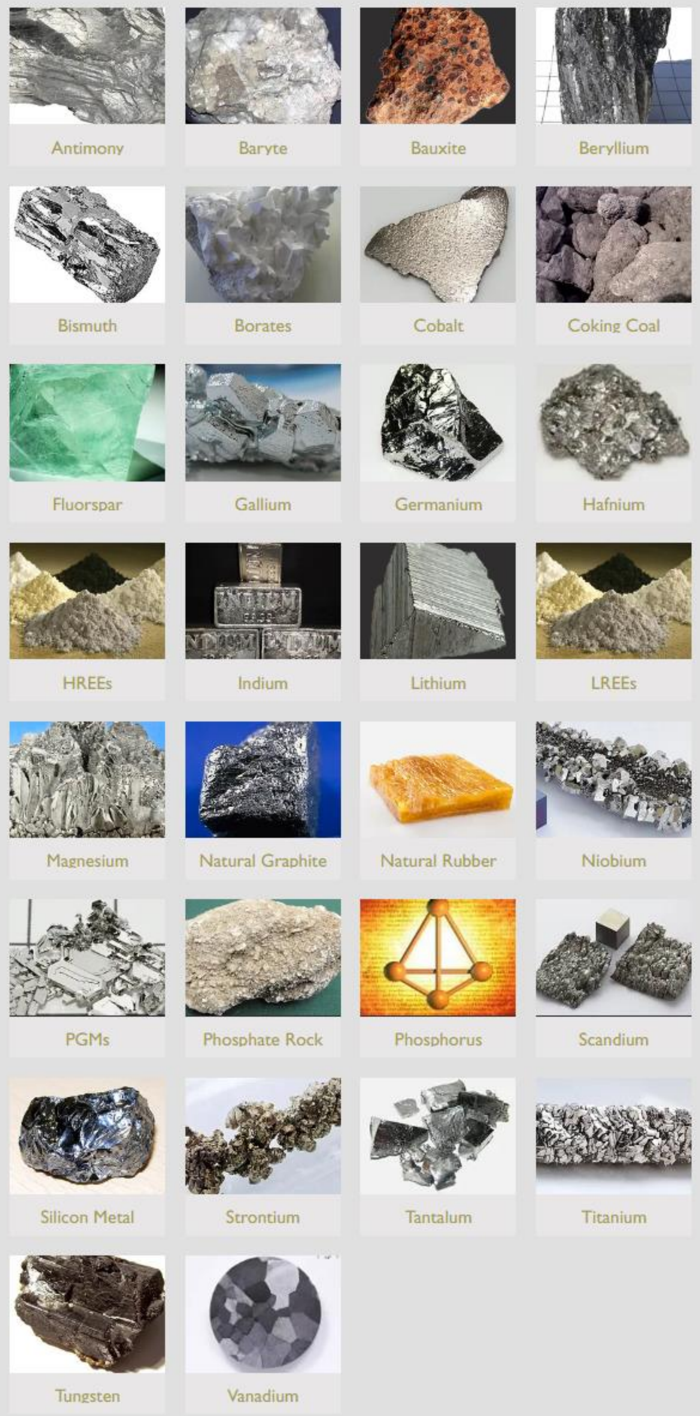
1. Plentiful – carbon is one of the most abundant elements on Earth; many forms – basis of life, minerals and organic compounds, GHGs (CO_2), fossil fuels, graphite, diamond
2. Serious threat – use of carbon in the form of fossil fuels is a serious threat to planet – GHG emissions, air pollution, water contamination, habitat destruction
3. From conflict resources - some carbon-containing resources (graphite) are mined in conflict regions or controlled by a monopoly. Additionally, emissions related to war; conflicts around carbon resources.

Emissions from war_2024

Critical raw materials

- Significant **economic importance** for key sectors in the European economy, such as consumer electronics, environmental technologies, automotive, aerospace, defense, health, and construction
- **High-supply risk** due to the very high import dependence and high level of concentration of set critical raw materials in particular countries
- Lack of (viable) substitutes, due to the unique and reliable properties of these materials for existing and future applications

CRMs



Two main criteria to assign criticality:

1. **Economic importance**: importance of material to EU economy in terms of end-use applications and the value added (VA) of corresponding EU manufacturing sectors

2. **Supply risk**: reflects the risk of a disruption in the EU supply of the material. It is based on the concentration of primary supply from raw materials producing countries, considering their governance performance and trade aspects.

- Assessment carried out by the EU commission
- 2023 iteration screened 70 candidate raw materials
- Copper and nickel do not meet the CRM thresholds but are included on the CRM list as SRMs (**strategic raw materials**)

Critical raw materials Europe

Main results of 2023 criticality assessment

2023 Critical Raw Materials (*Strategic Raw Materials in italics*)			
aluminium/bauxite	coking coal	*lithium*	phosphorus
antimony	feldspar	*LREE*	scandium
arsenic	fluorspar	*magnesium*	*silicon metal*
baryte	*gallium*	*manganese*	strontium
beryllium	*germanium*	*natural graphite*	tantalum
bismuth	hafnium	niobium	*titanium metal*
boron/borate	helium	*PGM*	*tungsten*
cobalt	*HREE*	phosphate rock	vanadium
		*copper**	*nickel**

* Copper and nickel do not meet the CRM thresholds, but are included as Strategic Raw Materials.

- Some critical raw materials (CRMs) are also categorized as strategic raw materials (SRMs)
- Whether a CRM is also classified as a SRM depends on whether the material is needed for issues of national security, technological innovation, and in general to meet overall policy goals, like net zero goals, etc.,

Critical raw materials Europe

Closer look at some EU-assessed CRMs

CRM&SRM	Main uses	Why critical?	Supply chain
Natural graphite	Li-ion batteries, lubricants, Refractories	Needed for key technologies, supply limited to a few countries	China (dominates), India, Brazil
Cobalt	Li-ion batteries, alloys for aerospace	Serious supply concern & economic importance	DRC
Copper	Electrical wiring/components, plumbing, renewable energy, electronic devices, defense	Essential to infrastructure development, energy transition, limited to a few countries	Chile, Peru, China, US
Lithium	Batteries (e.g., EVs), electronic devices, renewable energy technologies	Needed for key technologies, demand high/supply limited	Australia, Chile, China, Argentina, Bolivia, US
REEs	Electronic devices, renewable energy technologies, EVs, advanced defense systems	Unique magnetic, catalytic, and luminescent properties make them irreplaceable in many applications	Supply chain dominated by China (issues of supply chain security and geopolitical dependencies)

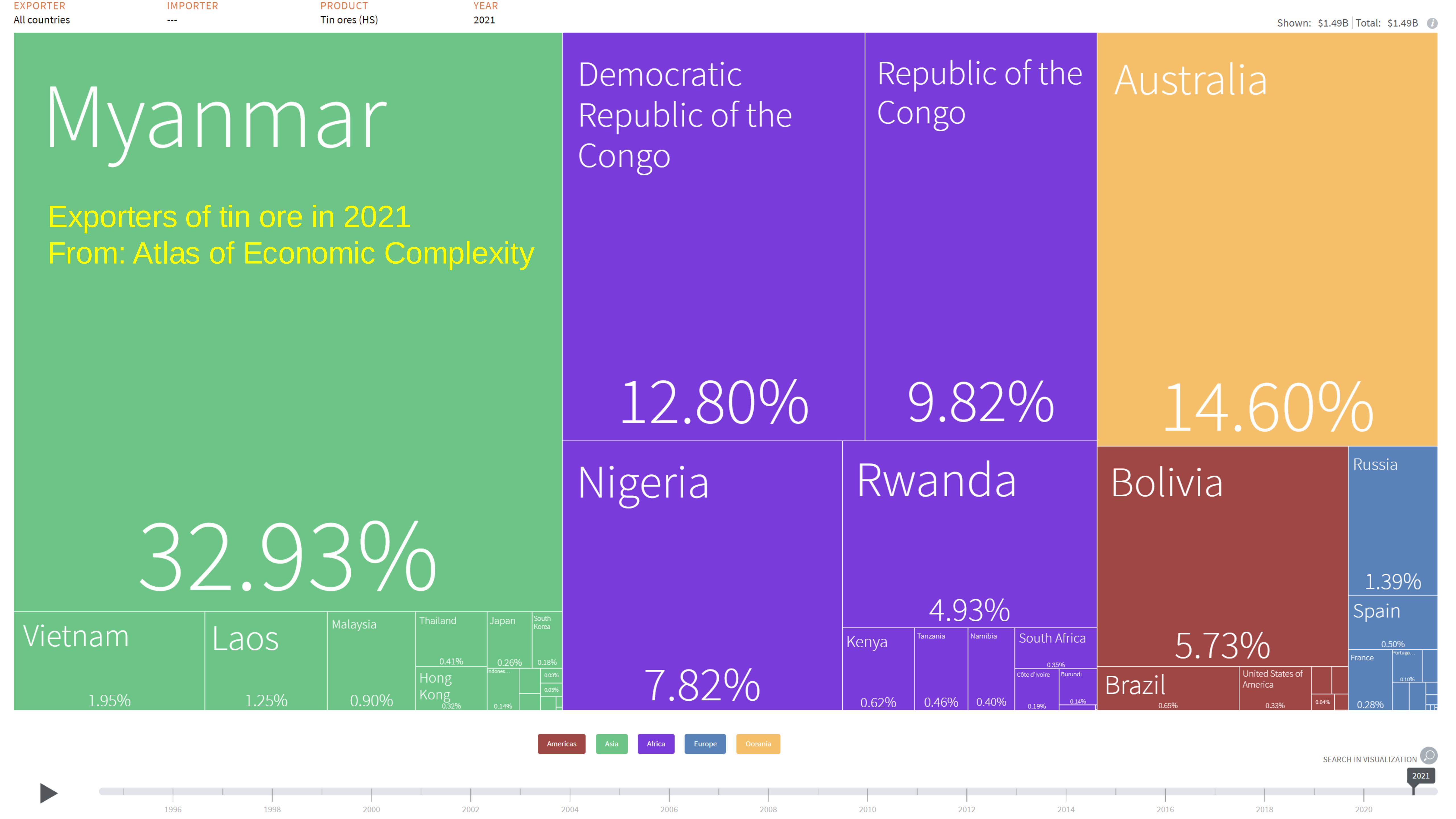
Critical raw materials Europe

Conflict materials

- DRC, nearby countries: conflict affected areas
- 3TG
- Tin (Sn), tungsten (W), tantalum (Ta), gold (Au)
- Defined as conflict wherever extracted (can be labeled DRC-conflict free)
- Essential in consumer electronics, industrial applications, jewelry
- 2010 Dodd-Frank Wall Street Reform in US, requiring supply chain audits and disclosure of conflict minerals
- 2017 in EU supply chain due diligence for 3TGs
- Aim to increase transparency and to promote ethical sourcing

The main topic of conflict minerals regulations, clockwise from top left: coltan (tantalum ore), cassiterite (tin ore), gold ore, and wolframite (tungsten ore).

https://www.oecd.org/corporate/mne/mining.htm
https://en.wikipedia.org/wiki/Conflict_minerals_law


EXPORTER
All countries
IMPORTER

PRODUCT
Tin ores (HS)
YEAR
2021
Shown: $1.49B | Total: $1.49B
Myanmar
Exporters of tin ore in 2021
From: Atlas of Economic Complexity
32.93%
Democratic Republic of the Congo
12.80%
Republic of the Congo
9.82%
Australia
14.60%
Nigeria
7.82%
Rwanda
4.93%
Bolivia
5.73%
Russia
1.39%
Spain
0.50%
Vietnam
1.95%
Laos
1.25%
Malaysia
0.90%
Thailand
0.41%
Japan
0.26%
South Korea
0.18%
Hong Kong
0.32%
0.14%
0.03%
0.03%
Kenya
0.62%
Tanzania
0.46%
Namibia
0.40%
South Africa
0.35%
Côte d'Ivoire
0.19%
Burundi
0.14%
Brazil
0.65%
United States of America
0.33%
0.04%
France
0.28%
0.10%
Americas
Asia
Africa
Europe
Oceania
SEARCH IN VISUALIZATION
2021
1996
1998
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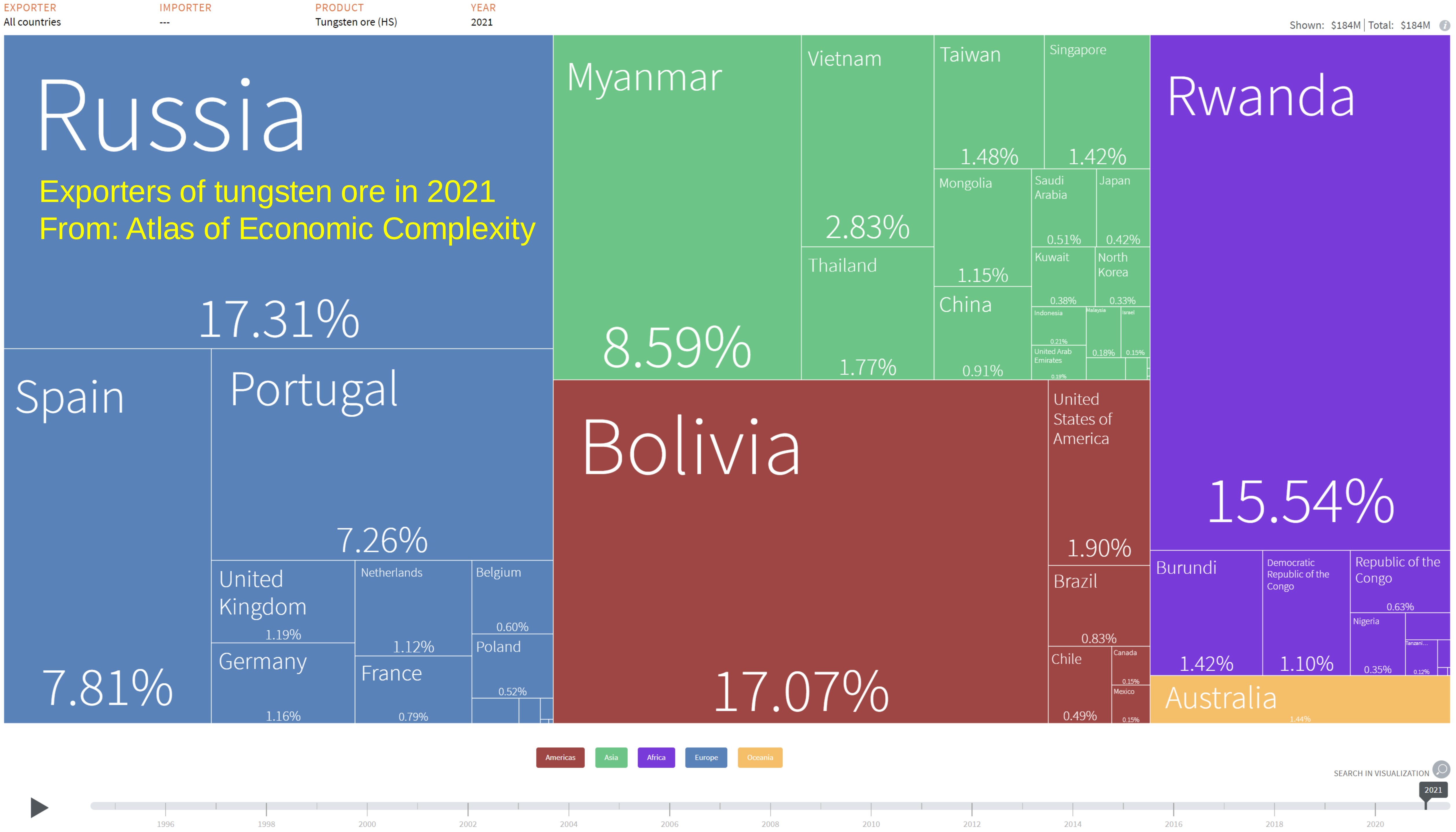
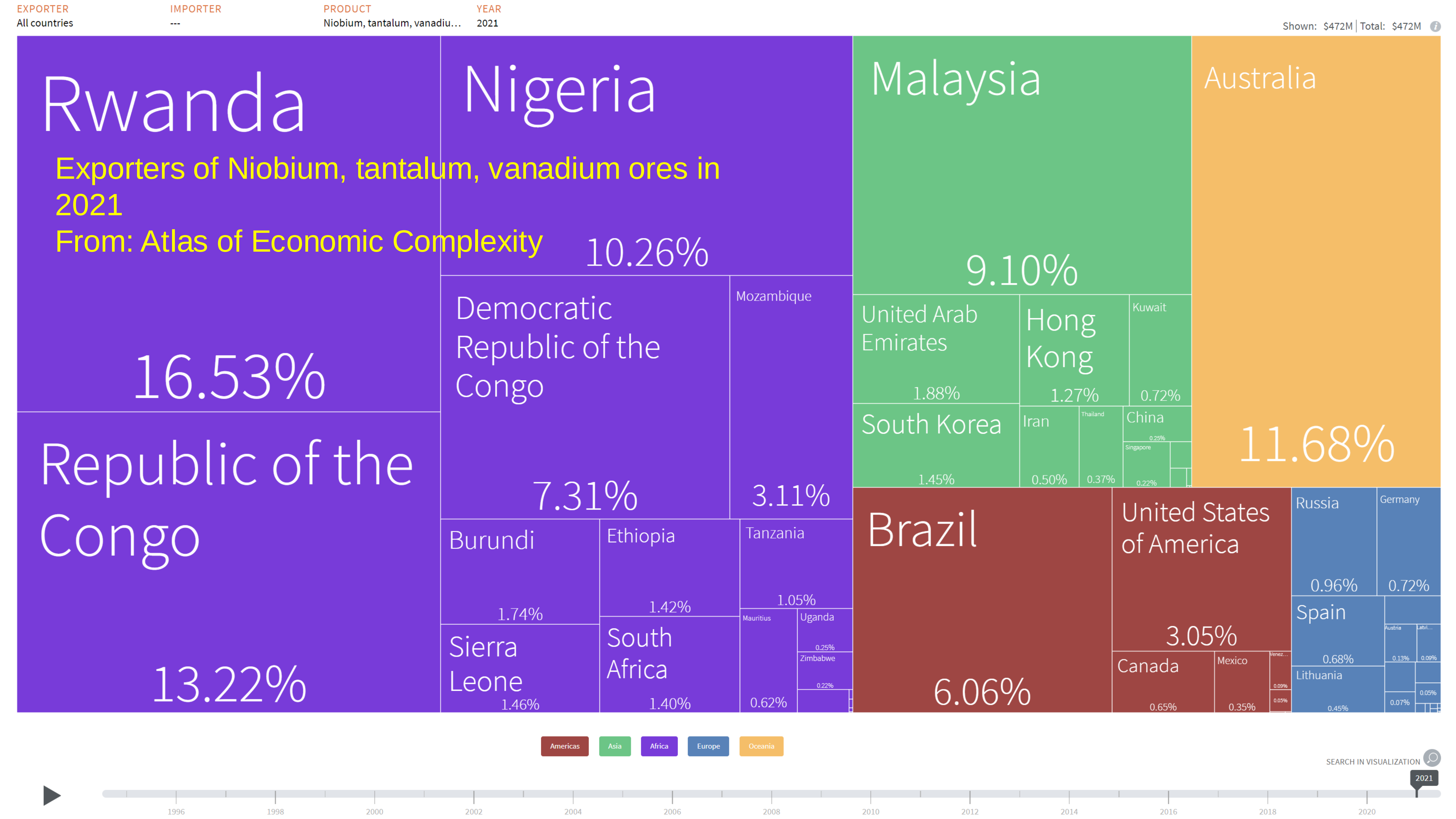
2020

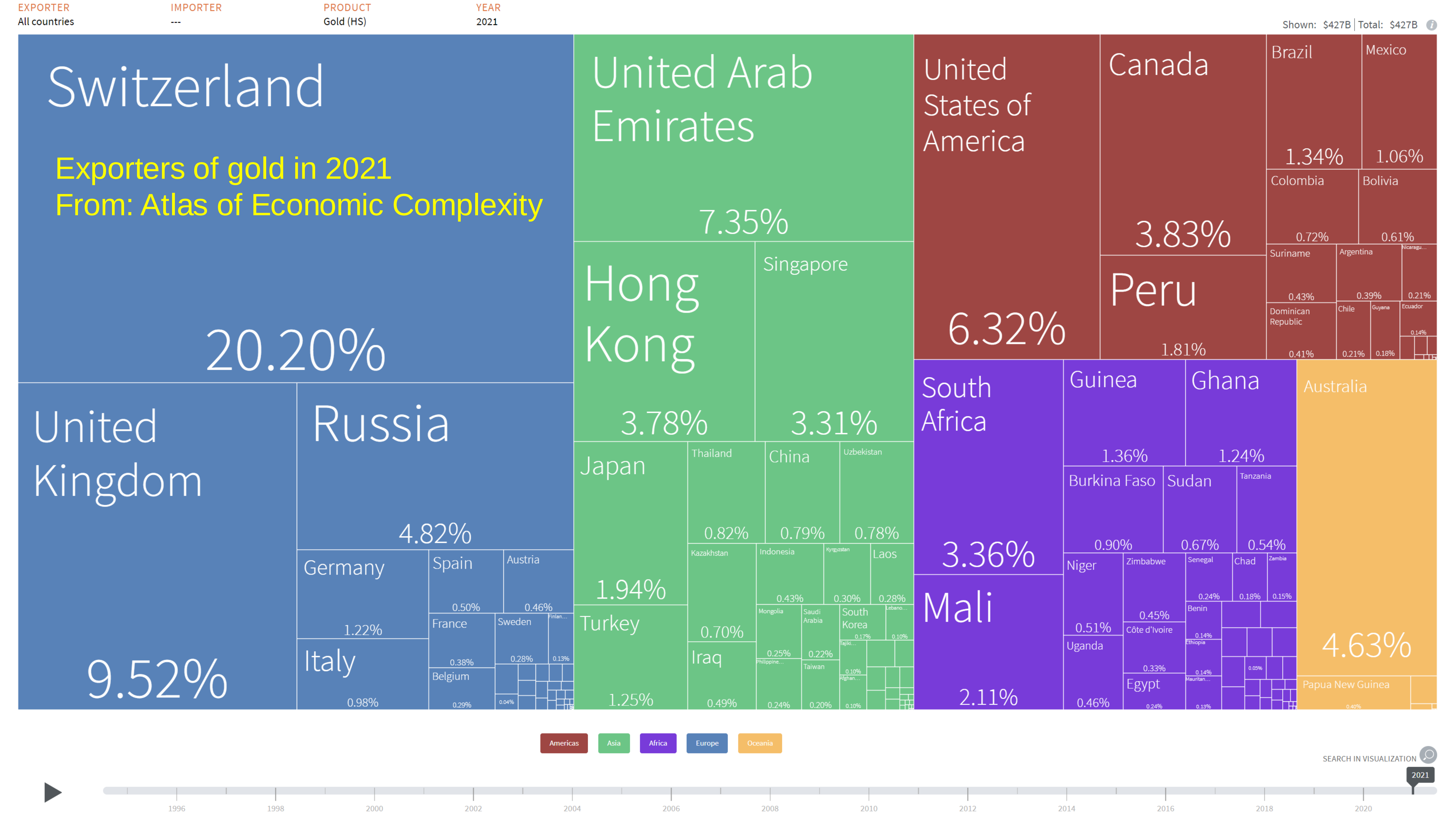


EXPORTER
All countries
IMPORTER

PRODUCT
Tungsten ore (HS)
YEAR
2021
Shown: $184M | Total: $184M
Russia
Exporters of tungsten ore in 2021
From: Atlas of Economic Complexity
17.31%
Spain
7.81%
Portugal
7.26%
United Kingdom
1.19%
Netherlands
1.12%
Belgium
0.60%
Germany
1.16%
France
0.79%
Poland
0.52%
Myanmar
8.59%
Vietnam
2.83%
Thailand
1.77%
Taiwan
1.48%
Singapore
1.42%
Mongolia
1.15%
Saudi Arabia
0.51%
Japan
0.42%
Kuwait
0.38%
North Korea
0.33%
China
0.91%
Indonesia
0.21%
0.18%
0.15%
United Arab Emirates
0.19%
Bolivia
17.07%
United States of America
1.90%
Brazil
0.83%
Chile
0.49%
Canada
0.15%
Mexico
0.15%
Rwanda
15.54%
Burundi
1.42%
Democratic Republic of the Congo
1.10%
Republic of the Congo
0.63%
Nigeria
0.35%
0.12%
Australia
1.44%
Americas
Asia
Africa
Europe
Oceania
SEARCH IN VISUALIZATION
2021
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020


EXPORTER
All countries
IMPORTER

PRODUCT
Niobium, tantalum, vanadiu…
YEAR
2021
Shown: $472M | Total: $472M
Exporters of Niobium, tantalum, vanadium ores in 2021
From: Atlas of Economic Complexity
Rwanda
16.53%
Republic of the Congo
13.22%
Nigeria
10.26%
Democratic Republic of the Congo
7.31%
Mozambique
3.11%
Burundi
1.74%
Ethiopia
1.42%
Tanzania
1.05%
Sierra Leone
1.46%
South Africa
1.40%
Mauritius
0.62%
Uganda
0.25%
Zimbabwe
0.22%
Malaysia
9.10%
United Arab Emirates
1.88%
Hong Kong
1.27%
Kuwait
0.72%
South Korea
1.45%
Iran
0.50%
Thailand
0.37%
China
0.25%
Singapore
0.22%
Australia
11.68%
Brazil
6.06%
United States of America
3.05%
Canada
0.65%
Mexico
0.35%
Russia
0.96%
Germany
0.72%
Spain
0.68%
Lithuania
0.45%
Austria
0.13%
0.09%
0.07%
0.05%
Americas
Asia
Africa
Europe
Oceania
SEARCH IN VISUALIZATION
2021
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020


EXPORTER
All countries
IMPORTER

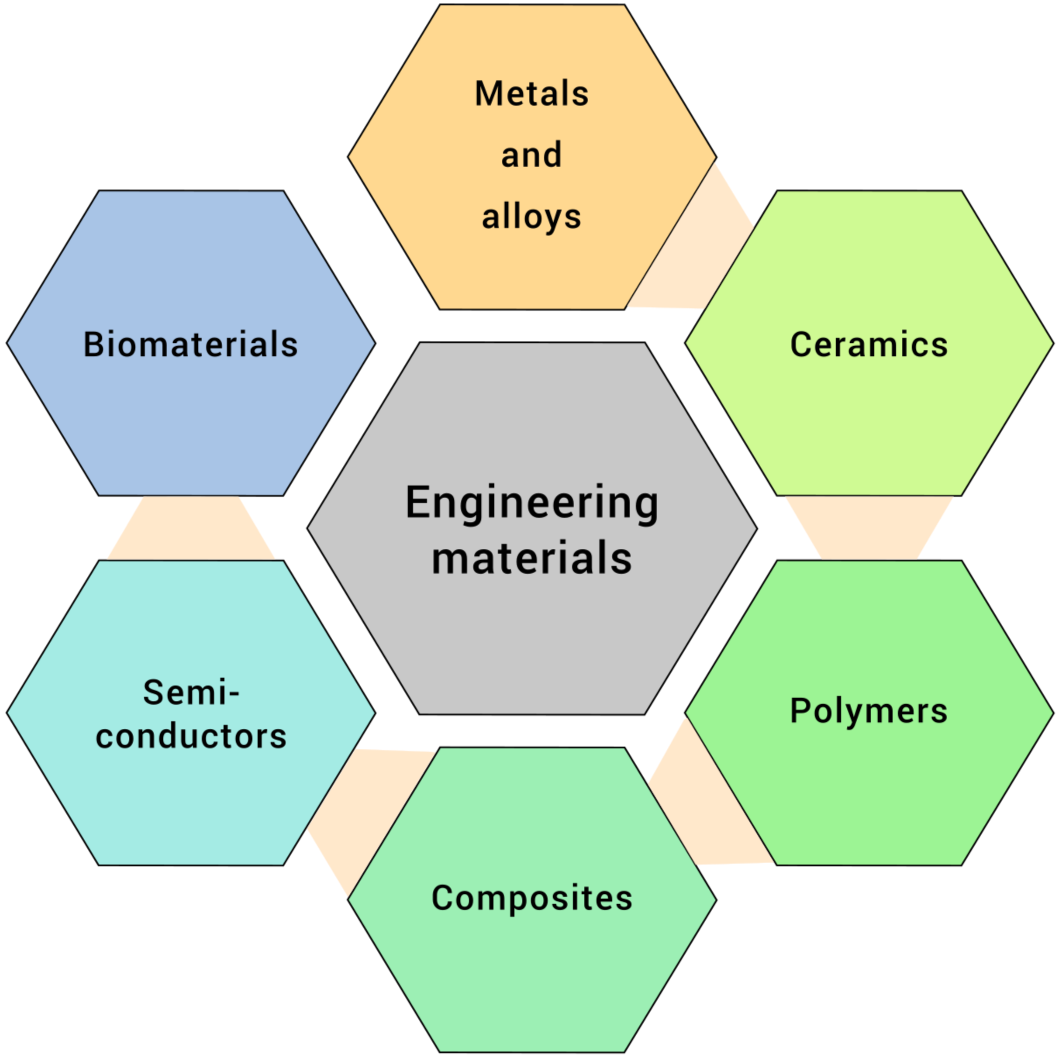
PRODUCT
Gold (HS)
YEAR
2021
Shown: $427B | Total: $427B
Exporters of gold in 2021
From: Atlas of Economic Complexity
Switzerland
20.20%
United Kingdom
9.52%
Russia
4.82%
Germany
1.22%
Spain
0.50%
Austria
0.46%
Italy
0.98%
France
0.38%
Sweden
0.28%
0.13%
Belgium
0.29%
0.04%
United Arab Emirates
7.35%
Hong Kong
3.78%
Singapore
3.31%
Japan
1.94%
Thailand
0.82%
China
0.79%
Uzbekistan
0.78%
Kazakhstan
0.70%
Indonesia
0.43%
Kyrgyzstan
0.30%
Laos
0.28%
Turkey
1.25%
Iraq
0.49%
Mongolia
0.25%
Saudi Arabia
0.22%
South Korea
0.17%
0.10%
Philippine...
0.24%
Taiwan
0.20%
Tajiki...
0.10%
Afghan...
0.10%
United States of America
6.32%
Canada
3.83%
Peru
1.81%
Brazil
1.34%
Mexico
1.06%
Colombia
0.72%
Bolivia
0.61%
Suriname
0.43%
Argentina
0.39%
Nicaragu...
0.21%
Dominican Republic
0.41%
Chile
0.21%
Guyana
0.18%
Ecuador
0.14%
South Africa
3.36%
Mali
2.11%
Guinea
1.36%
Ghana
1.24%
Burkina Faso
0.90%
Sudan
0.67%
Tanzania
0.54%
Niger
0.51%
Zimbabwe
0.45%
Senegal
0.24%
Chad
0.18%
Zambia
0.15%
Benin
0.14%
Ethiopia
0.14%
Mauritan...
0.13%
Côte d'Ivoire
0.33%
Uganda
0.46%
Egypt
0.24%
0.05%
Australia
4.63%
Papua New Guinea
0.40%
Americas
Asia
Africa
Europe
Oceania
SEARCH IN VISUALIZATION
2021
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020

Moving on:

- ~~Snapshot of the Swiss economy (recall, less than 7% circular) – why? Economy tracks with carbon footprint~~
- ~~Two important periodic tables, leading into a discussion of CRMs, 3TG~~
- Look for sustainability hotspots: metals and ceramics (two materials classes)
- Why? Through this lens, we can start to see what critical technologies or material alternatives are needed to reduce impact

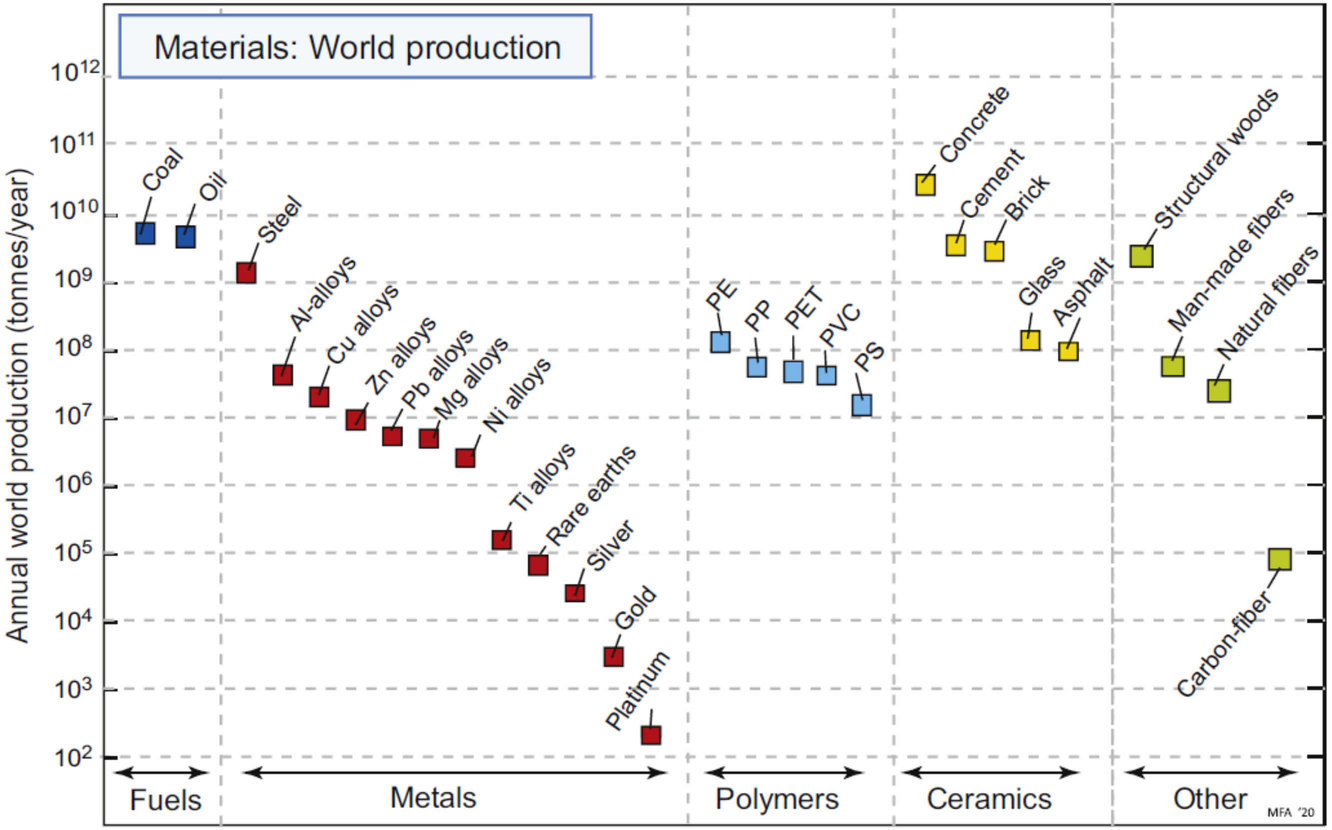
Engineering materials categories (one version)

- Metals and alloys
- Polymers
- Ceramics
- Composites
- Semiconductors
- Biomaterials



Materials science classifications

Materials: World Production



- Engineering materials – used in the construction of manmade structures and components
- Every year, we consume about 20 billion tonnes of engineering materials

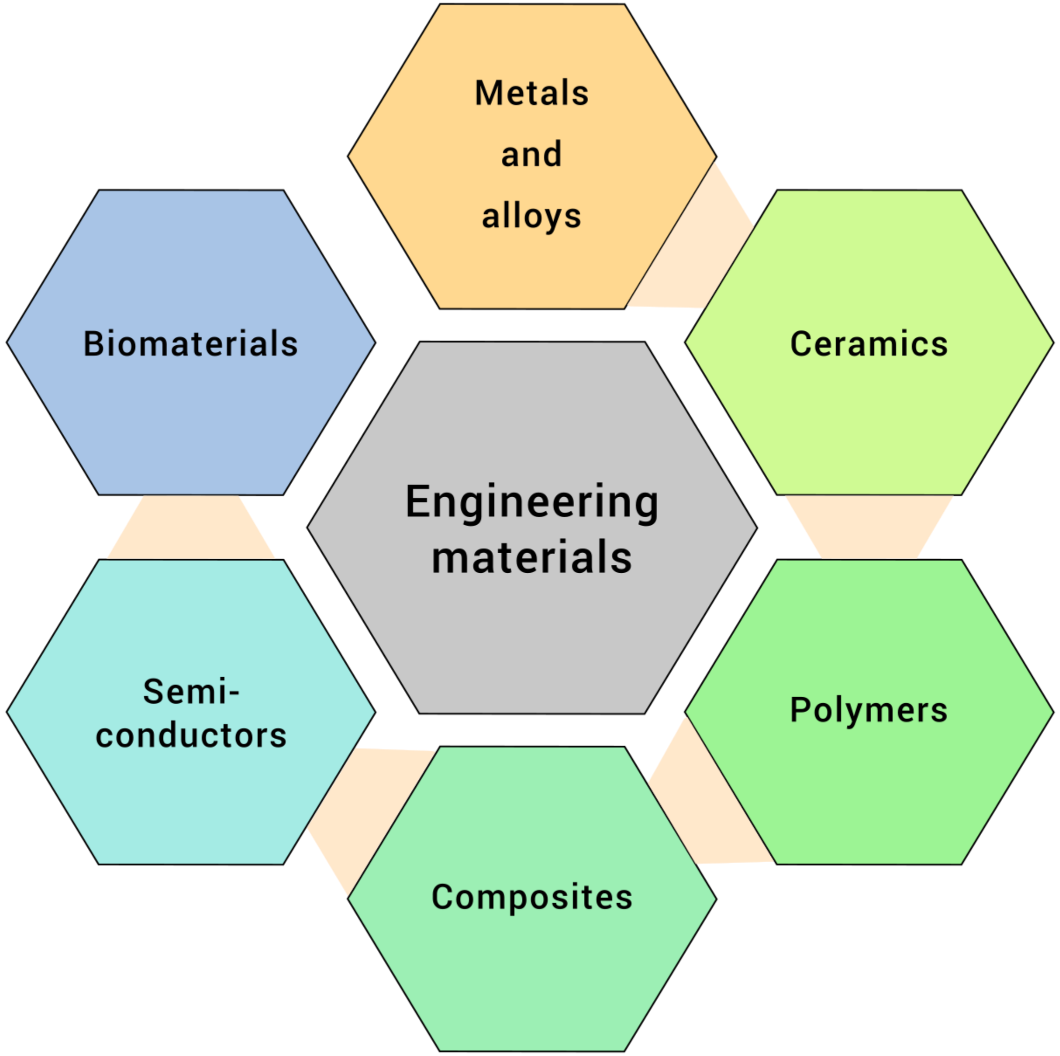
From: Materials and the Environment, Michael F. Ashby, Copyright 2021 Elsevier

Environmental impacts of materials production

- **Energy depletion**
  - Fossil fuels are burned irreversibly, causing a continuous demand for extraction
- **Water, air, and soil pollution**
  - Water used in industrial processes gets contaminated by chemicals, metals, and waste products
  - Pollutants like gas, smoke, or particulate matter reduce air quality
  - Solid pollutants (e.g. chemicals) can accumulate in the soil posing a threat to the health of the ecosystem
- **Ecological consequences**
  - Pollution can affect ecosystem "homeostasis", making natural disasters more common
  - Habitat destruction
  - Loss of biodiversity
- **Atmospheric changes**
  - Global warming – unregulated CO_2 and other greenhouse gases emissions pose a serious threat to temperature increase and climate change

Engineering materials categories (one version)

- Metals and alloys (after break)



Materials science classifications