

Abiotic resources

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EV14 – Modeling of Human-System-Nature interactions

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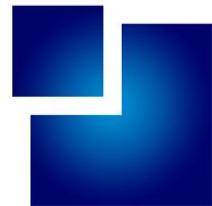


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[1] BEYLOT, A. et al, 2020. DOI [10.1016/j.resconrec.2020.104748](https://doi.org/10.1016/j.resconrec.2020.104748)

« Abiotic resources » [1]

- Firstly, ***biotic resources*** refers to ressources coming from living things, or more precisely, organic matter. Ex: animals, plants.
- Consequently, ***abiotic resources*** refers to all ressources but biotic ones. So, it encompasses minerals, but also air, water, sunlight, etc.
- Fossil fuels can be classified either as biotic or abiotic resources, depending on the timescale considered. Indeed they're coming from living things, resulting of bio-geochemical cycles, but were definitively formed million years ago. In EV14, we'll consider them as abiotic.

[1] BEYLOT, A. et al, 2020. DOI [10.1016/j.resconrec.2020.104748](https://doi.org/10.1016/j.resconrec.2020.104748)

But what even are « resources »? [1]

- Surprisingly, it is not often explicitly defined, even in major texts. Ex: ISO 14040 norm (giving framework for all Life-cycle analysis), or the classical 1983 report of the United Nations.
- Analysis of varied definitions highlights some converging points: a *resource* is considered as such if:
 - It has an value or utility (from material properties for an industrial process to cultural valorization of precious stones)
 - For a certain subject (generally considered: the humans)

1.2 General characterizations

[2] Resource, 2020. Wikipedia [online].

A. The *renewable/non-renewable* polarity [2]

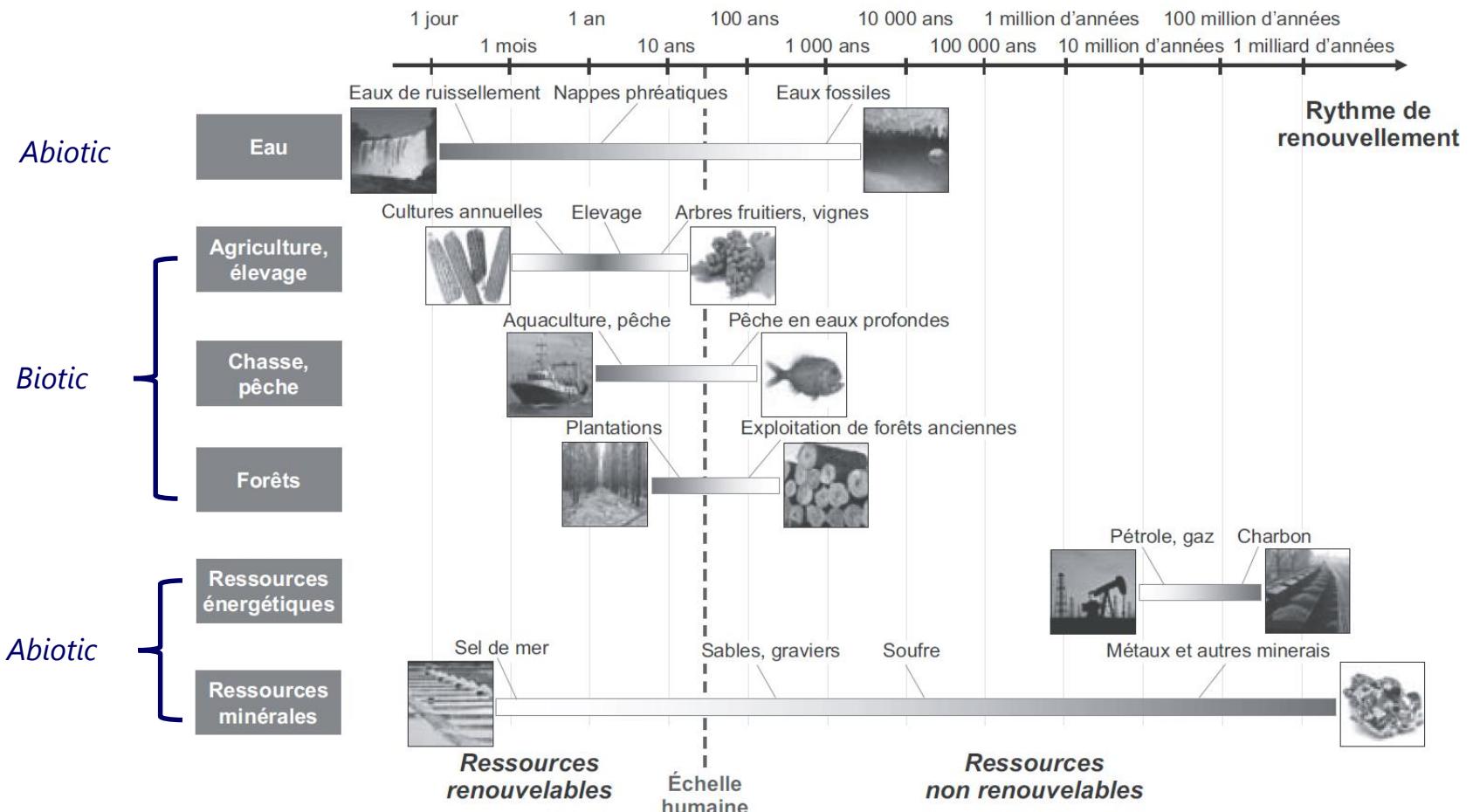
- Renewable when the stock reconstitutes itself at a « sufficiently quick rate ». Usual threshold: timespan of a human life.
- Non-renewable when they constitute themselves on a long period of time, way longer than a human life. Their use is always a depletion in available stocks.

1.2 General characterizations

[2] Resource, 2020. Wikipedia [online].

[3] BIHOUIX, P., GUILLEBON, B., 2010. Quel futur pour les métaux?

A. The *renewable/non-renewable* polarity [2]

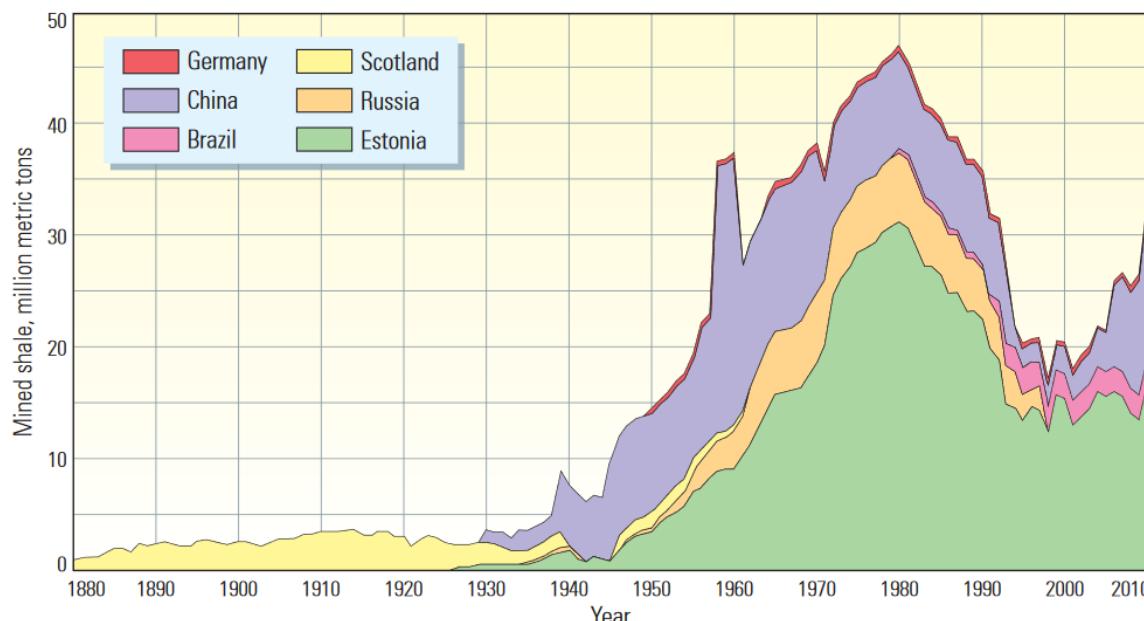


1.2 General characterizations

[4] History of the oil shale industry, 2020. Wikipedia [online].
 [5] Allix et al., 2010. Coaxing Oil from Shale. Oilfield Review [online]. 2011.

B. The *availability/non-availability* polarity

- Available when concentration and position let them be technically AND economically usable by humans.
- More or less available according to the variation of these dimensions.
 Ex: Oil shale in the XXth, depending on stocks' concentrations and competition with conventional crude oil. [4] and [5]



Extracted from [6]

▲ More than a century of commercial oil shale mining. Tonnage of mined shale rose dramatically in the 1970s when oil prices were also rising; it peaked in 1980, but declined as oil prices made shale oil noncompetitive. Several countries continue to mine oil shale as a source of heat, electricity, liquid fuel and chemical feedstock. Since 1999, mined shale tonnage has started to increase again.

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- Main threads of the course : Metals and Oil
- Metals
 - Brief global history
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- Oil :
 - Brief global history
 - Contemporary trends
- Sociotechnical perspective (Tutorial work)

3. Extraction of abiotic resources

4. Perspectives of abiotic resources

2.1 Main threads of the course

[3] BIHOUIX, P., GUILLEBON, B., 2010. *Quel futur pour les métaux?*

[6] BP, 2020. BP Statistical Review of World Energy. [online]. 2020.

The mineral resource example: Metals

- Why metals? On the 118 known atoms, most of them are metals:^[3]
 - 85 metals
 - 6 metalloids
 - 17 non metals
 - 10 non determined
- General properties:
 - electrical & thermal conductors
 - mechanical ductility
- Geological forms: oxides (common) > sulfides (less common) > natives (uncommon)

The energetical resource example: Oil

- Currently, most used source in main primary energy consumption:
 - Oil (33,1%)
 - Coal (27%)
 - Natural gas (24,2%)^[6]
- Regroup varied forms of derived fuels (petrol, shale oil) and secondary resources
- General properties: gives a lot of secondary resources when refined, good energy density, easy and convenient to transport and to use as energy vector in varied contexts

[3] BIHOIX, P., GUILLEBON, B., 2010. *Quel futur pour les métaux?*

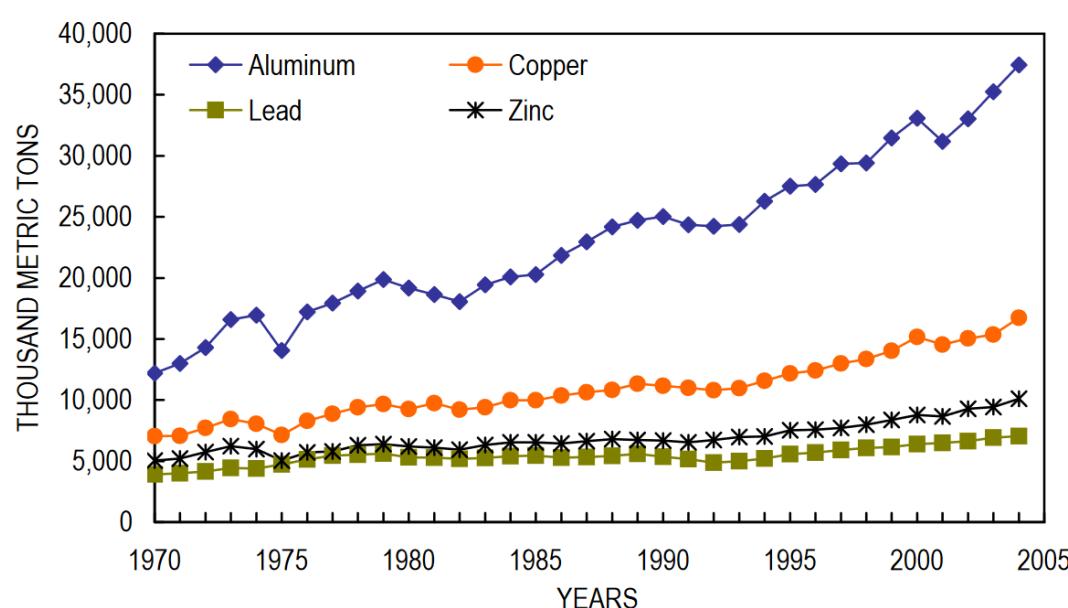
A very brief summary [3]

- Contrary to first intuition: native metals were the first to be used. Although uncommon (often mixed) they were easily recognizable:
 - Copper (at least 8000 BC, and melted since 4000 BC), Gold and Silver (4000 BC)
 - Alloys starting in 2500 BC with Bronze (Tin & Copper)
 - Furnaces since at least 1000 BC let reduce oxides (notably, Iron oxide) and develop experiments on alloys (Steel = Iron + Carbon)
 - Lead, Antimony, Mercury used pure or in alloys during Antiquity
- This tiny number of metals has constituted the main uses until the XIXth century and structured economical and geopolitical relationships between populations
 - Besides native platinum in Peru, other metals like Nickel, Zinc, Cobalt have been identified by chemistry and metallurgy (beginning of XVIIIth). And then: Manganese, Molybdenum, Tungsten, Titanium (end of the XVIIIth).
 - Electrolysis in XIXth allows to separate most elements in pure form, but weak rate of use until the XXth century.

2.2.2 Contemporary trends

[7] ROGISH, D.G., and MATOS, G.R., 2008, The global flows of metals and minerals: USGS Open-File Report 2008-1355

A. Continuous growth in use of base metals



Extracted from [7]

Figure 3. Global aluminum, copper, lead, and zinc consumption.

- Heterogeneous rise of world consumption for base metals: by a factor from 1,5 (Lead) to 3 (Alumunium)

2.2.2 Contemporary trends

[7] ROGISH, D.G., and MATOS, G.R., 2008, The global flows of metals and minerals: USGS Open-File Report 2008-1355

A. Continuous growth in use of base metals

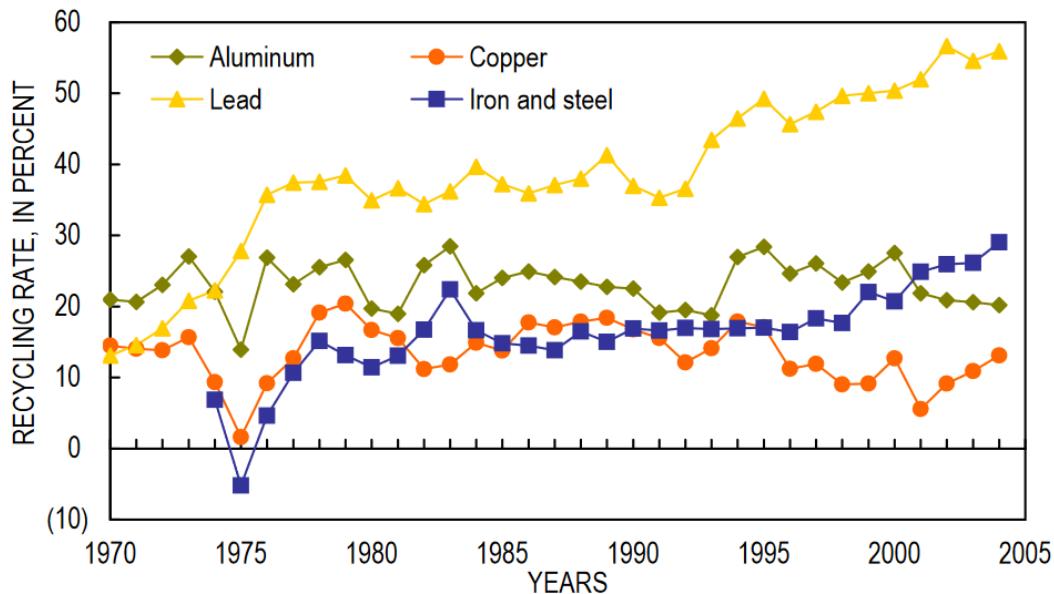


Figure 24. Graph illustrating calculated world metals recycling rates.

Extracted from [7]

- Recycling rates not progressing as much

2.2.2 Contemporary trends

[7] ROGISH, D.G., and MATOS, G.R., 2008, The global flows of metals and minerals: USGS Open-File Report 2008-1355

B. Countries high disparities

Extracted from [7]

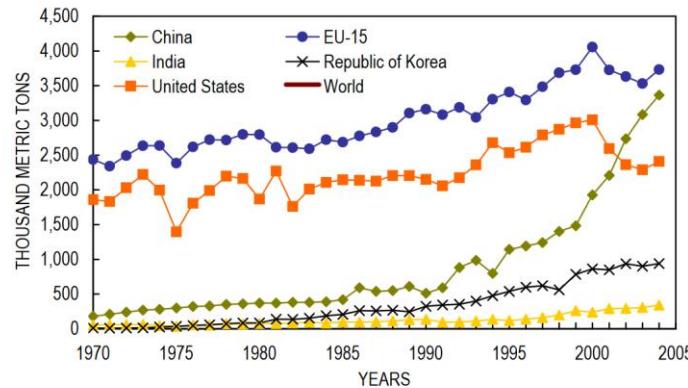


Figure 11. Copper consumption by country.

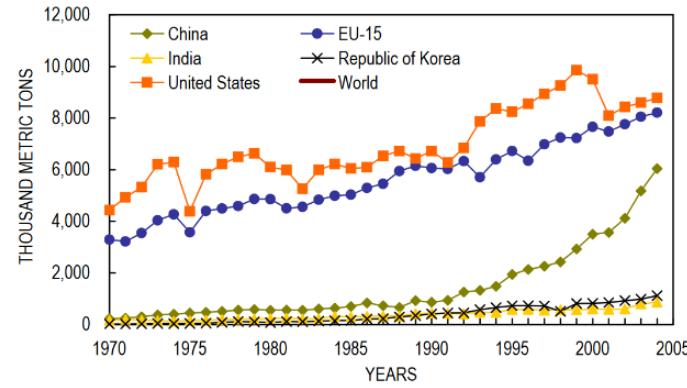


Figure 12. Aluminum consumption by country.

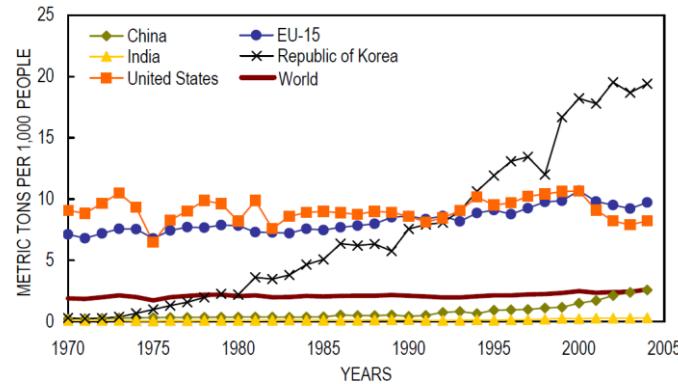


Figure 15. Copper consumption per capita by country.

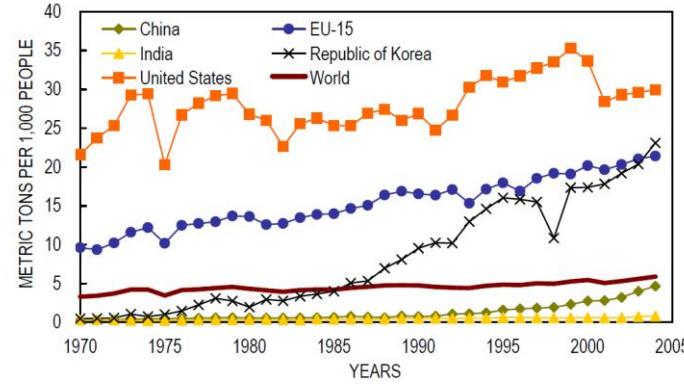


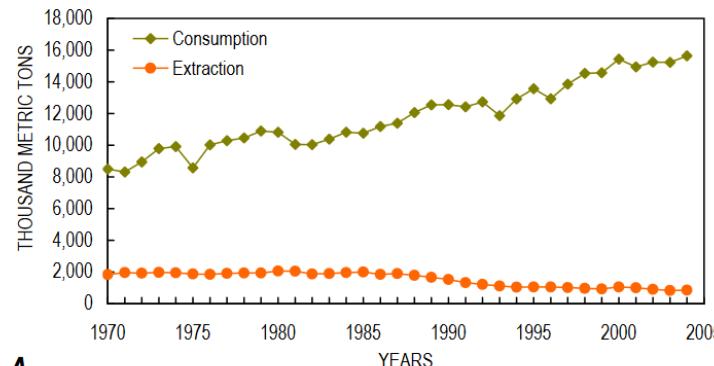
Figure 16. Aluminum consumption per capita by country.

2.2.2 Contemporary trends

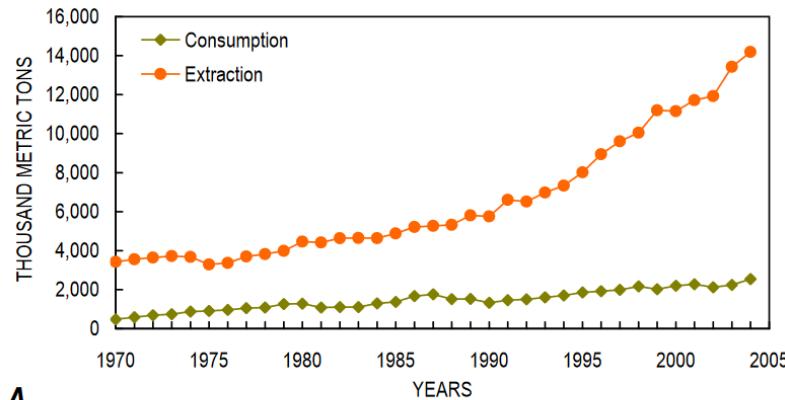
[7] ROGISH, D.G., and MATOS, G.R., 2008, The global flows of metals and minerals: USGS Open-File Report 2008-1355

C. Global Extraction/Consumption pattern

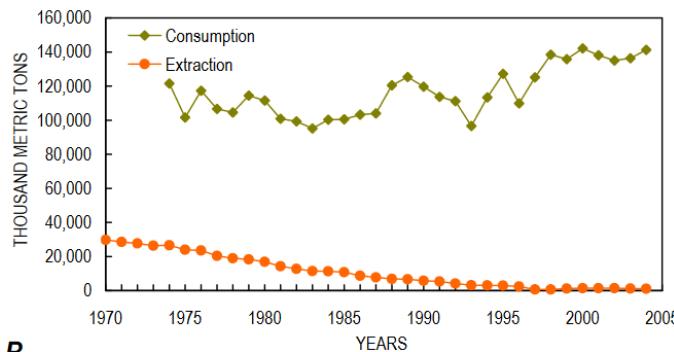
Extracted from [7]



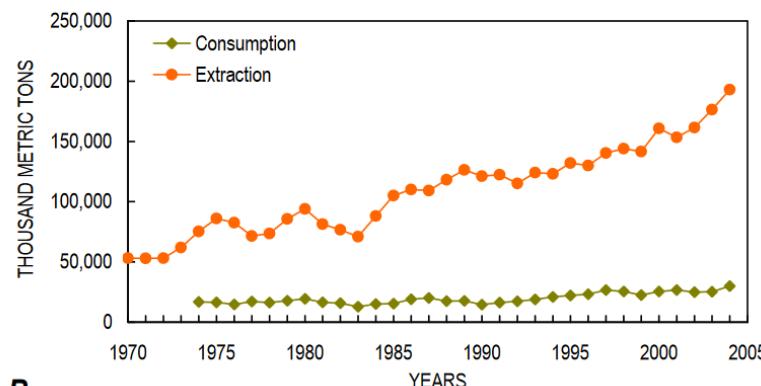
A



A



B



B

Figure 18. Consumption and extraction in the European Union group of 15 countries (EU-15). A, Base metals. B, Iron and steel.

Figure 19. Consumption and extraction in South America. A, Base metals. B, Iron and steel.

2.2.2 Contemporary trends

[3] BIHOIX, P., GUILLEBON, B., 2010. *Quel futur pour les métaux?*

D. Growing variety of metals for expanding specific uses

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18				
1	1 H																2 He					
2	3 Li	4 Be															5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg															13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	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				
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo		44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe				
6	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							
7			**																			
*Lanthanides (Terres rares)			57 La	58 Ce	59 Pr	60 Nd		62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu					
**Actinides				90 Th		92 U																

Adapted from [3]

1970s: <20 metals

2000s: >60 metals

[8] Petroleum, 2020. Wikipedia [online].

[9] BONNEUIL, C., FRESSOZ, J-B, 2016. *The Shock of the Anthropocene. The Earth, History and Us.*

A very brief summary [8]

- Oil has been used for a long time in varied forms
 - Used as fuel as back as 400 BC in China
 - Used for lighting or in the asphalt form for construction as back as 2000 BC in Babylon
 - Crude oil already distilled by Persian chemist in 9th century to obtain tar, used for streets' paving
 - Distillation arrive in Europe in 12th century through Islamic Spain
- The mid 19th – early 20th turning point [9]
 - First industrial oil well and oil refinery around 1850
 - Consumption stayed low (5% of world energy in 1910), as oil was not that interesting at first, compared to wind or animals for transport, solar & coal were largely dominant for thermal power, etc.
 - Complex and crossing technical but mostly political phenomena let oil grow in varied uses, to represent more than 60% of world energy as soon as 1970



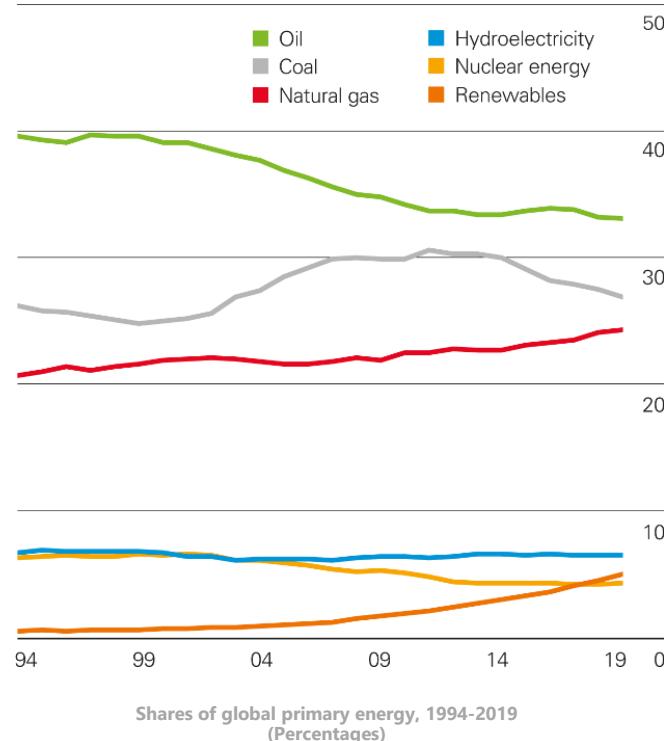
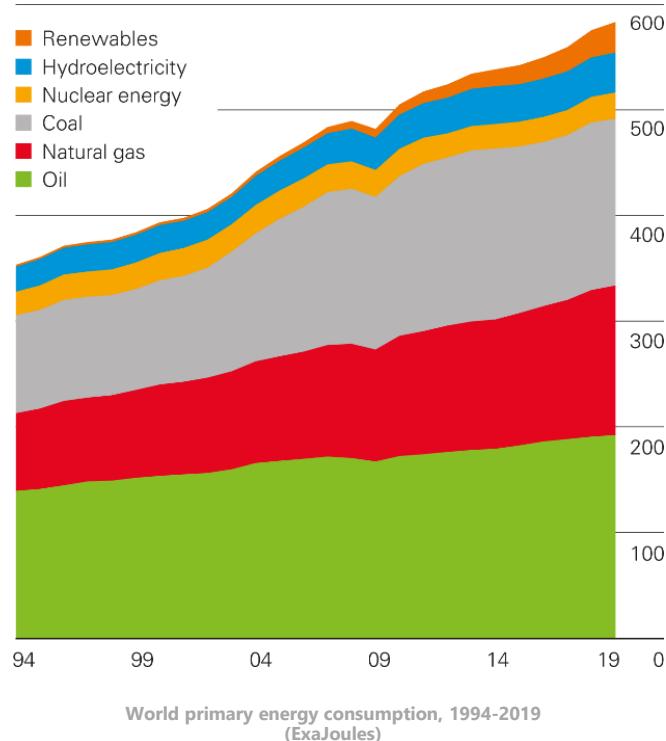
We'll see that in Tutorial Work...

2.3.2 Contemporary trends

[6] BP, 2020. BP Statistical Review of World Energy. [online].

A. No primary energy transition

Extracted from [6]



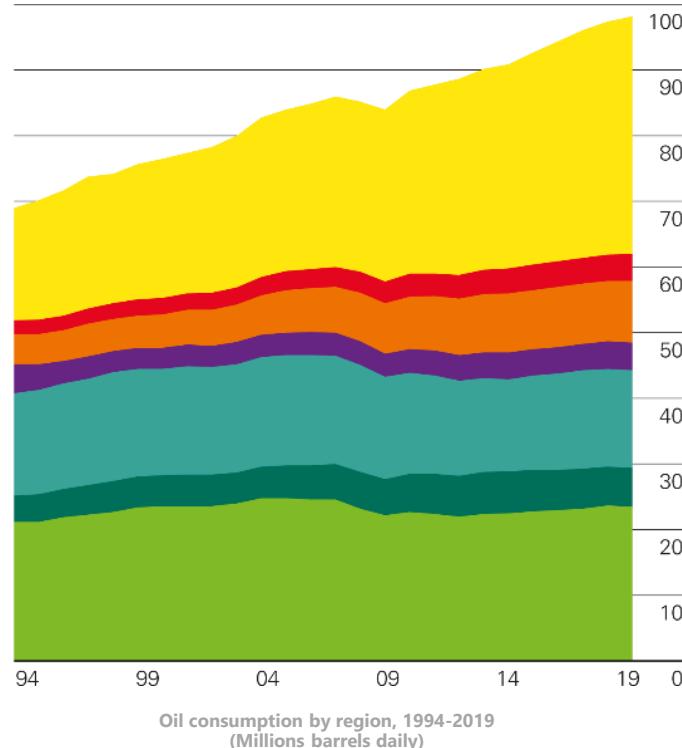
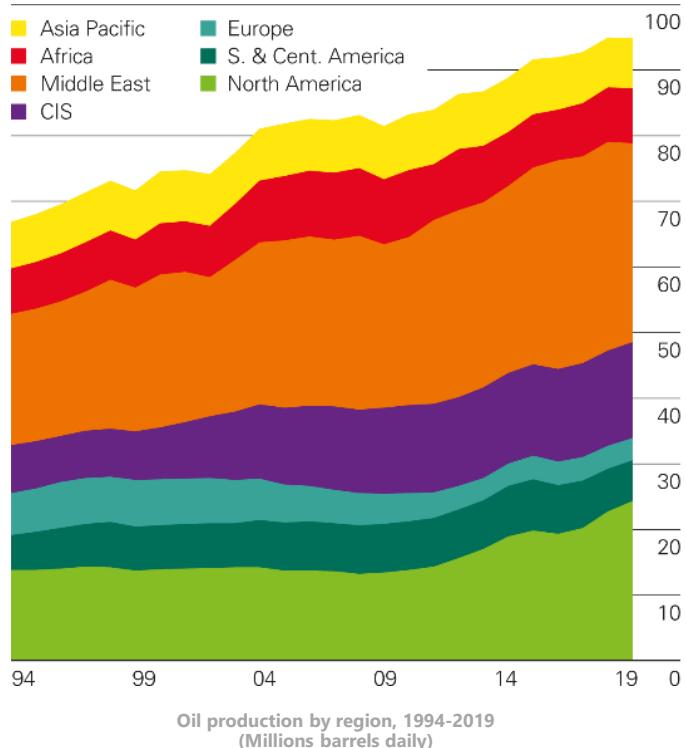
- Oil's share in primary energy is steadily decreasing for more than 30 years, but:
 - Oil is still the dominant energy vector
 - In absolute quantity, it is not declining at all, as for all energy vectors!

2.3.2 Contemporary trends

[6] BP, 2020. BP Statistical Review of World Energy. [online].

B. Three main profiles

Extracted from [6]



- High ratio of Production/Consomption
- Low ratio of Production/Consomption
- Ratio of Production/Consomption near 1

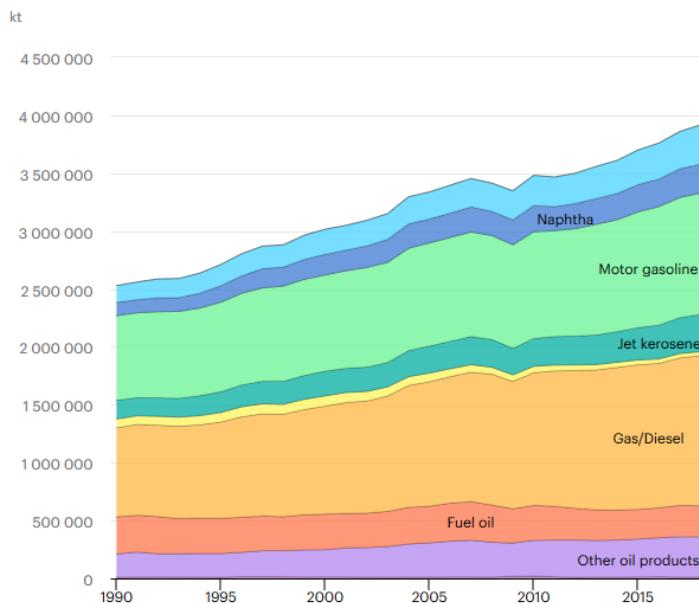
2.3.2 Contemporary trends

[10] Data & Statistics,. IEA [online]. Available from: <https://www.iea.org/data-and-statistics>

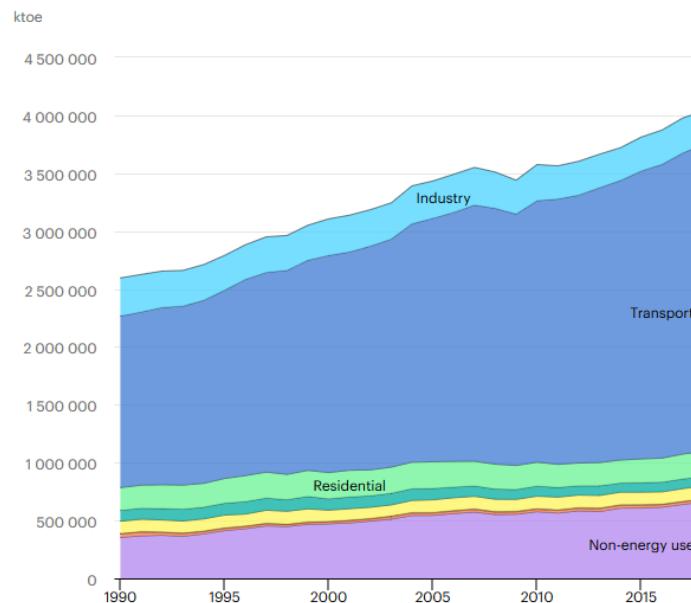
C. Consistency of uses

Extracted from [10]

Oil final consumption by product, World 1990-2018



Oil products final consumption by sector, World 1990-2018



IEA. All rights reserved.

● LPG/Ethane ● Naphtha ● Motor gasoline ● Jet kerosene ● Other kerosene
● Gas/Diesel ● Fuel oil ● Other oil products ● Crude oil/NGL

● Industry ● Transport ● Residential ● Commercial and public services
● Agriculture / forestry ● Fishing ● Non-specified ● Non-energy use

2.4 Sociotechnical perspective

See Tutorial work

- Available by the end of the week

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 - Caution in interpretation
- Impacts of extractive activities
 - Growing interdependancies
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 - Material footprint of energy
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 - Other abiotic resources: water & air quality
 - Biotic resources: wildlife and land
 - Socio-economical focus
 - Contrasted local realities
 - Global frictions...
 - Rooted in historical inequalities

4. Perspectives of abiotic resources

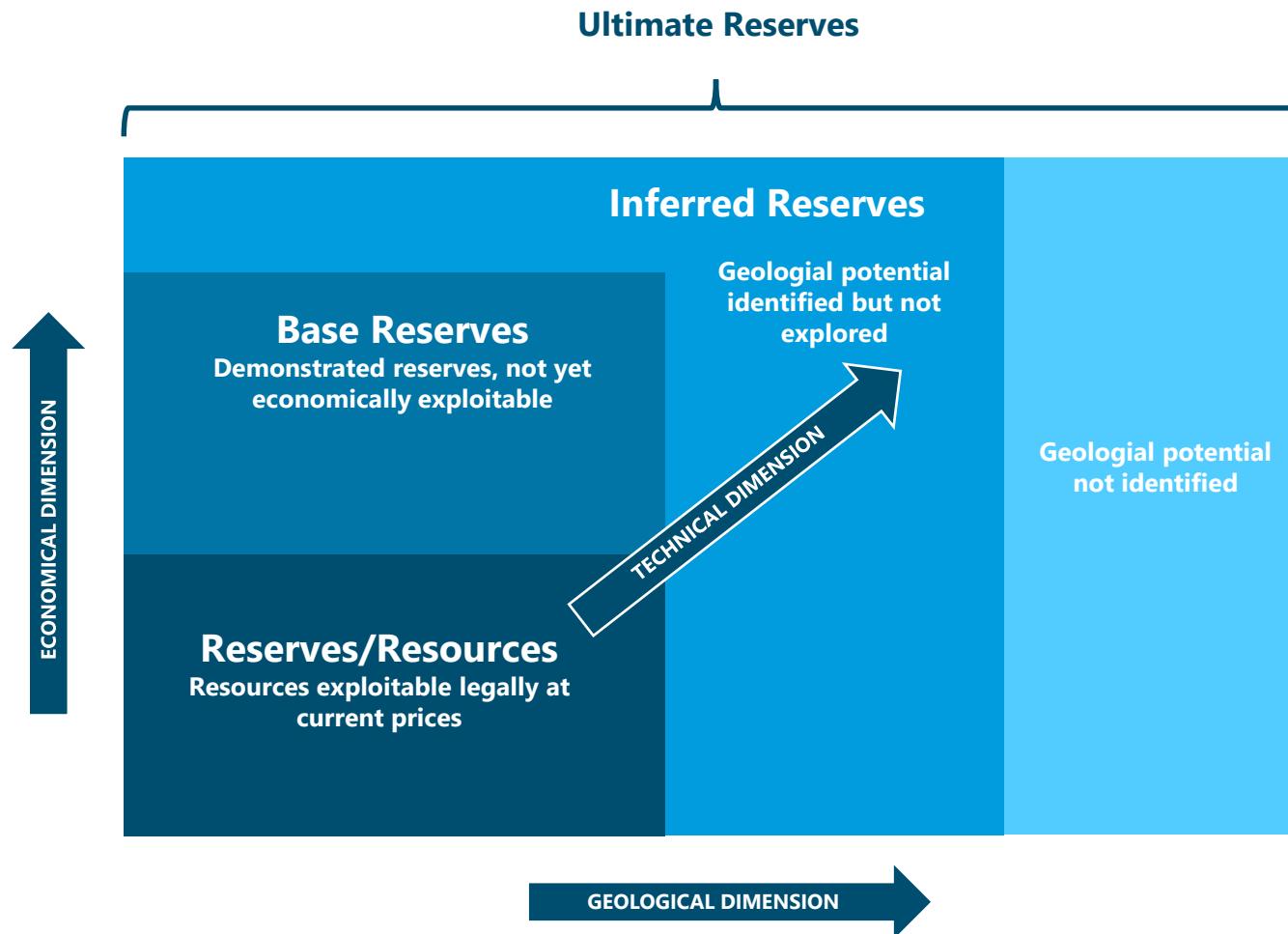
[3] BIHOUIX, P., GUILLEBON, B., 2010. *Quel futur pour les métaux?*

[11] USGS, 2014. *Estimate of Undiscovered Copper Resources of the World* [online]. Fact Sheet.

[12] USGS, 2020. *Mineral Commodity Summaries* [online].

Definitions

Adapted from [3]



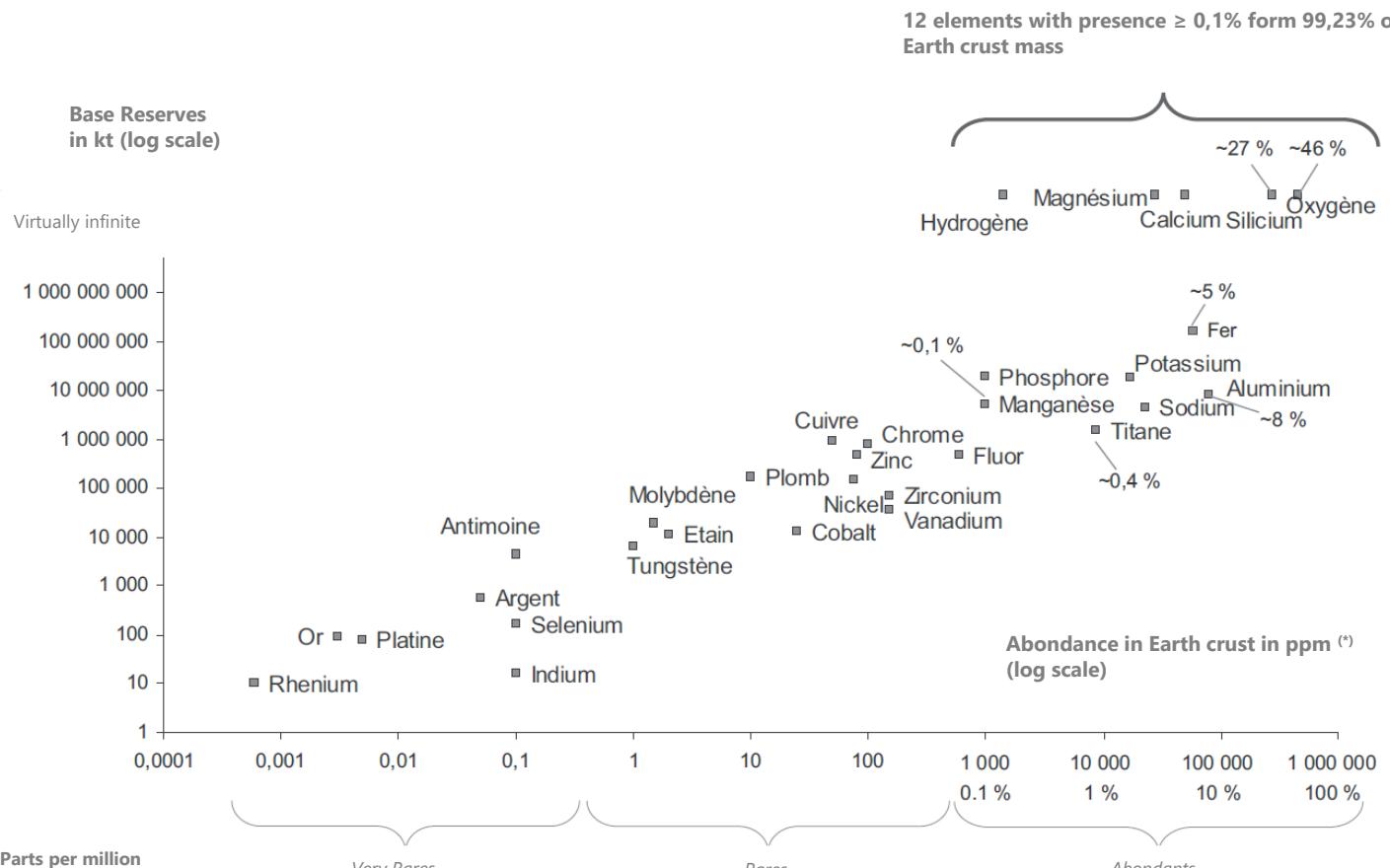
[3] BIHOUIX, P., GUILLEBON, B., 2010. *Quel futur pour les métaux?*
[11] USGS, 2014. *Estimate of Undiscovered Copper Resources of the World* [online]. Fact Sheet.
[12] USGS, 2020. *Mineral Commodity Summaries* [online].

Definitions

- Reserves/Resources data are highly dynamic
 - May be reduced as
 - ore is mined
 - feasibility of extraction diminishes
 - May increase as
 - additionnal deposits are discovered
 - currently exploited deposits are thoroughly explored
- The Copper example: [11] & [12]
 - Reserves/Resources \simeq 500 Mt (2014) \rightarrow 870 Mt (2020)
 - Inferred Reserves \simeq 2.1 Bt (2014)
 - Ultimate Reserves \simeq 3.5 Bt (2014)

[3] BIHOUIX, P., GUILLEBON, B., 2010. *Quel futur pour les métaux?*

A. Concentration of minerals



Sources: BRGM, USGS 2007

Extracted from [3]

[3] BIHOIX, P., GUILLEBON, B., 2010. *Quel futur pour les métaux?*

A. Concentration of minerals

- Average concentrations of minerals in Earth crust must be compared to typical concentrations in exploited ores
- Even for abundant elements, high ratio between economically viable concentrations and Earth crust average
 - Iron (Fe) example: 30-60 % in ores versus 5 % average in Earth crust
- Precious metals are logically the only ones where the order of magnitude is equivalent
 - Typical example: Gold (Au)

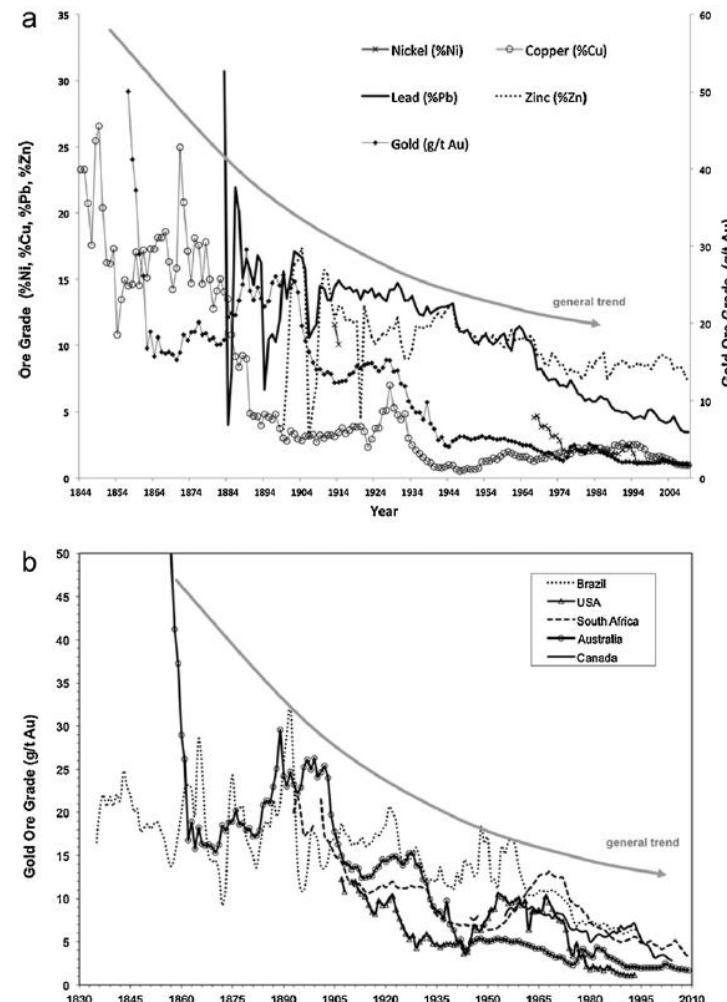
Metal	Typical concentration of exploited ores	World mean	Metal mass per ton of ore
Fe	[30-60] %		[300-600] kg
Al	[20-30] %		[200-300] kg
Zn	[3-9] %	8%	[30-90] kg
Pb	[2-7] %	5%	[20-70] kg
Ni	[1,5-3] %		[15-30] kg
Cu	[0,5-2] %	0,8 %	[5-20] kg
Au	[0,0002-0,0006] %	0,0003 %	[2-6] kg

Extracted from [3]

[3] BIHOUIX, P., GUILLEBON, B., 2010. *Quel futur pour les métaux?*
 [24] PRIOR, T *et al.*, 2012. Resource depletion, peak minerals and the implications for sustainable resource management.

A. Concentration of minerals

- If no major discoveries, historical tendency is a decrease in average concentration causing an increase in cost and impacts:
 - Example of Copper (Cu): 1,8% (1930) → 0,8% 2010
 - See opposite: (a) Concentration of varied ores in Australia (b) Concentration of Gold ores in the world

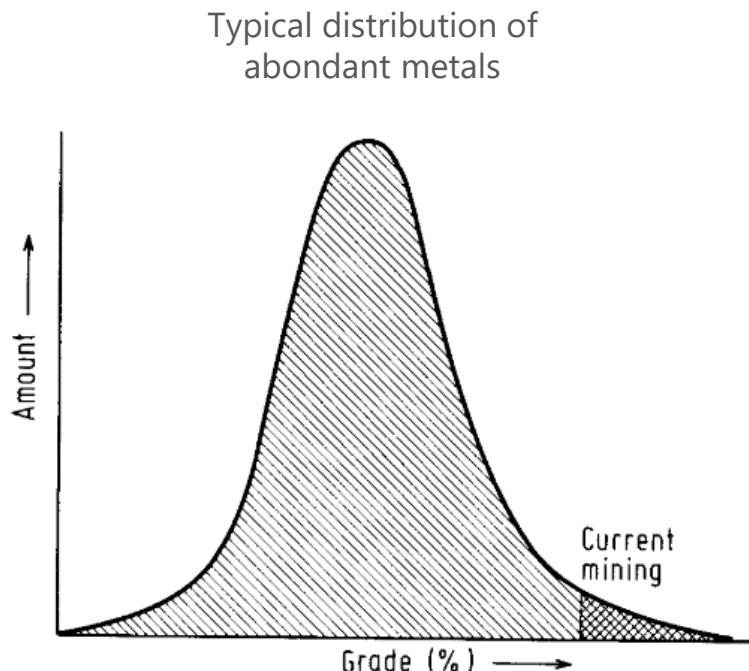


Extracted from [24]

[13] SKINNER, B.J., 1979. Chapter 10 A Second Iron Age Ahead? In: *Studies in Environmental Science*.
[14] AYRES, Robert U, 2001. Resources, Scarcity, Growth and the Environment. . 2001. P. 35.

B. Mineralogical barrier

- Abondant metals mining follows a simple curve:
 - Highest-grade ores are mined first, as they're the most available ones – technically and economically
 - Like for any finite resources, mining depletes stocks, then target less high-grade ores, until a production peak happen, after what availability diminishes

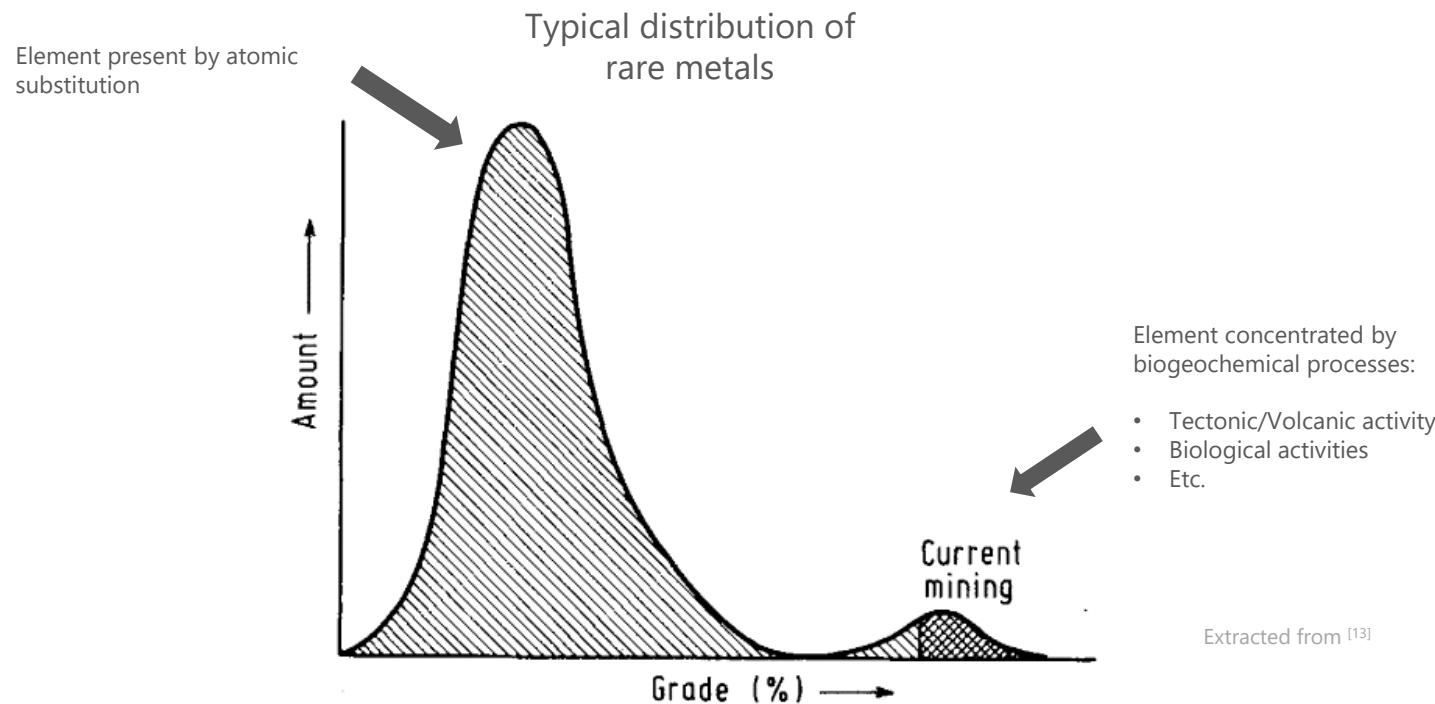


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B. Mineralogical barrier

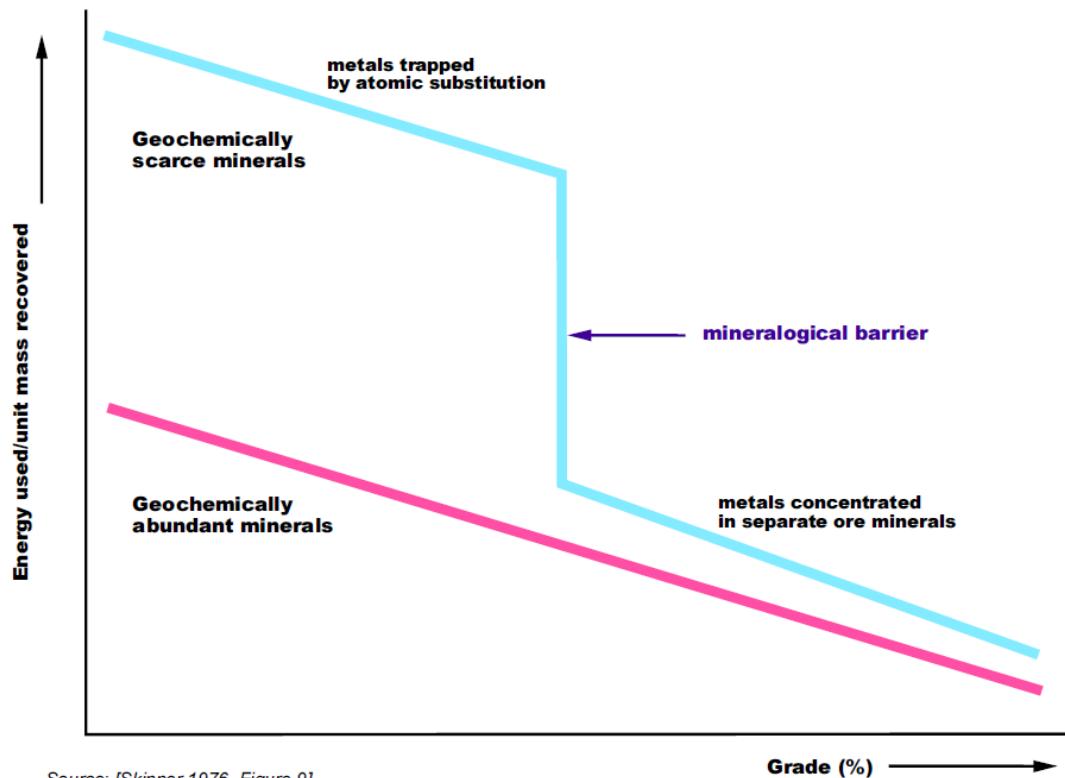
- Scarce metals are usually not found in common rocks as separate minerals but as atoms substitutions (that's makes them rare)
 - Consequently, mining activities directly seek concentrated ores (geologically rarer themselves), then must rely on more common ores, following a bimodal mining curve



[13] SKINNER, B.J., 1979. Chapter 10 A Second Iron Age Ahead? In: *Studies in Environmental Science*.
 [14] AYRES, Robert U, 2001. Resources, Scarcity, Growth and the Environment. . 2001. P. 35.

B. Mineralogical barrier

- The shift to these more common rocks can be a turning point in processes needed, and generate a mineralogical barrier



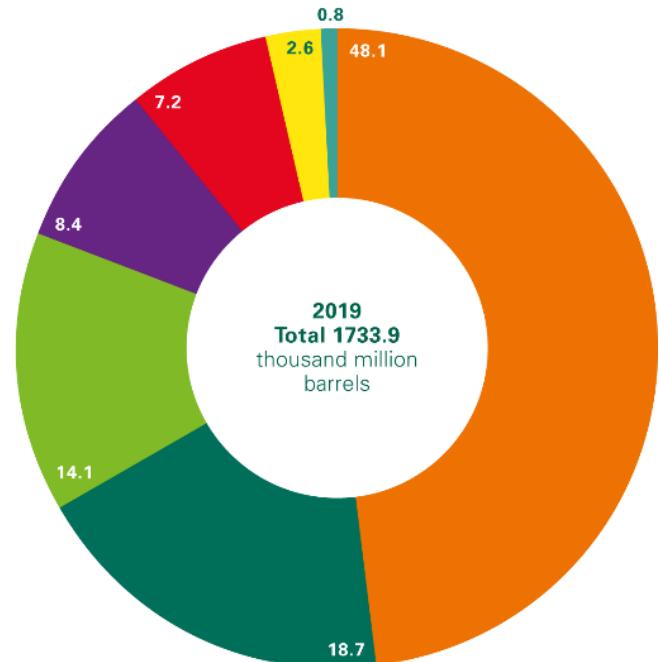
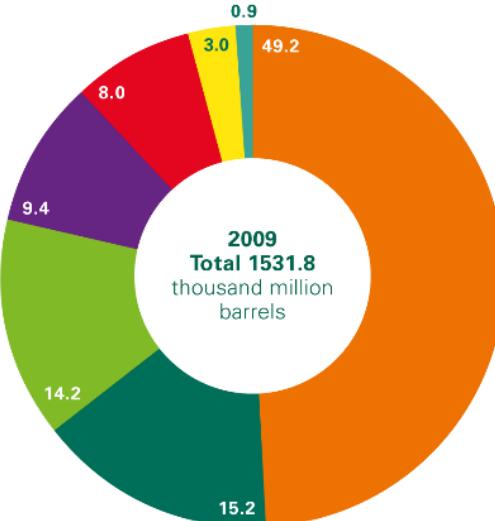
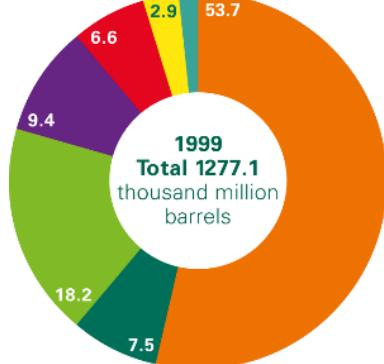
[6] BP, 2020. BP Statistical Review of World Energy. [online].

[15] JANCOVICI, Jean-Marc, 2019. Les Energies fossiles. Ecole des Mines [online].

A. Assessing reserves [15]

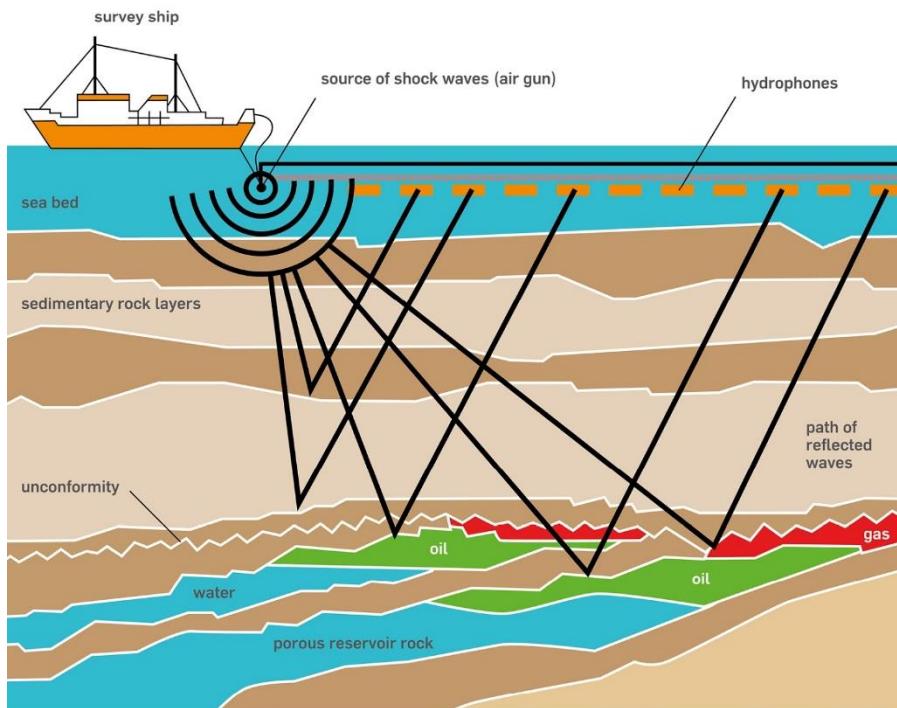
Extracted from [6]

- Middle East
- S. & Cent. America
- North America
- CIS
- Africa
- Asia Pacific
- Europe



A. Assessing reserves [15]

- When a potential reserve of oil is suspected, sismography combined with exploratory drilling is used to estimate:
 - Quantities of oil
 - Probable recovery rate of the oil



[15] JANCOVICI, Jean-Marc, 2019. Les Energies fossiles. Ecole des Mines [online].

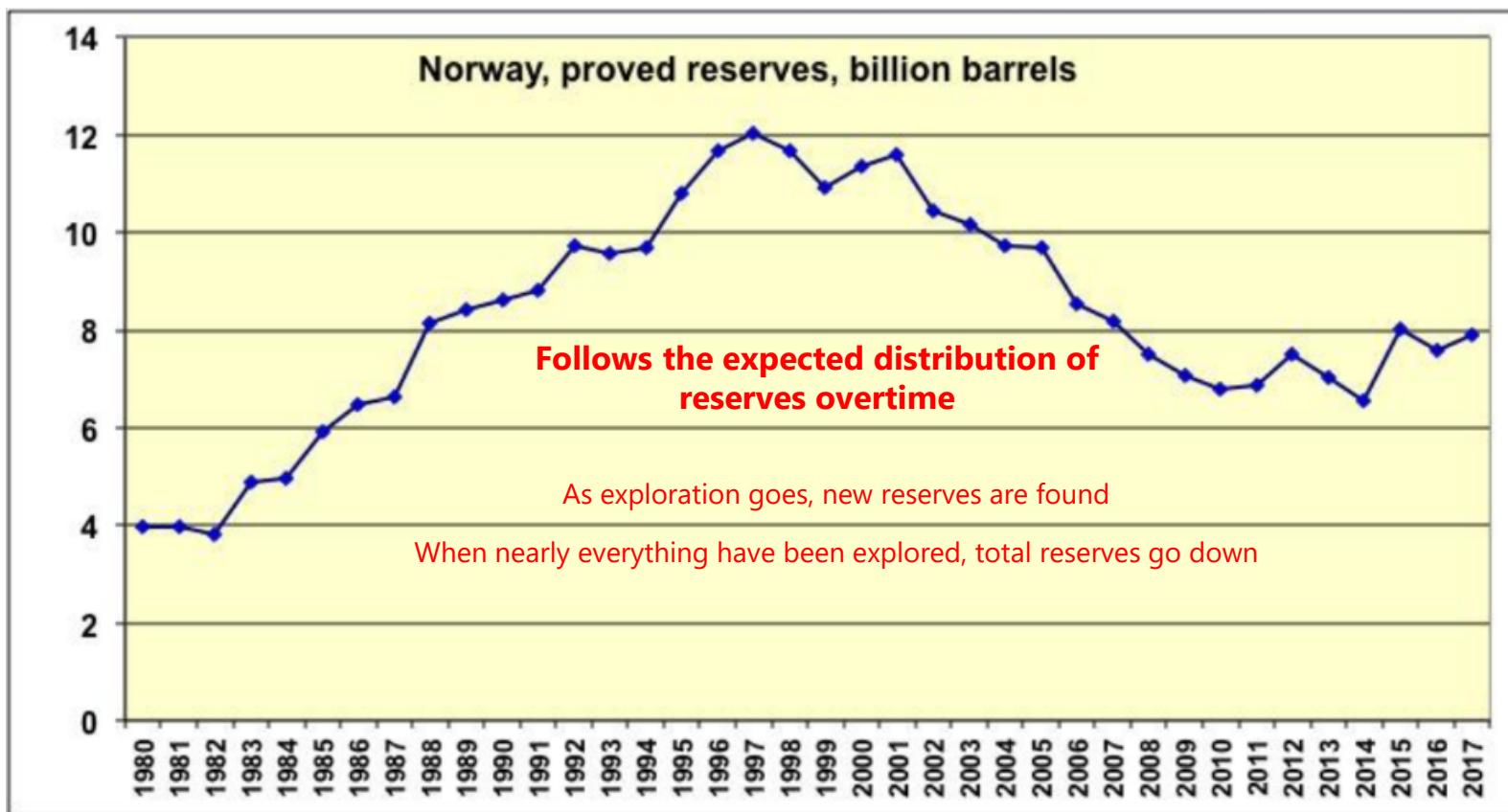
A. Assessing reserves [15]

- As any oil extraction needs heavy infrastructure → CAPEX>>OPEX.
Which means the dynamics of a specific reserve are:
 - Strongly dependant on quantities & recovery rates estimations accuracy
 - Weakly dependant of variations in oil price (infrastructure already there)
- Who evaluate & declare the reserves?
 - A lot of oil companies are state-owned. Around 10% of oil companies are listed on the stock exchange → legally binded to communicate the estimations
 - Large part of data comes from countries but:
 - Geopolitical strategies due to production international agreements
 - Different conventions on what to count and in which category
 - No independant verifications

[15] JANCOVICI, Jean-Marc, 2019. Les Energies fossiles. Ecole des Mines [online].

B. Caution in interpretation

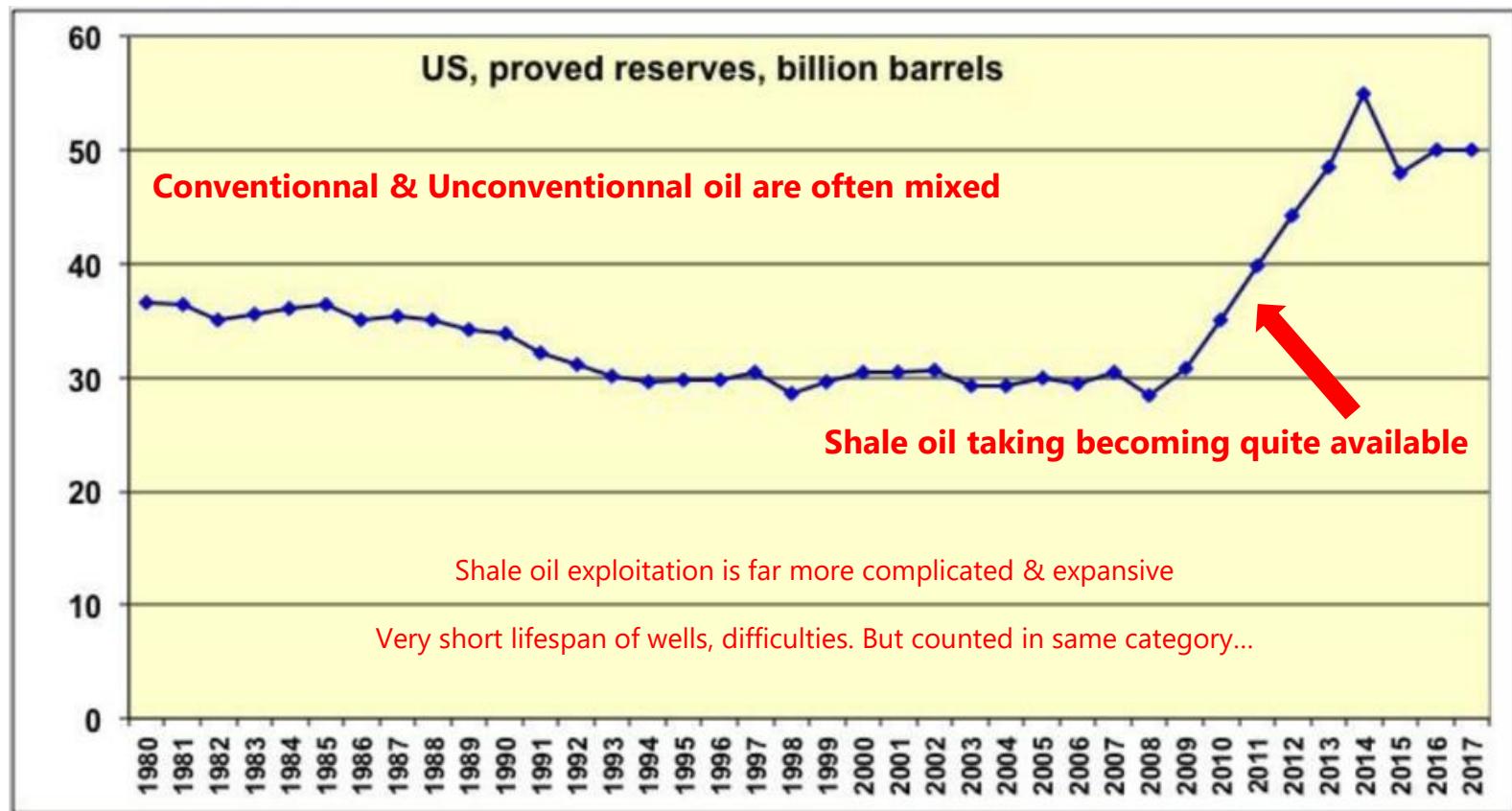
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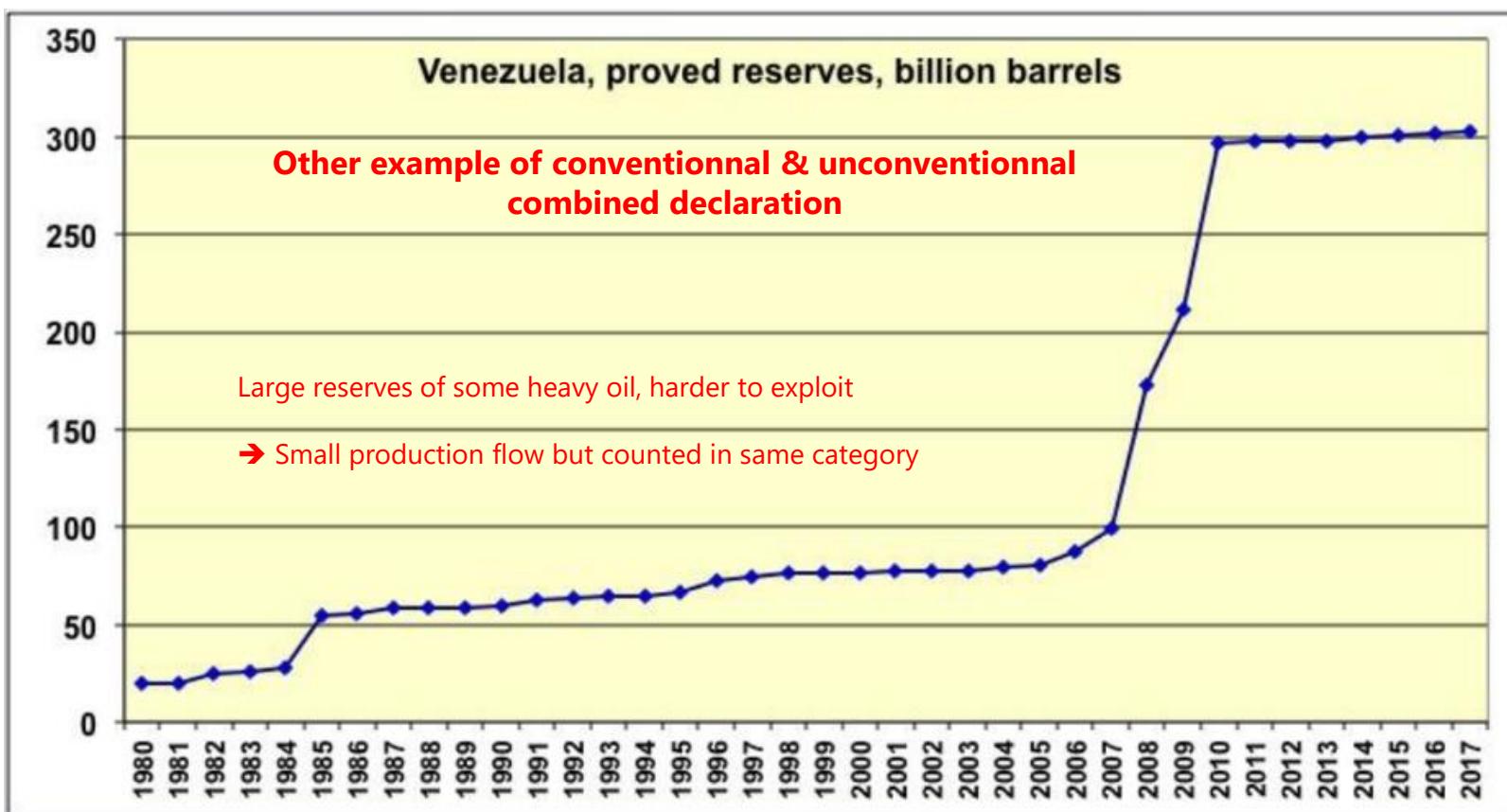
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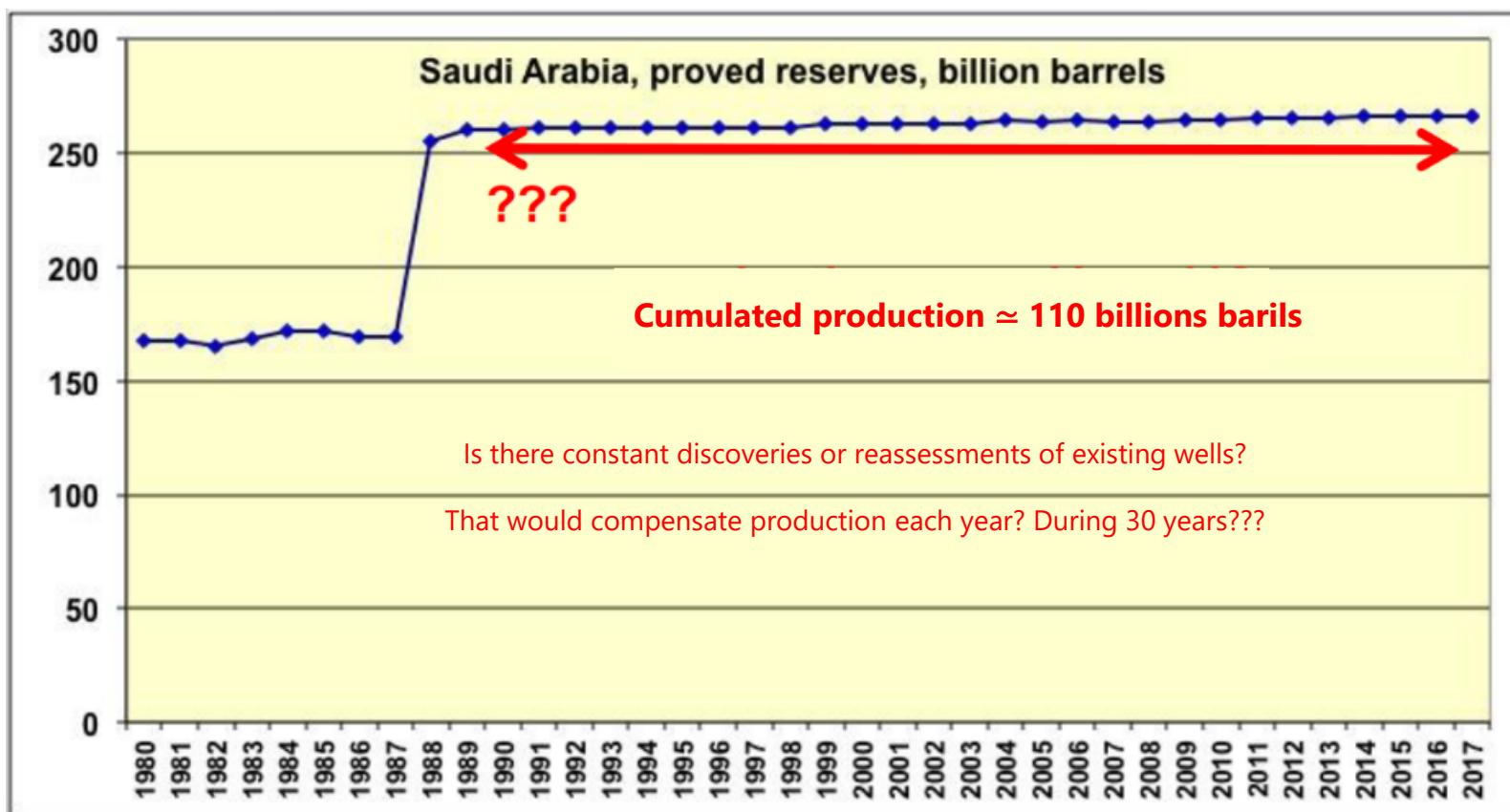
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B. Caution in interpretation

Adapted from [15]



[3] BIHOUIX, P., GUILLEBON, B., 2010. *Quel futur pour les métaux?*

A. Energy footprint of minerals

- A lot of operations involved
 - Extraction, mineral processing, metal working
 - 1st order transformation: smelting and refining
 - Transport between steps
 - This raw metal undergo varied 2nd order transformations to become raw products with diverging final energetical footprint
 - Copper example: tubes 20-30% higher footprint than foils
- Uncertainties in data
 - Diversity of production sites (mineral concentration, efficiency of processes)
 - Varied studies perimeter (no standard approach, weigh of hypothesis)
 - Disparities in sources of information available

3.2.1 Growing interdependancies

[3] BIHOUIX, P., GUILLEBON, B., 2010. *Quel futur pour les métaux?*

A. Energy footprint of minerals

Extracted from [3]

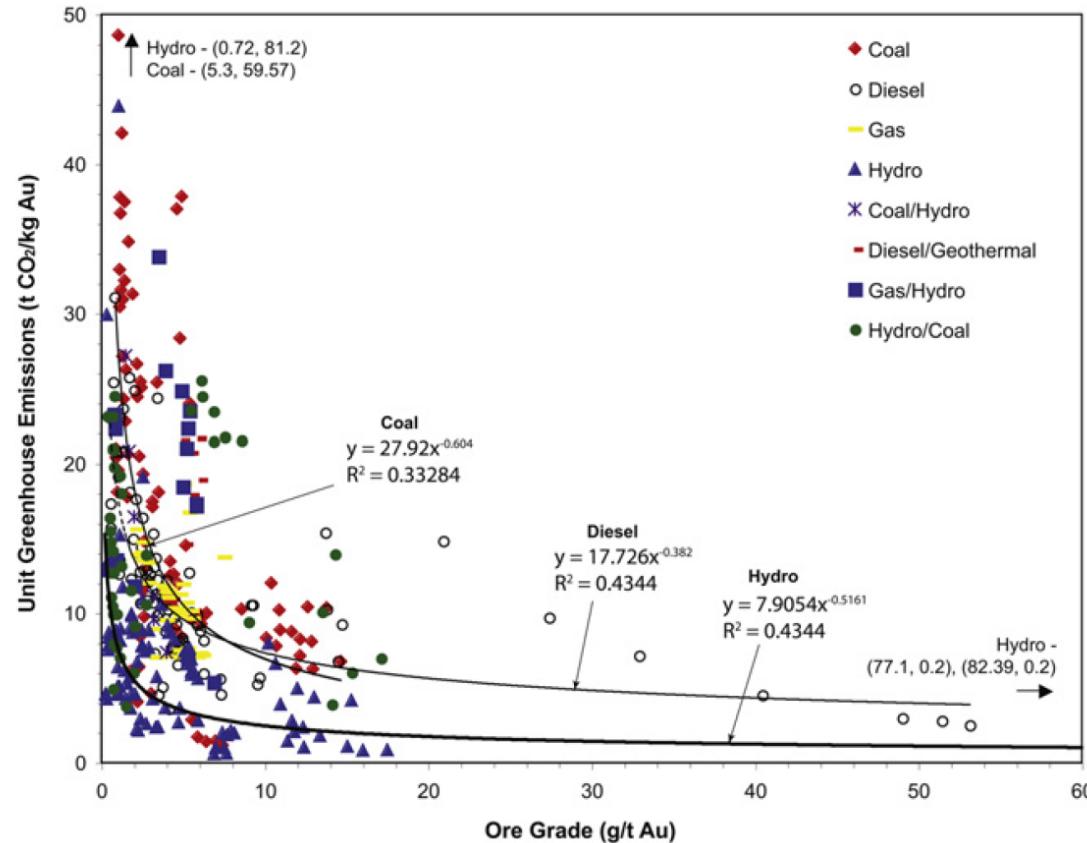
Metal	Production energy (tep/t)	Mining production (Mt)	Total energy (Mtep)
Steel	0,4-0,5	1360	544-680
Al	3,8-7,4	39,7	147-288
Cu	0,8-3,6	3,6	12-56
Cr	?	21,5	?
Zn	0,9-1,9	11,3	10-21
Mn	?	14	?
Si	?	5,7	?
Ni	2,7-4,6	1,6	4-7
Mg	8,6-10,2	0,8	7-8
Pb	0,5-1,1	3,8	2-4
Sn	4,6	0,3	1-2
Total (2010)	In Mtep		730-1070
Total (2010)	For World	Primary energy	7-10%

3.2.1 Growing interdependancies

[24] PRIOR, T *et al.*, 2012. Resource depletion, peak minerals and the implications for sustainable resource management.

A. Energy footprint of minerals

- Extraction & Refining of metals
 - Less & less concentrated mineral resources → more & more energy



Extracted from [24]

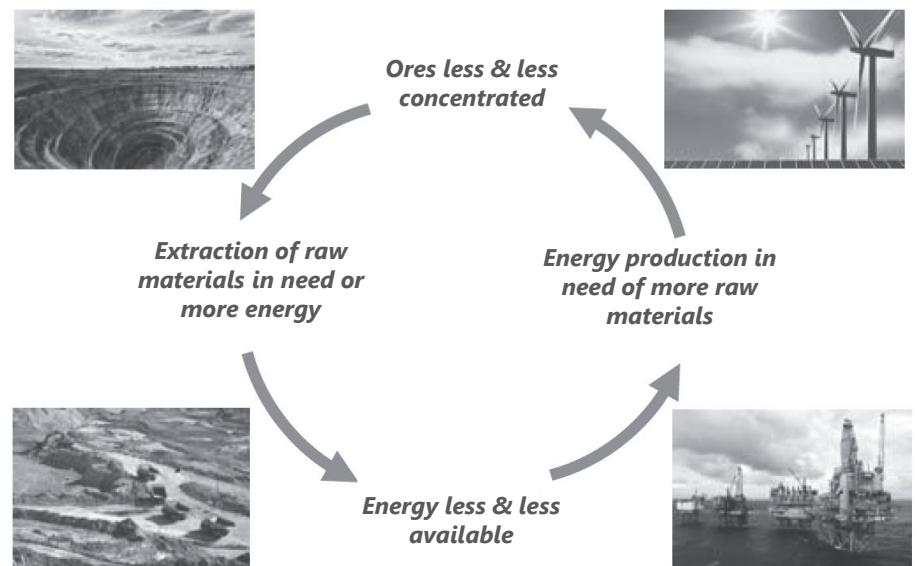
3.2.1 Growing interdependancies

[3] BIHOUIX, P., GUILLEBON, B., 2010. *Quel futur pour les métaux?*

B. Material footprint of energy

- Extraction & Refining of oil
 - $\simeq 5\%$ of world Steel use for gas/oil exploration & production
 - 'Offshore', 'Deep offshore', or Unconventional oil → rise in the use of platforms, ships, complex tools, etc.
- Even « Renewable energies » are quite materially dependant:
 - A 1MW windmill contains $\simeq 3t$ of Cu, and needs 10x more steel & concrete per kWh than a classical plant
 - A classical PV installation (Si) needs $\simeq 4kg$ of Cu per kW capacity.
 - Most these technologies also need rare metals like In, Ga, Se, Ne, etc.

Adapted from [3]



3.2.2 Environmental focus

[16] ELAW, 2010. 1st Edition: *Guide pour l'évaluation de EIE de projets miniers* [online].

[17] Hydraulic Fracturing 101. *Earthworks* [online].

[3] BIHOUIX, P., GUILLEBON, B., 2010. *Quel futur pour les métaux?*

A. Impacts on abiotic resources: water & air quality [16] & [17]

- Acid drainage:
 - Most ores contains sulfur → exposition to the surface through mining → formation of sulfuric acid → dissolves other metals and spills out in surrounding rivers or groundwater
Ex: Summitville (1992-1995) [3]



Wikipedia. *Drainage minier acide*

3.2.2 Environmental focus

[16] ELAW, 2010. 1st Edition: *Guide pour l'évaluation de EIE de projets miniers* [online].

[17] Hydraulic Fracturing 101. *Earthworks* [online].

[3] BIHOUIX, P., GUILLEBON, B., 2010. *Quel futur pour les métaux?*

A. Impacts on abiotic resources: water & air quality [16] & [17]

- Settling tanks
 - Containment of mining wastes → infiltration into groundwater or overflows in case of rain (one of the worst possible industrial accidents in terms of environmental impact)
Ex: Aznacollar 1998 in Spain



Wikipedia. Rupture du barrage de Brumadinho en 2019

[16] ELAW, 2010. 1st Edition: *Guide pour l'évaluation de EIE de projets miniers* [online].

[17] Hydraulic Fracturing 101. *Earthworks* [online].

[3] BIHOUIX, P., GUILLEBON, B., 2010. *Quel futur pour les métaux?*

A. Impacts on abiotic resources: water & air quality [16] & [17]

- Mines dewatering
 - Mining sometimes directly meet the groundwater table → pursuit of mining need pumping of water → reduction or elimination of water circulation in surrounding zones, varied degradations on soils and wildlife
Ex: Sadiola Gold mine pumped 5,6 Mm³ of water in a year (≈ consommation of 800 000 Malians) [3]
- Mobile or non-mobile sources of air pollutants
 - Fuel combustion & exhaust gases of machines or vehicles → CO₂, CO, organic compounds → climate change
 - Waste particles dispersed by wind
 - Precious metals are often melted onsite before sent to refineries → high levels of Hg, As, SO₂
- Uncontrolled mercury (Hg) rejections
 - [Hg] in ores can reach 10 mg/kg → 1 Mt of ores produced means 10t of Hg potentially emitted
 - Vaporization of Hg in gold melting is a major cause of Hg mission in atmosphere

Specifics to oil:

- *Hydraulic fracturing & Oil spills contaminations*
- *Details in [17]*

[16] ELAW, 2010. 1st Edition: *Guide pour l'évaluation de EIE de projets miniers* [online].

[17] Hydraulic Fracturing 101. *Earthworks* [online].

B. Biotic resources & beyond: wildlife & land

- Loss of habitat
 - Excavation or accumulation of waste → mobile species (birds and some mammals) are hunted out + sedentary species (little mammals, reptiles, invertebrates) are killed
 - Acid drainage or dewatering → severes impacts on surrounding aquatic life
 - These 2 points → perturbation of trophic chains (diminution of food for the higher-level predators)
 - Disparition of vegetation
- Fracture of habitat
 - Large portions of land occupied
→ perturbation of migrations or local isolation of species
- Specifics to oil (again):
 - Hydraulic fracturing & Oil spills contaminations
 - Details in ^[17]

[16] ELAW, 2010. 1st Edition: *Guide pour l'évaluation de EIE de projets miniers* [online].

[17] Hydraulic Fracturing 101. *Earthworks* [online].

B. Biotic resources & beyond: wildlife & land

- Perturbation of landscape
 - Visual changes → socio-cultural impacts
- Soil and mining waste erosion:
 - Sediments transported to surrounding water plants (storms or snowmelts) → water contamination
 - Fragile soils → higher probabilities of floods
- Noises & vibrations
 - Vehicles, machines & explosions → affect surrounding inhabitants and wildlife + stability of infrastructures
- Specifics to oil (again):
 - Hydraulic fracturing & Oil spills contaminations
 - Details in ^[17]

3.2.3 Socio-economical focus

[16] ELAW, 2010. 1st Edition: *Guide pour l'évaluation de EIE de projets miniers* [online].

[17] Hydraulic Fracturing 101. *Earthworks* [online].

[3] BIHOUIX, P., GUILLEBON, B., 2010. *Quel futur pour les métaux?*

A. Contrasted local realities

- Human migrations
 - Displacement & reinstallation of communities (expropriated or not) → resentment + power perturbations → local conflicts
 - New high economic activity → arrival of new populations → new pressures on land, water or waste management → tensions & potential conflicts with original inhabitants
Ex of Grasberg Mines in Indonesia: From < 1000 (1973) to 110 000 (1999) ; violent conflicts during 1970-1990
 - New needs of infrastructures → urbanization → wide-ranging effects
- Loss of drinkable water access
 - Due to uncontrolled exploitations & industrial pollutions
- Pressures on means of existence
 - Mining activities not correctly managed
→ economic cost on other sectors (agriculture & fishing in particular)

3.2.3 Socio-economical focus

[16] ELAW, 2010. 1st Edition: *Guide pour l'évaluation de EIE de projets miniers* [online].

[17] Hydraulic Fracturing 101. Earthworks [online].

[3] BIHOUIX, P., GUILLEBON, B., 2010. *Quel futur pour les métaux?*

A. Contrasted local realities

- Public health consequences
 - Potential sanitary risks are often neglected
→ example of improvised mining towns are been shown to threaten food security and availability
 - Indirect effects of exposition to mining activities are higher incidences of tuberculosis, asthma, chronic bronchitis, etc.
 - A review of metals direct toxicity impacts can be found in a dedicated chapter of [3]
- Cultural & Esthetics
 - Destruction of cultural resource by surface perturbation or excavation
 - Topographical or hydrological changes
 - Higher access to previously inacessible locations
→ theft or vandalism of cultural artifacts
 - Visual impacts due to deforestation & presence of infrastructures

3.2.3 Socio-economical focus

[25] HUISMAN, J., PAVEL, C., et al. 2020. *Critical Raw Materials in Technologies and Sectors - Foresight* [online].
[3] BIHOUIX, P., GUILLEBON, B., 2010. *Quel futur pour les métaux?*

B. Global frictions...

- Emerging geopolitical stakes for metals
 - As for oil, the main consumer countries are also the ones with the smallest reserves
 - Understanding of these problematics is more recent for metals and is parallel to the recent rise of metals prices in the 2000s
 - The EU Commission now regularly publish reports on the matter [25]
 - Strategical stocks of metals constituted during Cold War, dismantled after the 90s, are back since 15-20 years
- Capitalistic concentration of companies:
 - in 2008, 4173 companies in mining but 149 majors (3,6%) were controlling 83% of the market [3]
 - Power to initiate struggles with states over natural resources and their exploitation, in order to maximize private profits and mutualize losses or environmental externalities
 - Complex conflicts with explicit and implicit actors

3.2.3 Socio-economical focus

[3] BIHOUIX, P., GUILLEBON, B., 2010. *Quel futur pour les métaux?*

B. Global frictions...

Armed conflicts already existing

- Not as visible as oil conflicts yet
- DRC (Democratic Republic of the Congo) being the richer african country in metals, its history since mid-XXth is a paradigmatic example
- Crossings with colonization & neocolonization
 - 1961 Defense agreements between France, Niger, Dahomey & Ivory Coast guarantee limitation of exportations to other countries than France in case of needs
 - 2007 contract of China & RDC: heavy construction work (6 billions \$) in exchange of metal mining authorizations (10 Mt of Cu, 200 000 t of Co, 372 t of Au)
 - With explicit intention of asking land if the metal provisionning does not meet expectations
 - Direct implication in local economy,

No need to developp on the well known history of oil geopolitical conflicts since mid-XXth!

3.2.3 Socio-economical focus

[3] BIHOUIX, P., GUILLEBON, B., 2010. *Quel futur pour les métaux?*

[18] RITCHIE, Hannah and ROSER, Max, 2017. CO₂ and Greenhouse Gas Emissions. *Our World in Data* [online].

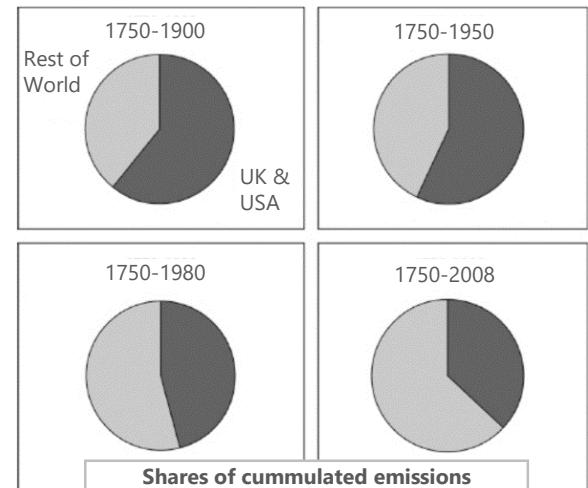
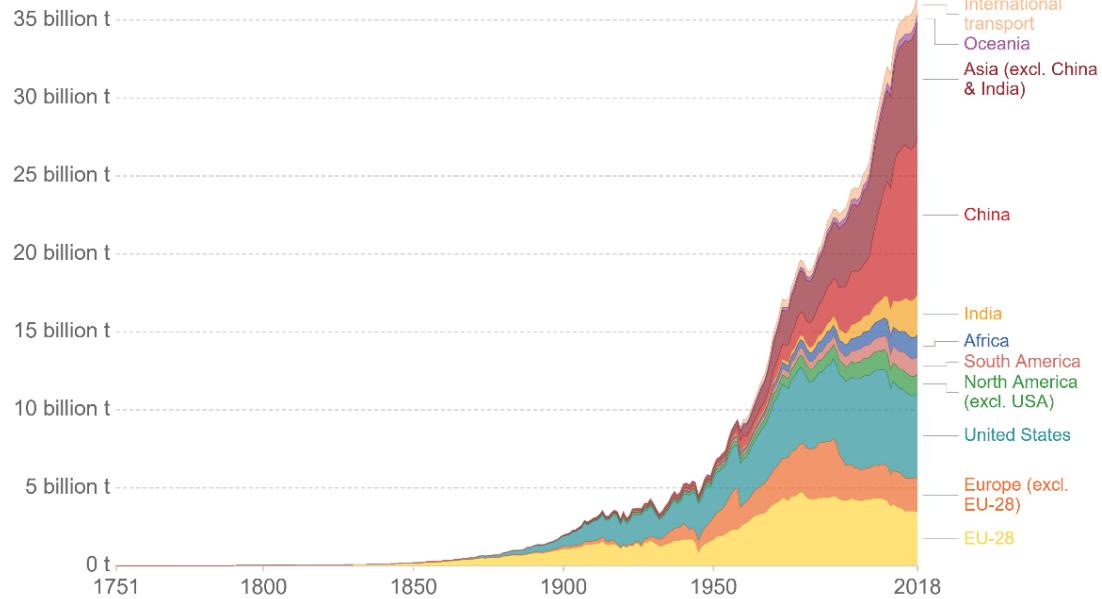
[19] BONNEUIL, C., FRESSOZ, J-B., 2016. *L'événement anthropocène: la Terre, l'histoire et nous.*

C. ... Rooted in historical inequalities

- Developed countries did develop themselves on the exploitation of countries now productors & consumers
 - Between 1815-1880, 5/6 of British investments were outside their empire, chiefly to develop mining (coal, in particular) and transport of ores by rail in dominated countries [19]

Annual total CO₂ emissions, by world region

This measures CO₂ emissions from fossil fuels and cement production only – land use change is not included.



Adapted from [19]

Source: Carbon Dioxide Information Analysis Center (CDIAC); Global Carbon Project (GCP)

Note: 'Statistical differences' included in the GCP dataset is not included here.

OurWorldInData.org/co2-and-other-greenhouse-gas-emissions • CC BY

Extracted from [18]

3.2.3 Socio-economical focus

[3] BIHOUIX, P., GUILLEBON, B., 2010. *Quel futur pour les métaux?*

[18] RITCHIE, Hannah and ROSER, Max, 2017. CO₂ and Greenhouse Gas Emissions. *Our World in Data* [online].

[19] BONNEUIL, C., FRESSOZ, J-B., 2016. *L'événement anthropocène: la Terre, l'histoire et nous.*

C. ... Rooted in historical inequalities

Adapted from [19]

- 20th century have mainly reorganized exploitation, but it continued on
 - USA based its economic rise on intensive use of its own resources during 1870-1940
 - Supported decolonization mainly to gain access to material resources of newly independant countries
 - Conversely, East block exploited its own environment above all
- Emerging trend →
 - Reappropriations of national resources & path of developpment
 - Setting of export restrictions [3]

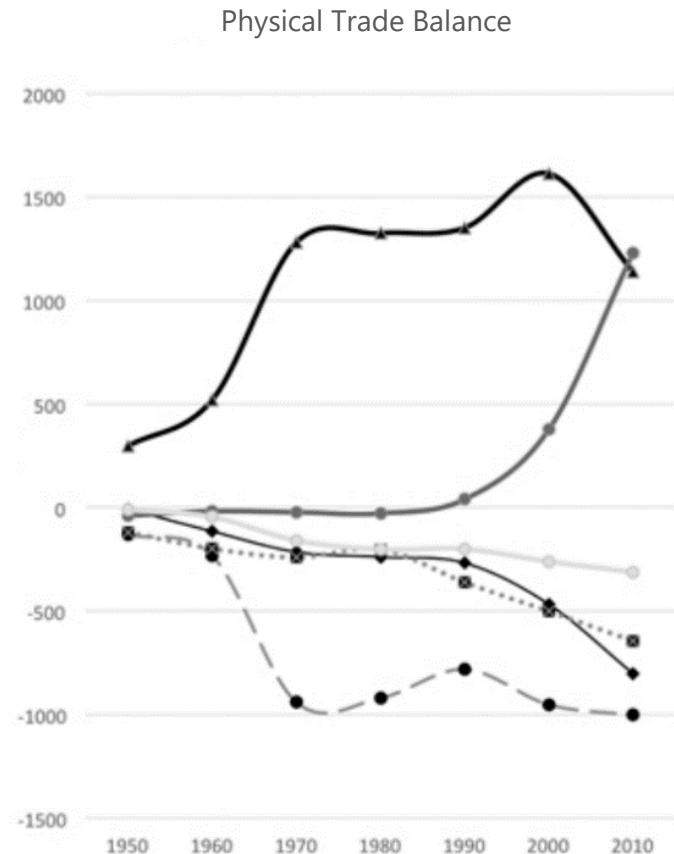


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3. Extraction of abiotic resources

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 - Production peak
 - Criticity
 - Preserving stocks
 - Necessity & Limits of Recycling
 - Substitution
 - Challenging needs
- A matter of Flow
 - The flow's stakes
 - Climate change
 - Economics interdependancies
 - Volatility of prices
 - Contracting flows
 - Limits of efficiency
 - Physics inevitability
 - Managing consequences, tackling causes

4.1.1 The stock's stakes

[6] BP, 2020. BP Statistical Review of World Energy. [online]

[20] EIA, U.S. Energy Information Administration, 2016. Carbon Dioxide Emissions Coefficients. [online].

[21] IPCC. 2018. Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. . P. 82.

A. Climate change – CO₂ eq stock

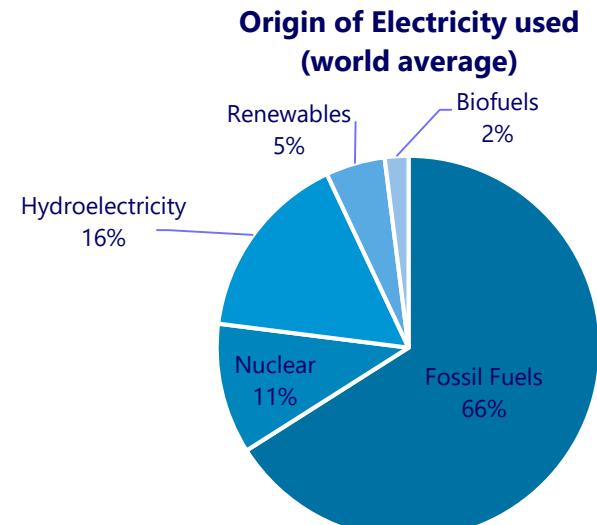
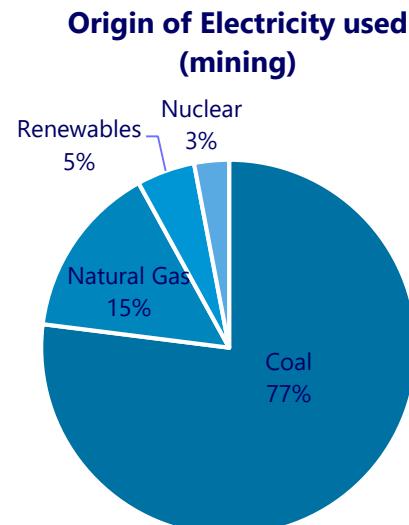
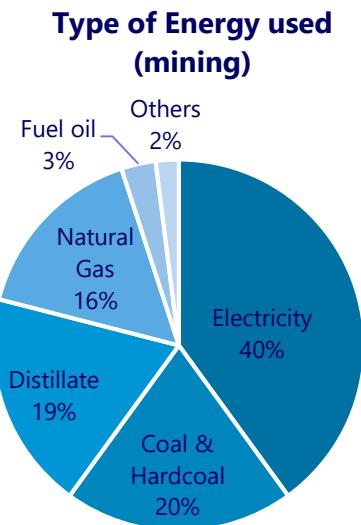
- Oil emissions of current reserves
 - Proven reserves: 1733,9 billions barrels [6]
→ 53750,9 billion gallons
 - Average on varied oil uses gives \simeq 10 kg CO₂ emitted per gallon [20]
→ 537,5 Gt CO₂
- World CO₂ eq budget, current estimations: [21]
 - 1170 Gt CO₂ eq to stay <2°C of global warming
 - 420 Gt CO₂ eq to stay <1,5°C of global warming
- Consumption of all current proven oil reserves is half of our total 2°C world budget and more than our total 1,5°C budget!
 - Without even considering natural gas, coal, or other emissions (CH₄, for example) contributing to radiative forcing...
 - This considered, without changes, the 2°C threshold should be crossed in about 26 years

4.1.1 The stock's stakes

[3] BIHOUIX, P., GUILLEBON, B., 2010. *Quel futur pour les métaux?*
 [10] Data & Statistics,. IEA [online]. Available from: <https://www.iea.org/data-and-statistics>

A. Climate change – CO₂ eq stock

- And mining is very dependant of highly carbonated, non renewable energy vectors



Adapted from [3]. The values for World averages of Electricity origin were replaced by updated data from [10]

4.1.1 The stocks's stakes

[6] BP, 2020. BP Statistical Review of World Energy. [online].

[15] JANCOVICI, J-M, 2019. Les Energies fossiles. Ecole des Mines [online].

[22] World Energy Outlook 2018. IEA – International Energy Agency.

B. Production peak

- Hypothesis: we don't mind CO₂ eq emissions
 - Either we consider it's not a problem
 - Or we think innovation or start-ups will solve that

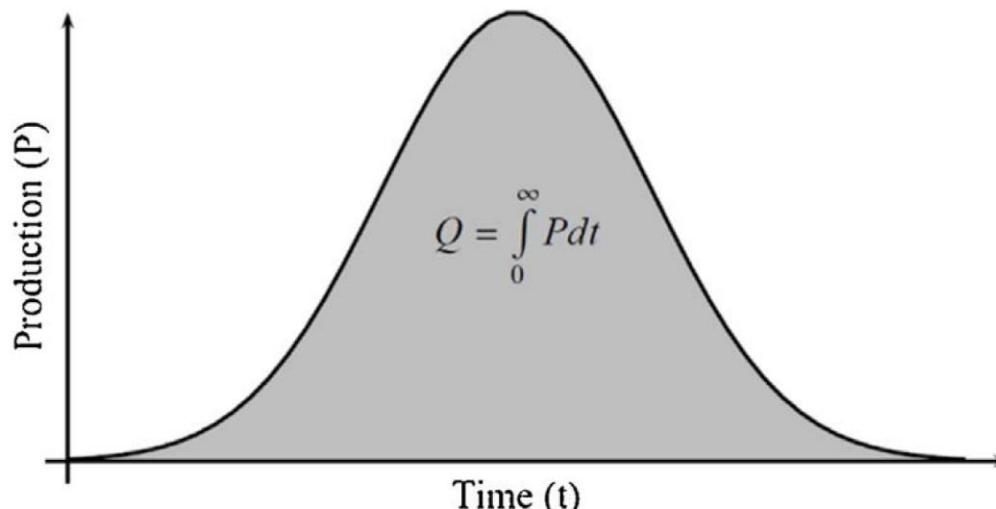
➔ Exhaustion of Reserves through Production will still occur!

- R/P ratio: most simplified model
 - Considering current reserves ^[6]
 - And 2019 rate of consumption^[6] taken as constant for the years to come (quite unrealistic hypothesis of no flow reduction)
- ➔ No oil remaining in ≈ 50 years

[23] CALVO, G. et al., 2017. Assessing maximum production peak and resource availability of non-fuel mineral resources.
 [15] JANCOVICI, J-M, 2019. Les Energies fossiles. Ecole des Mines [online].
 [22] World Energy Outlook 2018. IEA – International Energy Agency.

B. Production peak

- A slightly better estimate: the Hubbert peak model (1956)
 - We know there is no production at $t = 0$ and $t = t_{\text{final}}$
 - The area below the production curve must be equal to the reserve
 - Regarding conventional oil, several countries seems to have peaked already. A review can be found here ^[15]
 - It is commonly believed that world production peak of conventional oil already happened, in 2008 ^[22]



Extracted from [23]

4.1.1 The stocks's stakes

[23] CALVO, G. et al., 2017. Assessing maximum production peak and resource availability of non-fuel mineral resources.

B. Production peak

Extracted from [23]

- Reliability is influenced by several parameters
 - Uncertainty regarding reserves information
 - Particular environmental issues: health, water use, ore grade
 - Sociopolitical issues: new objects, changes of regulation, or armed conflicts
 - Interdependencies of byproducts
 - Substitution & recycling

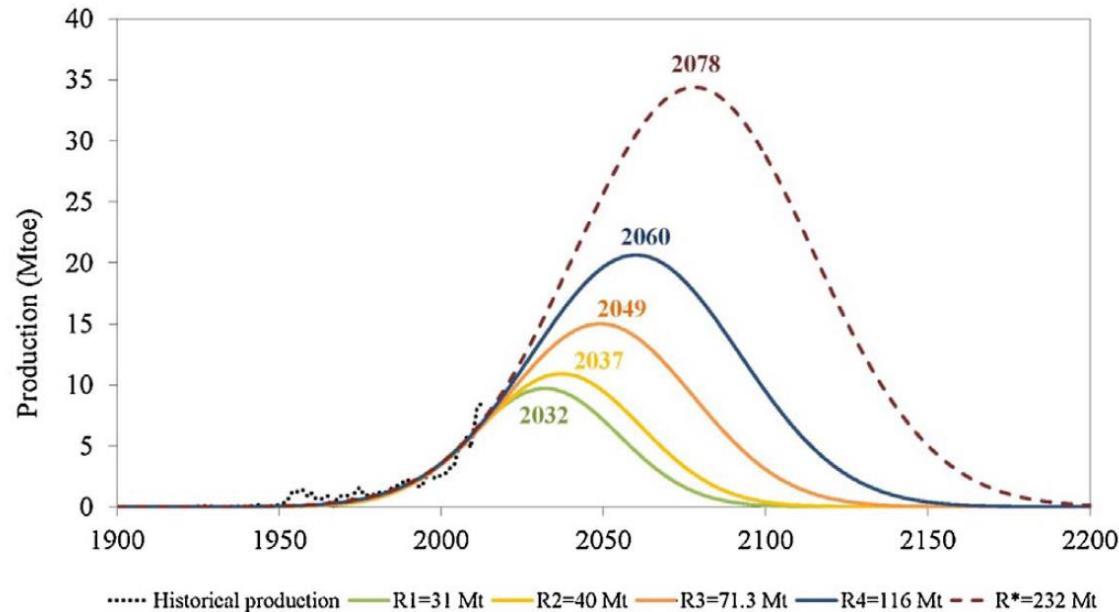


Fig. 4. The Hubbert peak applied to lithium with different resources estimations. The curve corresponding to R^* values was calculated assuming that the most optimistic estimations ($R4$) were doubled.

- That said, influence of reserves' variation is limited when rapported to the current trends in production and growth of production
 ➔ Li case study: estimated reserves x 8 only delayed the peak by 46 years

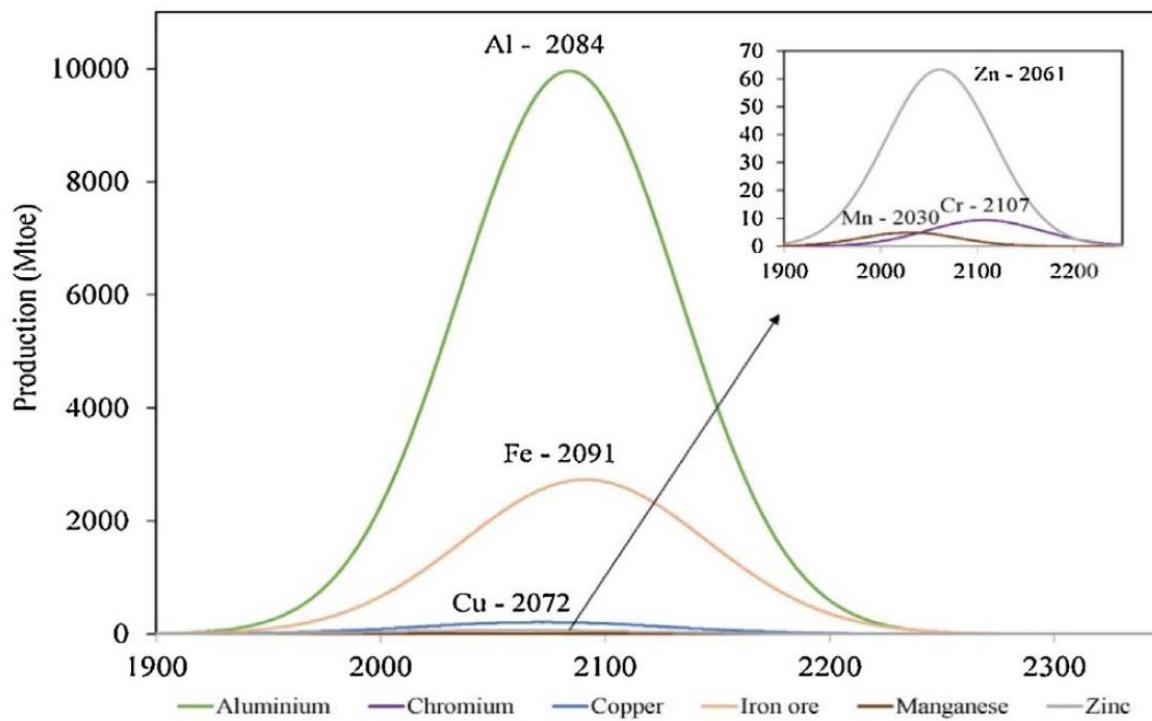
4.1.1 The stocks's stakes

[3] BIHOUIX, P., GUILLEBON, B. 2010. *Quel futur pour les métaux?*

[23] CALVO, G. et al., 2017. Assessing maximum production peak and resource availability of non-fuel mineral resources.

B. Production peak

- This recent try of systematic assessment is quite interesting to read [23] and accessible!
 - The time scaling is quite short, even for base metals



Extracted from [11]

Fig. 5. The Hubbert peak applied to the “big six” resources.

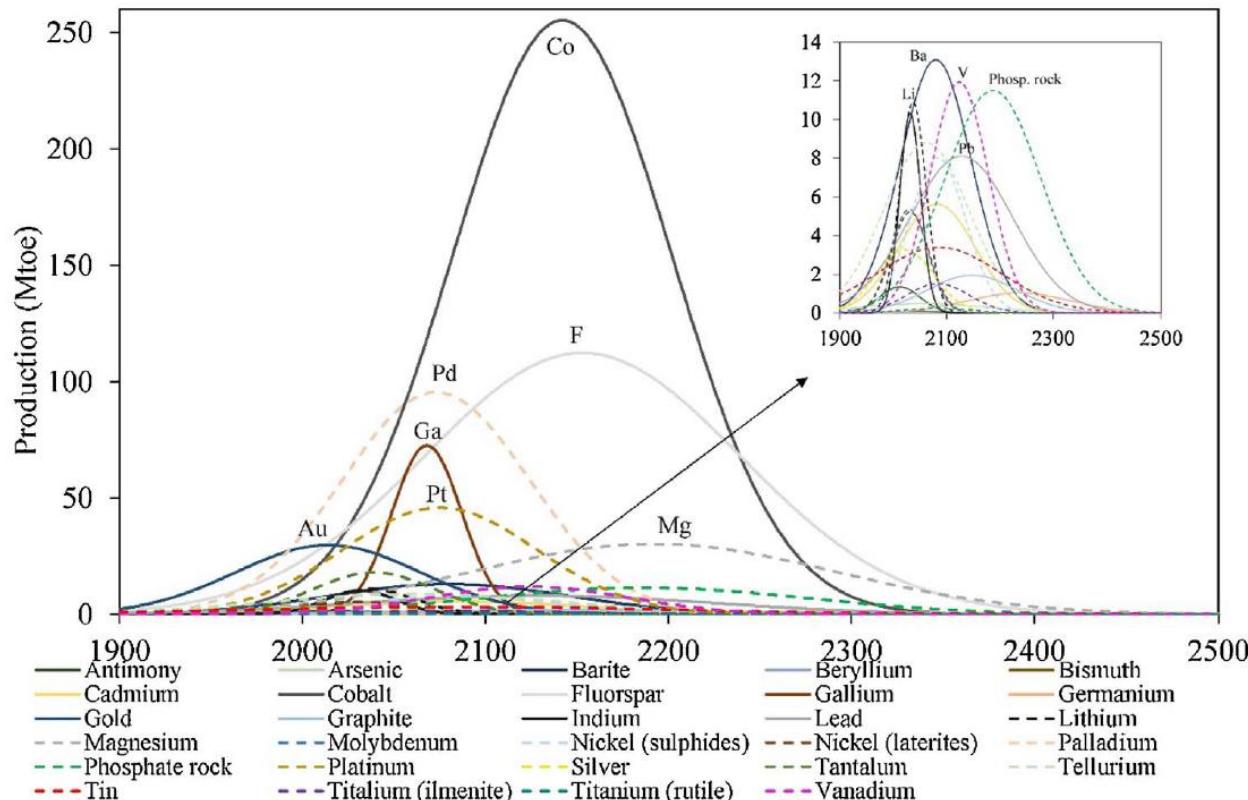
4.1.1 The stocks's stakes

[3] BIHOUIX, P., GUILLEBON, B. 2010. *Quel futur pour les métaux?*

[23] CALVO, G. et al., 2017. Assessing maximum production peak and resource availability of non-fuel mineral resources.

B. Production peak

- Expected peak in the next 50 years: 12 metals over 47 studied: As, Bi, In, Li, Mn, Mo, Ni, Ag, Ta, Te, Zn
- 30 metals over 47 have their expected peak in the next 100 years
- Gold & Antimony peaked around 2015 (agreement for Gold with [3])



Extracted from [23]

[3] BIHOUIX, P., GUILLEBON, B. 2010. *Quel futur pour les métaux?*

B. Production peak

- Taking into account the interdependencies of metals
 - Bold indicates it is the main production process of said **metal**

Major metals exploited	Main non-dependent byproducts	Main dependent byproducts
Fe	Zb, Pb	
Al		Ga , V
Cr	Pd, Pt	
Cu	Ag, Au, Mo, Pd, Pt, Zn	As , Bi, Co, Ir, Os, Re , Rh, Ru, Se , Te
Ti		Zr, Hf
Pb/Zn	Ag	As, Bi , Cd , Co, Ga, Ge , In , Sb , Tl
Ni	Ag, Au, Cu, Pd, Pt	Co , Ir, Os, Rh, Ru, Se, Te
Sn	Ag	In, Nb

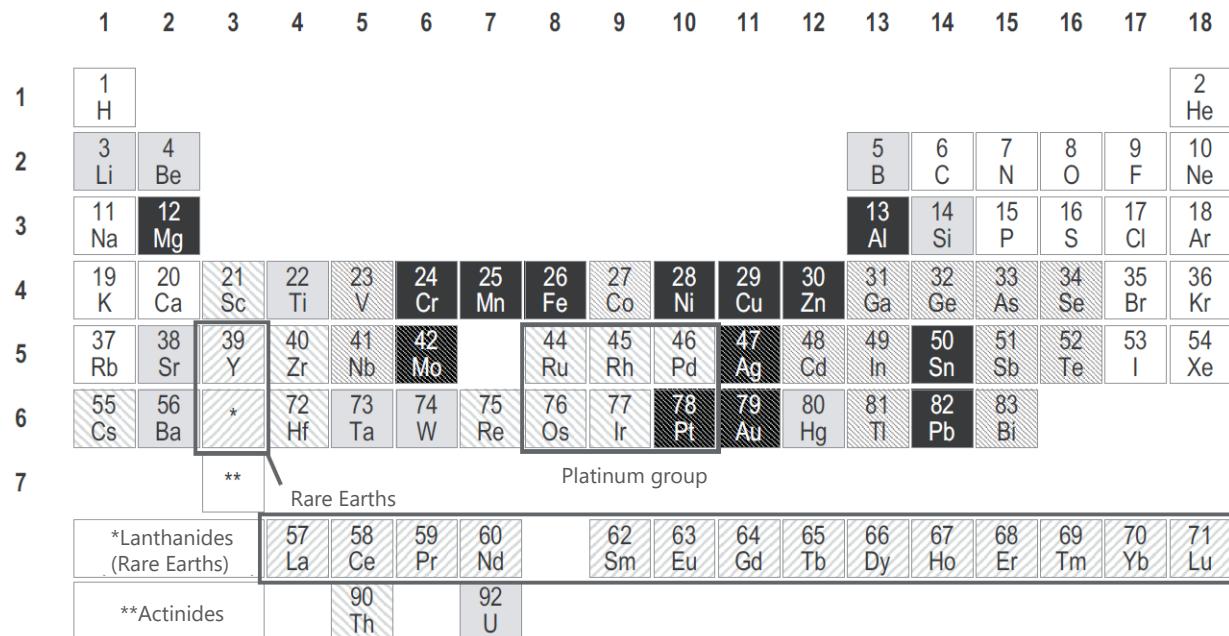
Extracted from [3]

4.1.1 The stocks's stakes

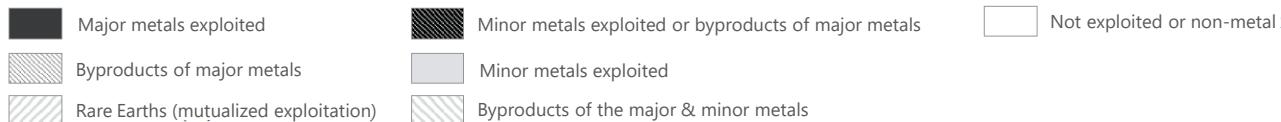
[3] BIHOUIX, P., GUILLEBON, B. 2010. *Quel futur pour les métaux?*

B. Production peak

- Nearly a half of metals today exploited are interlinked



Adapted from [3]



Sources : E. Verhoef, G. Dijkema and M.A. Reuter (2004), USGS, BRGM

[26] GRAEDEL, T. et al., 2015. Criticality of metals and metalloids. DOI [10.1073/pnas.1500415112](https://doi.org/10.1073/pnas.1500415112).

C. Criticality

- Notion related to the attempt to assess the relative risks concerning the availability of resources
 - Relatively recent preoccupation
 - As availability is an already complex notion, its risk analysis is also complex
 - Geological abundance & concentrations
 - Potential for substitution
 - State of the art of mining technology
 - Amount of regulatory oversight
 - Geopolitical initiatives
 - Governmental instability
 - Economic policy
 - As reserves are part of the assessment, it is also dynamic
- Several methodologies
 - At different scales of organizations
 - For different scales of time
 - With then varied results difficult to compare between each other

4.1.1 The stocks's stakes

[26] GRAEDEL, T. et al., 2015. Criticality of metals and metalloids. DOI [10.1073/pnas.1500415112](https://doi.org/10.1073/pnas.1500415112).

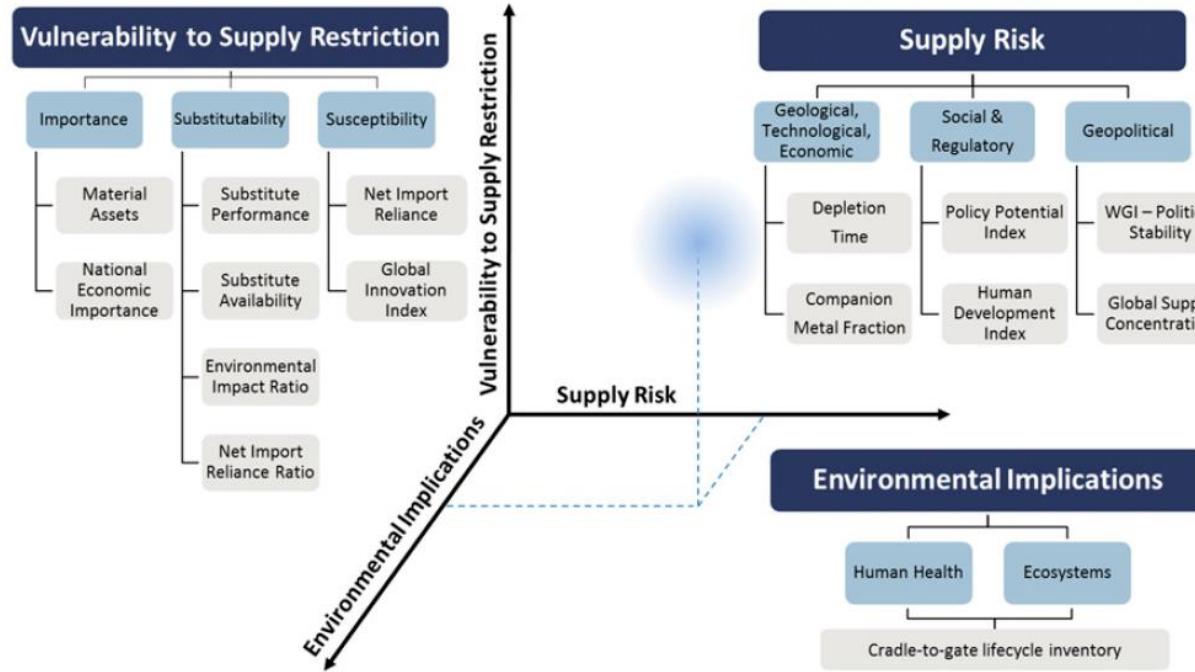


Fig. 2. The methodology of criticality at the national level. The axes in criticality space are supply risk, environmental implications, and vulnerability to supply restriction. Several indicators on each axis are aggregated to arrive at a criticality assessment, as indicated in the diagram. WGI, World Governance Institute. Data sources for the assessment are metal in-use stock determinations, metal material flow analysis, metal substitution potential, country-level information, and environmental life cycle assessment results (comparison on the basis of 1 kg of each element at the factory gate). The global methodology is similar, but omits social and regulatory and geopolitical components on the supply risk axis and the susceptibility component and net import reliance ratio and national economic importance from the vulnerability to supply restriction axis.

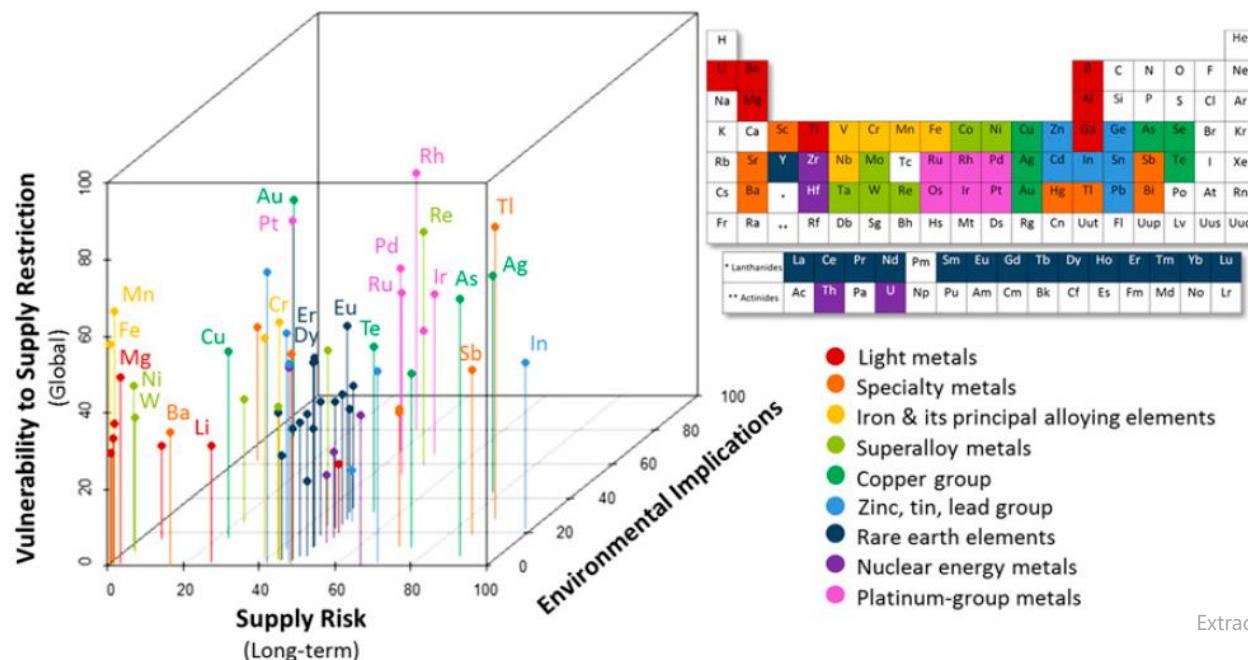
Extracted from [23]

C. Criticality

[26] GRAEDEL, T. et al., 2015. Criticality of metals and metalloids. DOI [10.1073/pnas.1500415112](https://doi.org/10.1073/pnas.1500415112).

C. Criticality

- Criticality space: a first step is to get an overall idea
 - A number of metals are concentrated on the middle: moderately high on at least 2 axis (rare earths, Cr, Te, etc.)
 - Some are regrouped toward lower left: relatively low criticality (Fe, Mg, Ni, Mn, etc.)
 - The right side: high supply risk (In, Ag, Tl, As, Sb)
 - The particular case of Au & Pt



Extracted from [23]

4.1.1 The stocks's stakes

[26] GRAEDEL, T. et al., 2015. Criticality of metals and metalloids. DOI [10.1073/pnas.1500415112](https://doi.org/10.1073/pnas.1500415112).

C. Criticality

- This methodology allow the comparison of varid elements for (here at global level):
 - A. Supply risk
 - B. Environmental implications
 - C. Vulnerability to supply restriction
- Keep in mind it is a relative assessment
 - Per kg comparison
- Results may be underestimated
 - Database of 2008 (they were in the process of updating up to 2012 at publication in 2015)
 - As data revisions are not frequent & major technology changes occurs slowly, they recommand reassessment on a 5 years basis

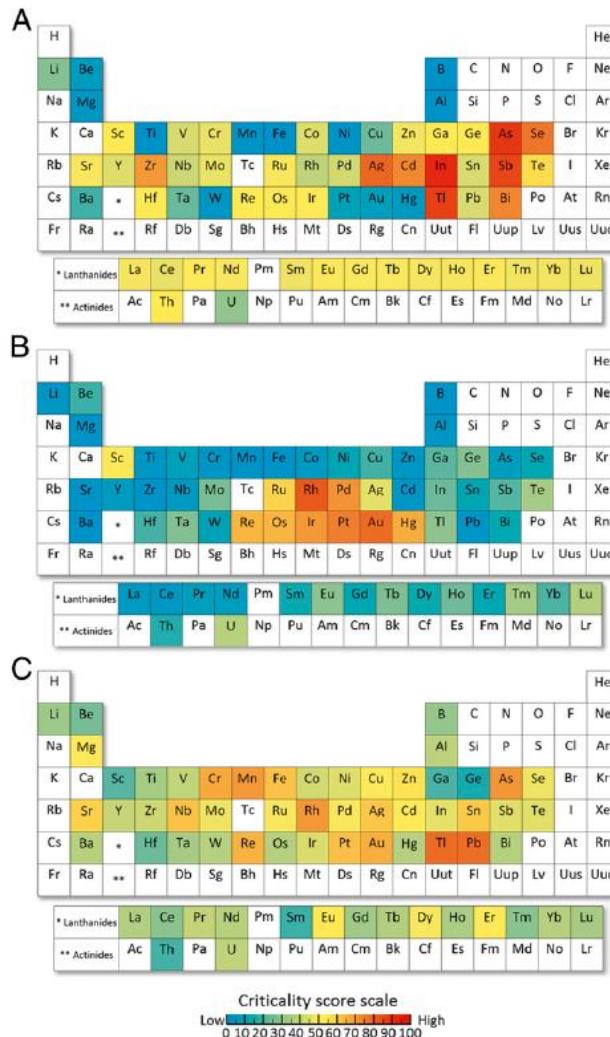


Fig. 6. Periodic tables of criticality for 62 metals, 2008 epoch, global level for (A) supply risk, (B) environmental implications, and (C) vulnerability to supply restriction.

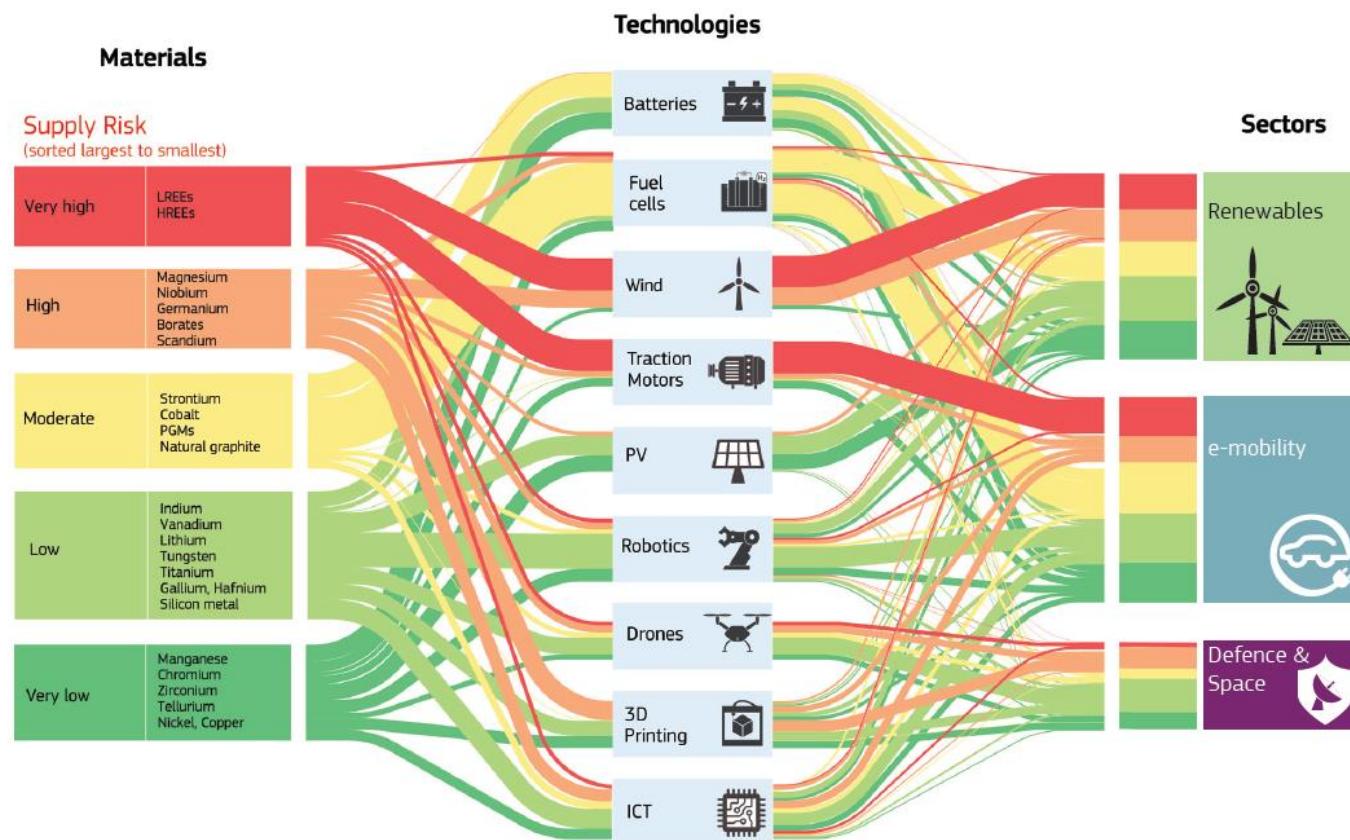
Extracted from [23]

4.1.1 The stocks's stakes

[25] HUISMAN, J., PAVEL, C., et al. 2020. *Critical Raw Materials in Technologies and Sectors - Foresight* [online].

C. Criticality

Figure 2. Semi-quantitative representation of flows of raw materials and their current supply risks to the nine selected technologies and three sectors (based on 25 selected raw materials, see Annex 1 – Methodological notes)



[3] BIHOUIX, P., GUILLEBON, B. 2010. *Quel futur pour les métaux?*

A. Necessity and Limits of Recycling

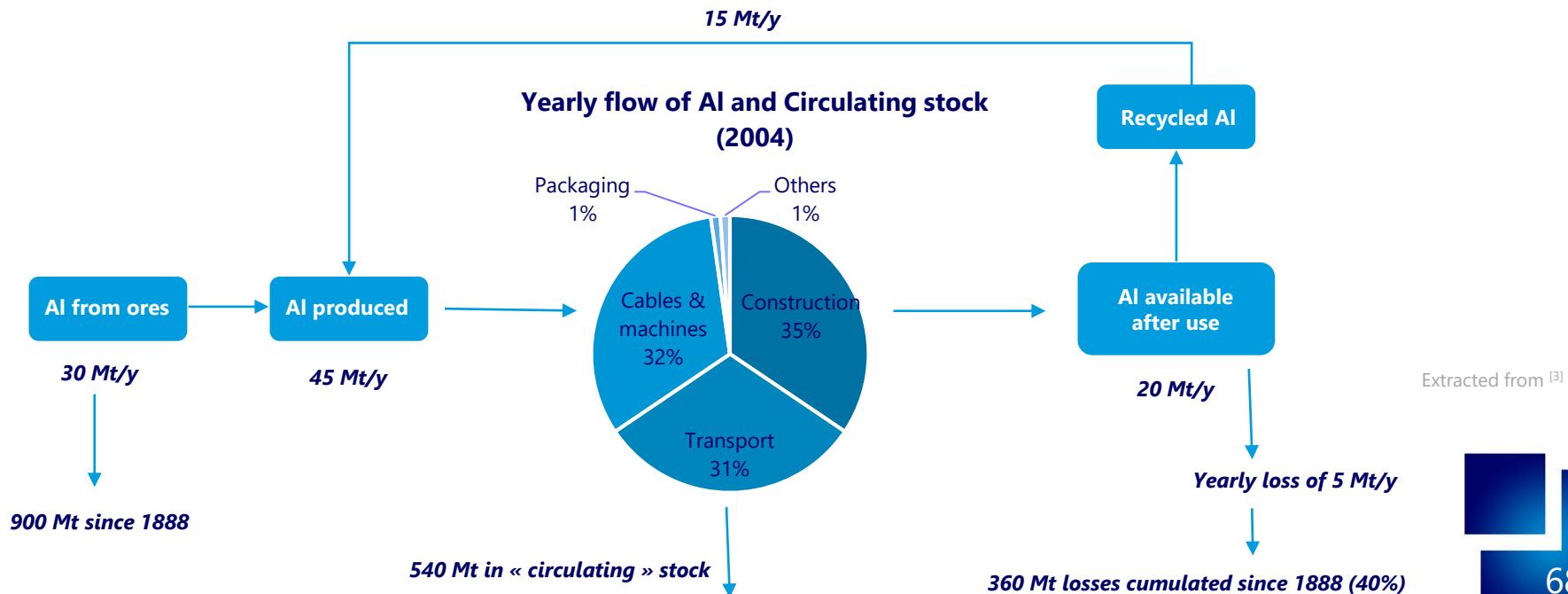
Extracted from [11]

- Major difference between oil (energy resources) and metals (mineral ressources):
 - Oil, Coal & Natural Gas → mostly burned → The flow is not retrievable
 - Metals → mostly materially conserved → The flow is retrievable + there is a stock in circulation!
- Each year, stocks of metals:
 - Increases of the produced quantity
 - Decreases of the lost quantity
 - Dispersive uses (metals used as dyes or fertilizers)
 - No recycling (incineration or landfill disposal)
- What are the trends?
 - Precious metals (Au) or with moderately high value (Cu): few losses
 - Less noble metals (Al, Zn) have more important loss rates
 - No data for a lot of metals used in specific applications (electronics...)

[3] BIHOUIX, P., GUILLEBON, B. 2010. *Quel futur pour les métaux?*

A. Necessity and Limits of Recycling

- Current recycling
 - Precious metals (Au) or with moderately high value (Cu): few losses
 - Less noble metals (Al, Zn) have more important loss rates
 - No data for a lot of metals used in specific applications (electronics...)



[3] BIHOUIX, P., GUILLEBON, B. 2010. *Quel futur pour les métaux?*

A. Necessity and Limits of Recycling

- Metals are one of the most interesting category of materials for recycling
 - Theoretically recyclable an infinite amount of time without diminishing their properties
 - Have high yield for stock preservation
40% recycling rate → 80% recycling rate ⇔ Reserves x 3
50% recycling rate → 99,9% recycling rate ⇔ Reserves x 500
- Rich countries show that recycling rate can reach high levels for base metals
 - France (2010): 85% for Fe ; 80% for Al & Cu ; 70% Pb ; 50% Zn [3]
- But it cannot do everything
 - No industrial process have a 100% efficiency → same for recycling (remelt Al generate a dispersed loss of 1-2%)
 - A lot of our uses are not compatible with recycling

[3] BIHOUIX, P., GUILLEBON, B. 2010. *Quel futur pour les métaux?*

A. Necessity and Limits of Recycling

- The trend of higher complexity
 - > 30 metals in a computer
 - > 10 alloys of Steel in a car
 - Prevent us from retrieving the resources: not easy and sometimes technically impossible to detect or separate metals of an allow
- This phenomena exist for a lot of our materials
 - Glass: mix of transparent & colored glasses → no more use in most of construction or cars, only bottles
 - Plastic: often reused in less demanding uses (technically or aesthetically)

➔ Important to rethink life-cycles of products, raw materials, and mostly uses

- ➔ Integrate less performant or pretty materials & more recycled materials
- ➔ Organize recovery channels to boost recycling rate
- ➔ But also question the trend of high tech solutions instead of low tech ones
- ➔ That is, question the needs

[3] BIHOUIX, P., GUILLEBON, B. 2010. *Quel futur pour les métaux?*

A. Necessity and Limits of Recycling

- The trend of direct dispersive uses
 - Dyes (98% of Ti used as TiO_2 for white dyes)
 - Fertilizers (P, Zn, etc.)
 - Additives (Cr in Glass)
 - Pesticides ($CuSO_4$ in some organic farming plants)
- And « indirectly » dispersive uses (very difficult to recover)
 - 33% of Sn is used in welding
 - 50% of Zn is used in galvanizing
- Some metals like Co or Mb are nearly exclusively used in dispersive uses or alloys
- The socioeconomic limits
 - Economical incentives to constructors are not present or sufficient
 - Lack of regulation and means to enforce it
 - Complexity of products and recovery channels does not help

[3] BIHOUIX, P., GUILLEBON, B. 2010. *Quel futur pour les métaux?*

B. Substitution

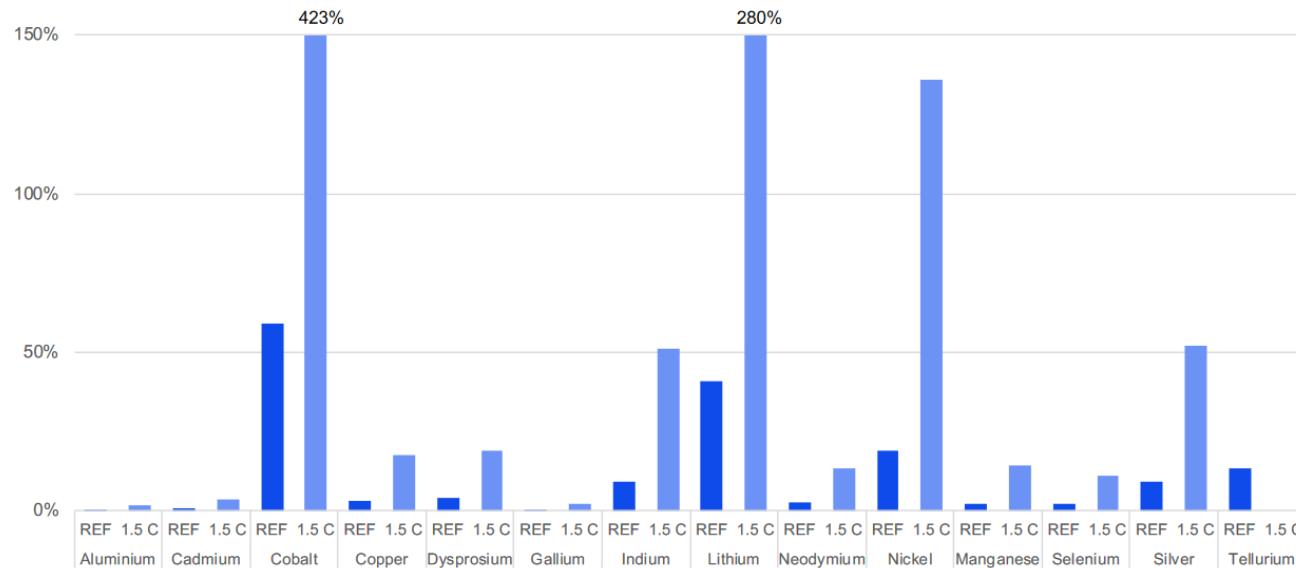
- Limit the use in rare or noble metals in favor of abundant metals
 - Critical lens on « innovation »
 - Aim to maximize a low tech approach as much as possible at the level of product and technology
 - ➔ For inorganic solar pannels, Si should be prefered to GaAs, CIGS, and others, even if the conversion efficiency is less important
- For critical cases, possibilities needs to be carefully explored:
 - Cr nearly indispensable for anti-corrosion
 - ➔ Ti can replace Cr in certain cases but its energy footprint is 4-5 times higher
 - Cu nearly indispensable for electrical applications
 - ➔ Al can replace Cu in certain cases but its energy footprint is 2-3 times higher

[27] Responsible minerals sourcing for renewable energy, 2019. University of Technology Sydney [online].

B. Substitution

- Substitute oil by electrification? [27]
 - Li-ion batteries represented 37% of Li consumption in 2016 (and 40% of Co)
 - Batteries for electric vehicles were only 10% of Li-ion consumption in 2018
 - Most elements at disposal indicates that strong choices of resources's uses will have to be made in the years to come:

Figure 6: Cumulative total demand from renewable energy and storage by 2050 compared to reserves in the 1.5 degree and Reference scenarios



Extracted from [27]

- [28] ABDALLA, A. *et al.*, 2018. Hydrogen production, storage, transportation and key challenges with applications: A review. DOI [10.1016/j.enconman.2018.03.088](https://doi.org/10.1016/j.enconman.2018.03.088)
- [29] SCHMIDT, O., *et al.*, 2017. Future cost and performance of water electrolysis: An expert elicitation study. DOI [10.1016/j.jhydene.2017.10.045](https://doi.org/10.1016/j.jhydene.2017.10.045).

B. Substitution

- Substitute oil by « hydrogen »?
 - Currently > 90% of H₂ is produced by steam reforming (10 kg CO₂ per kg of H₂ produced) ^[28]
 - Water electrolysis / fuel cells have problems of their own ^[29]
 - Alkaline electrolysis is not adapted for electric cars
 - New technologies currently depends either on Pt and are not industrially mature (PEM) or rare earths and are at the state of demonstrators (SO)

➔ We are back to the vicious circle of energy & material footprint

[30] BIHOUIX, Philippe, 2014. *L'Age des low techs: vers une civilisation techniquement soutenable*. Seuil.

C. Challenging needs

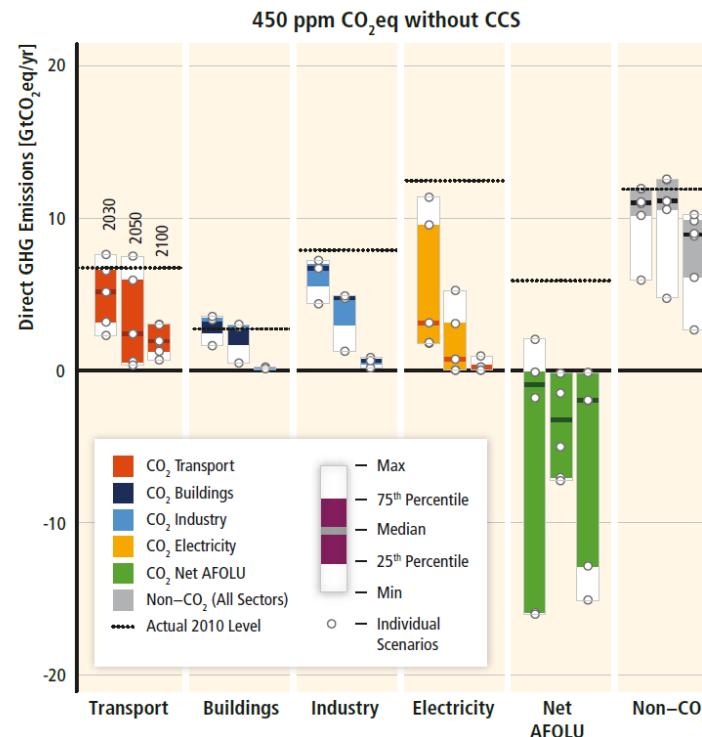
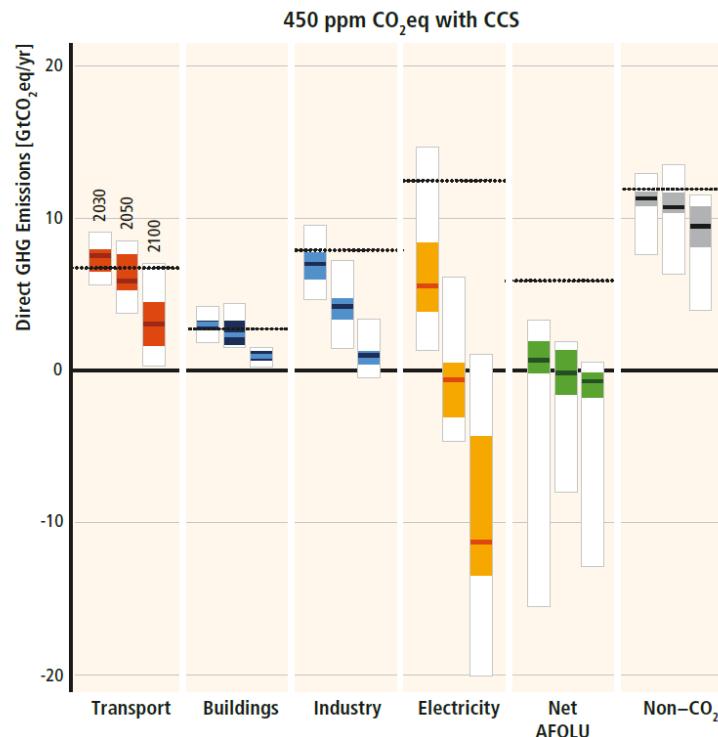
- The often most efficient strategy to preserve abiotic resources stock
 - House thermally isolated + put on a sweater >>> room heating technical solution
 - Most transport on bicycle (short distance) + train (long distance) with minimal use of a car (occasional rental) >>> electric cars replacing current diesel and petrol cars
 - Dismountable and repairable electronics >>> computer assembly with glue
- It is the first of the 7 principles of low-techs [30]
 1. Challenging needs
 2. Design and produce truly sustainable
 3. Orienting knowledge to resources' savings
 4. Striking a technical balance between performance & *conviviality*
 5. Relocalize without losing the right scale effects
 6. De-machinizing services
 7. Knowing to remain modest
- Indeed this kind of transition imply numerous socioeconomic consequences
 - As any kind of transition, it is also a matter of flows and their evolution

4.2.1 The flows's stakes

[31] IPCC. 2014: mitigation of climate change: Working Group III contribution to the 5th Assessment Report of the IPCC.

A. Climate change

- Trajectories mitigating climate change all require a global limitation of material & energy flows
 - Even with the hypothesis of a high development of the use of carbon capture and storage (CCS) technologies



Extracted from [31]

4.2.1 The flows's stakes

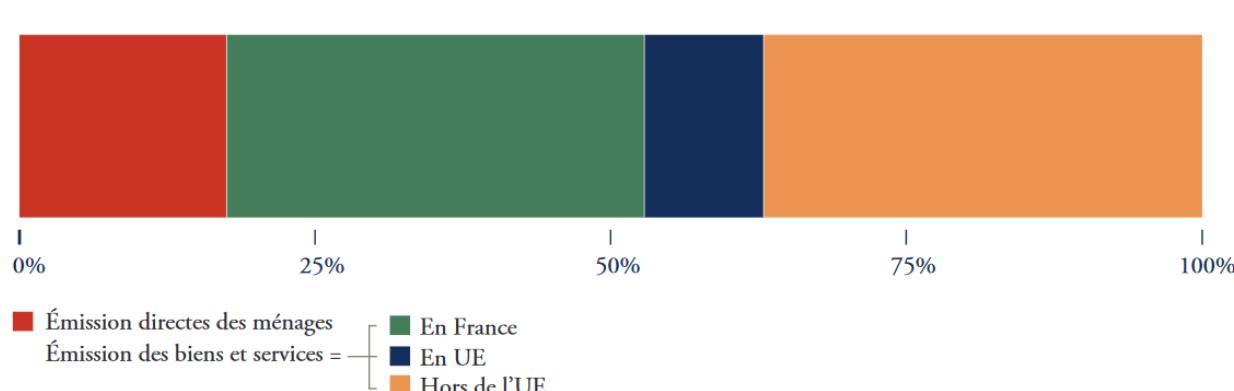
[32] HCC, 2020. Maîtriser l'empreinte carbone de la France. Haut Conseil pour le Climat [online].

A. Climate change

- The French carbon footprint
 - A large part of our carbon footprint comes from importations

Extracted from [32]

Figure 8 – Localisation des émissions
qui composent l'empreinte carbone de la France en 2011



Source : Traitements HCC 2020 d'après Malliet (2020)

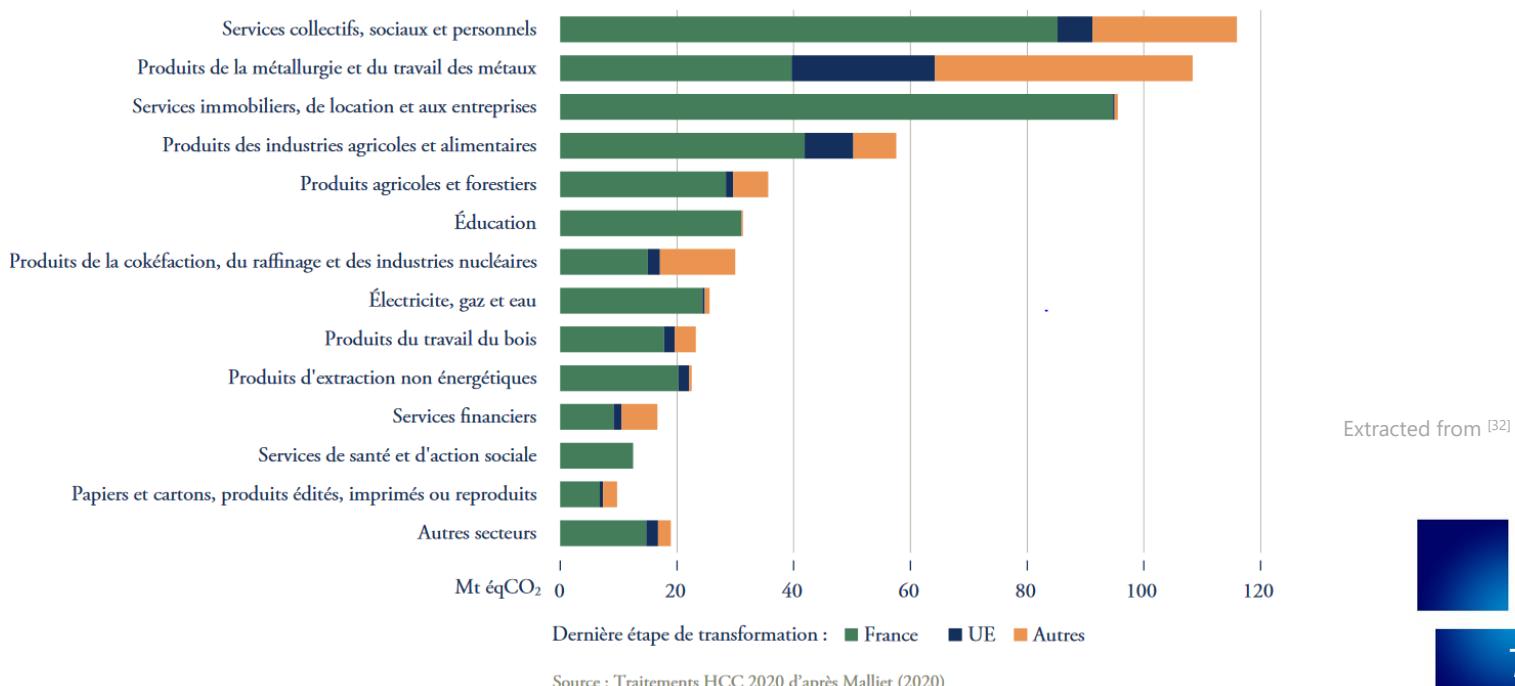
4.2.1 The flows's stakes

[32] HCC, 2020. Maîtriser l'empreinte carbone de la France. Haut Conseil pour le Climat [online].

A. Climate change

- The French situation
 - Abiotic resources are a large part of it, metals in particular!

Figure 12 – Répartition par bien ou service et par lieu de leur dernière transformation
des émissions de GES de la chaîne amont de l'empreinte carbone en 2011



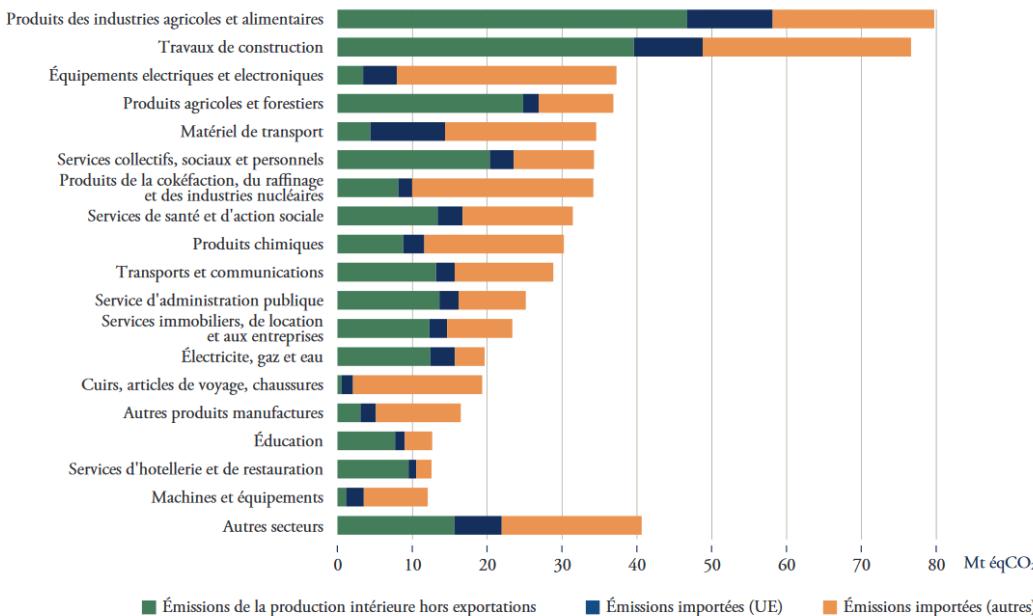
4.2.1 The flows's stakes

[33] HCC, 2020. Rapport annuel - Redresser le cap, relancer la transition. *Haut Conseil pour le Climat* [online]. 2020.

A. Climate change

- The French situation
 - Mineral resources: metals & cement
 - Energy resources & chemical products: oil

Figure 10 – Secteur et localisation des émissions qui composent l'empreinte carbone,
hors émissions directes des ménages, en 2011



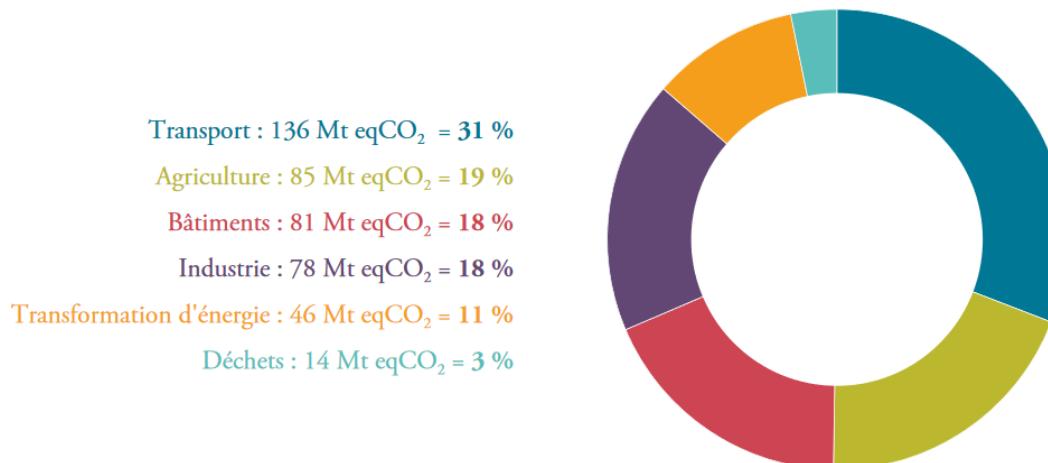
Extracted from [33]

[33] HCC, 2020. Rapport annuel - Redresser le cap, relancer la transition. *Haut Conseil pour le Climat* [online]. 2020.

A. Climate change

- The French situation
 - In terms of weight of abiotic resources in domestic emissions: oil is dominant, followed by metals & cement

Figure 1 – Émissions nationales de **gaz à effet de serre en 2019**



Extracted from [33]

Source : Citepa, avril 2020 – Format SECTEN

4.2.1 The flows's stakes

[31] IPCC. 2014: mitigation of climate change: Working Group III contribution to the 5th Assessment Report of the IPCC.

A. Climate change

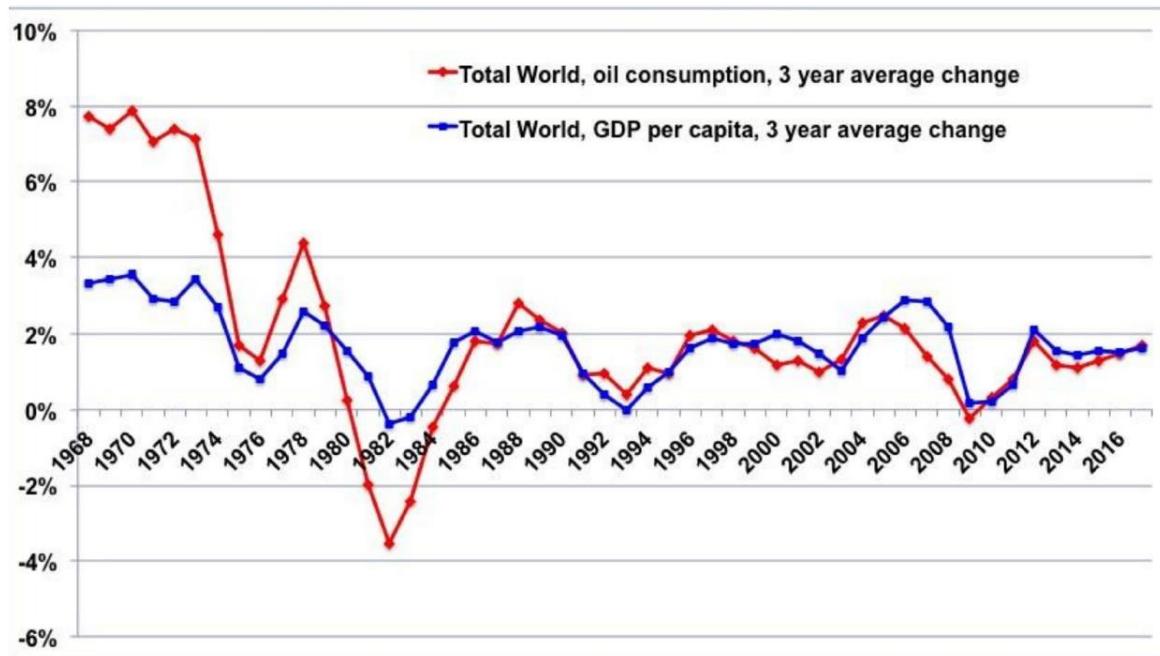
- High mitigation potential in transport ⇔ Combination of varied measures [31]
 - Low-carbon fuels → higher flows of metals & lower flow of oil
 - Lowering vehicles energy intensities → lower flows of oil & metals
 - Encouraging modal shift to lower-carbon passenger & freight systems
→ lower flows of oil + short-to-medium term higher flows of metals for infrastructure investments
 - Avoid journeys where possible → lower flows of oils
- This kind of configuration apply generally
 - Specific augmentations in flows of metal are required to lower oil flows
 - Competition between uses requiring metals → priorities will need to be established

4.2.1 The flows's stakes

- [15] JANCOVICI, Jean-Marc, 2019. Les Energies fossiles. *Ecole des Mines* [online].
- [34] HABERL, H., et al, 2020. A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights. DOI [10.1088/1748-9326/ab842a](https://doi.org/10.1088/1748-9326/ab842a).
- [33] HCC, 2020. Rapport annuel - Redresser le cap, relancer la transition. *Haut Conseil pour le Climat* [online]. 2020.

B. Economics interdependancies

- At world scale, there is a historical link between primary energy & material consumption, and economic production (as measured by GDP) [15] & [34]
 - There is no consensus on the exact nature of the relationship nowadays [33]
 - But we know that energy & material availability enables GDP growth
 - And GDP growth, by anticipation of economic growth causes energy & material use



Extracted from [15]

4.2.1 The flows's stakes

- [34] HABERL, H., et al, 2020. A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights. DOI [10.1088/1748-9326/ab842a](https://doi.org/10.1088/1748-9326/ab842a).
- [33] HCC, 2020. Rapport annuel - Redresser le cap, relancer la transition. *Haut Conseil pour le Climat* [online]. 2020.

B. Economics interdependancies

Extracted from [11]

- A lot of ambitious climate target rely on the concept of « decoupling » [34]
 - Promotion of economic growth while reducing material & energy footprint (EMF)
 - When theorized as absolute → EMF reduction & GDP growth
 - When theorized as relative → EMF slow growth & GDP high growth
- Recent systematic review clarifies that:
 - Relative decoupling is frequent for material use, GHG emissions, but not exergy
 - Relative decoupling of GDP and primary energy use can be caused by energy efficiency (higher ratio of exergy / primary energy use)
 - Absolute decoupling situations are very rare and are related to small short-term reductions of emissions
 - No evidence that absolute decoupling can be generalized

4.2.1 The flows's stakes

- [34] HABERL, H., et al, 2020. A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights. DOI [10.1088/1748-9326/ab842a](https://doi.org/10.1088/1748-9326/ab842a).
- [33] HCC, 2020. Rapport annuel - Redresser le cap, relancer la transition. *Haut Conseil pour le Climat* [online]. 2020.

B. Economics interdependancies

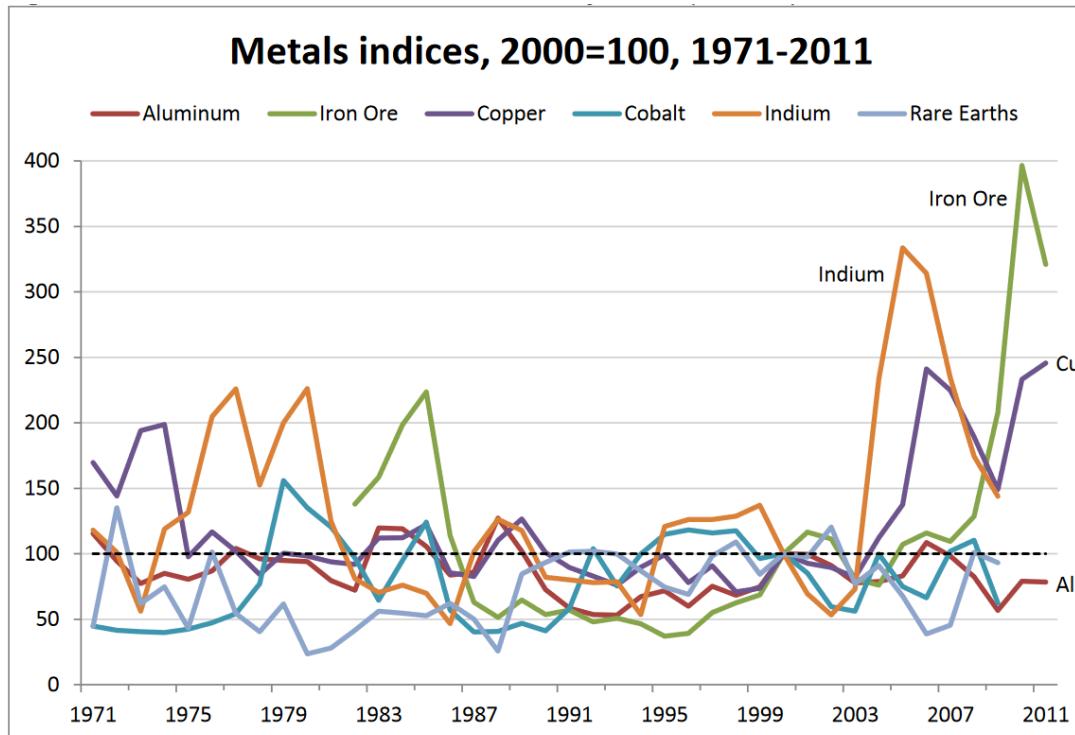
Extracted from ^[11]

- Degrowth/Sufficiency currently seems indispensable to meet climate target and sustainable use of abiotic resources:
 - Require a contraction of current economics functionning
 - And even fundamental changes in its functionning too
 - A byproduct of this scientific inquiries is that GDP is more & more considered as an irrelevant indicator for these problematics

[35] ECORYS, 2012. *Mapping resource prices: the past & the future* [online]. Final report to European Comission.

C. Volatility of prices

- Base metals' prices are historically quite constant relatively to each others but individual resource's price is highly volatile ^[35]



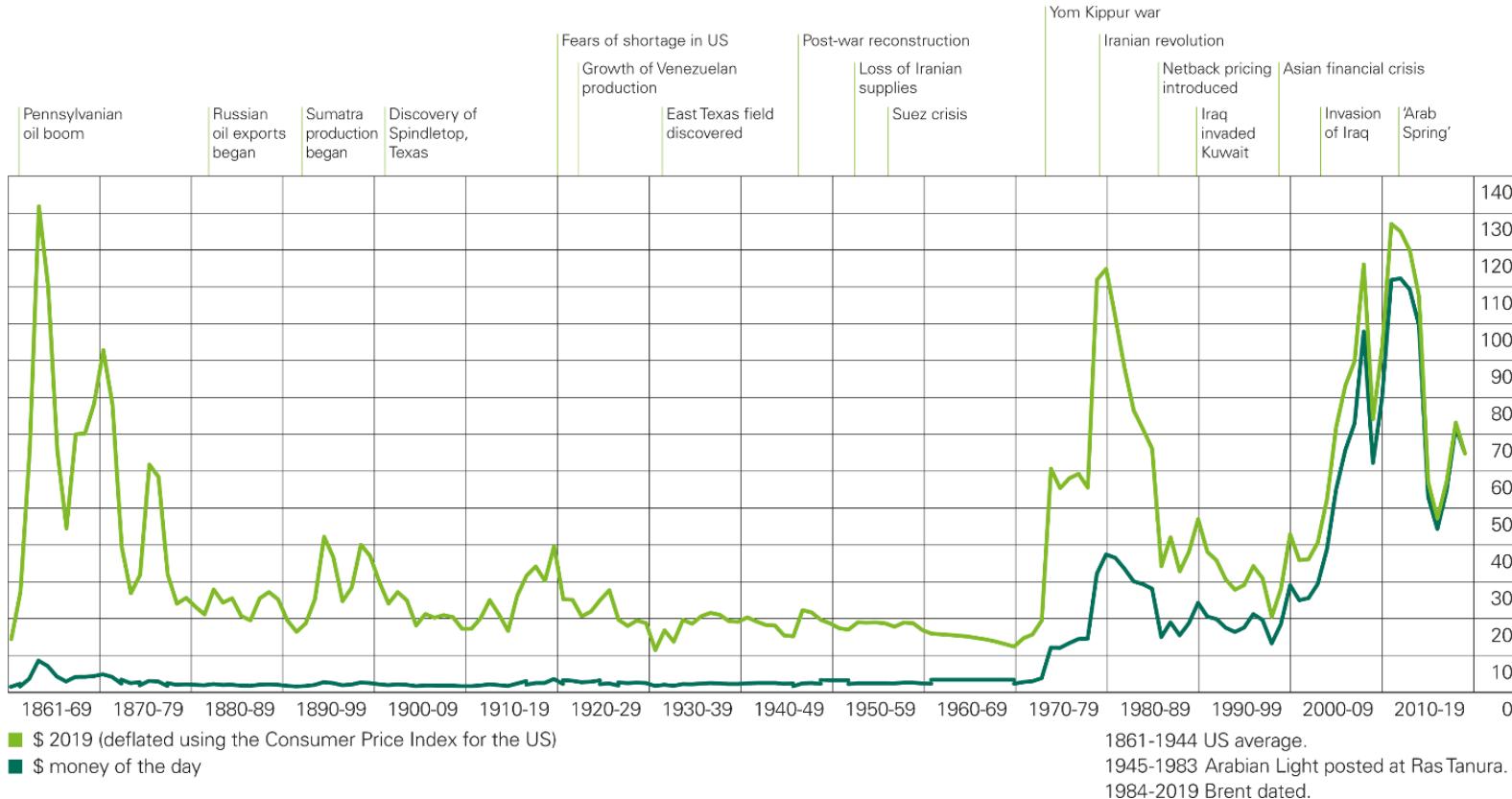
4.2.1 The flows's stakes

[6] BP, 2020. BP Statistical Review of World Energy. [online].

C. Volatility of prices

Extracted from [6]

- Oil's price is highly volatile too [6]



[3] BIHOUIX, P., GUILLEBON, B. 2010. *Quel futur pour les métaux?*

C. Volatility of prices

- Resources's prices underlying determinations
 - Perceived availability through control of producers
 - Degree of substitutability
- Resources's prices mechanisms of formations
 - Over-the-counter (OTC) markets: traditionnal mechanism
 - Annual or multi-year supply contracts: mainly, Fe and Fe allows
 - Pricing on forward markets
 - Special case of precious metals: considered as quasi-money or OTC.
- Historically, numerous resources exchanges were operated by intermediates
 - Contemporary period: developpment of financialization
 - Alignment of Raw materials on securities ➔ far less intermediaries

[36] MITTEAU, Gilles, 2018. Economie et finance du pétrole - Heureka. [online].

C. Volatility of prices

- Financial markets's effects
 - Efficiency of market → Trends of prices themselves tend to disappear
 - Short-term interest of traders → Short-term volatility
 - Complexity of the product and implications of prices variations on the economy
→ Long-term volatility + impossibility to know for sure the causes of prices variations
- ➔ There is no « natural price-signalling » mechanism that makes a non-renewable resource progressively more expensive overtime
- ➔ The « natural » functioning of Financial markets seems to imply that the reduction of energy & material flows lead to higher volatility, or maybe higher « volatility of volatility »

For detailed reasoning, strong recommendation of Youtuber Heureka on Economy & Finance of oil

A. Limits of efficiency

- Like recycling, energy efficiency is necessary
 - Allow to reduce flows for a given performance
 - 25% energy yield → 30% energy yield ⇔ 1/6 of oil flows spared per year
 - 25% energy yield → 50% energy yield ⇔ 1/2 of oil flows spared per year
 - Same goes for « material efficiency » (diminishing the quantity of material needed to achieve a given functionnality)
- But it is not sufficient, and could even be harmful on the global scale
 - Energy efficiency, when only measure applied, have mainly cost reduction effects
 - Cost reduction could then lead to democratize preexisting uses or create new ones
 - This then would lead to an overall increase in energy consumption

[37] SORRELL, Steve, 2007. *The Rebound Effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency*. [online]. UKERC

A. Limits of efficiency

- This would be called a « **rebound effect** » [37]
 - The « economy-wide » rebound effect is of combination of direct and indirect rebound effects that can interact with each other
- Some basic examples of direct rebound effect:
 - If fuel-efficient vehicles make travel cheaper → Consumers may choose to drive further / more often → Offsets the energy savings
 - If a factory uses energy more efficiently → Becomes more profitable → May generate further investments → More production
- Some basic examples of indirect rebound effect:
 - Drivers of fuel-efficient cars may spend the money saved bying petrol on other energy intensive goods or services (ex: overseas flight)

[38] JEVONS, William Stanley, 1865. The Coal Question. . 1865. P. 213.

A. Limits of efficiency

- Rebound effect concept comes back to the XIXth century
 - Firstly known as « Jevons paradox » from W. J. Jevons [38]
 - Steam-engines' efficiency had been increased by 10-fold at least in a century
 - Consumption of coal had greatly increased anyway (x 6 in 50 years)
 - The same considerations could be made about today:
 - Energy efficiency of cars' engines have never been better
 - Our oil consumption dedicated to it have never been higher
- ➔ Could be explained by:
- The growth of car use
 - And spared cost of cars invested in high-tech supplementary functions which increase car's weight and maintain oil consumption

[37] SORRELL, Steve, 2007. *The Rebound Effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency.* [online]. UKERC

[39] STERN, David I., 2017. How accurate are energy intensity projections?. DOI [10.1007/s10584-017-2003-3](https://doi.org/10.1007/s10584-017-2003-3).

A. Limits of efficiency

Extracted from [11]

- Quantified contemporary estimations are complicated:
 - There is indeed a correlation between various measures of energy efficiency and continuing overall energy consumption
 - But the causal links between these trends are not clear
 - Difficulty to assess other things than direct rebound effects
- That being said, evidence suggest that: [37]
 - It has the potential to widely vary between technologies, sectors, income groups
 - In OECD countries, automotive transport, household heating & cooling can relatively robustly be considered subjects to a direct rebound effect of 10-30% (microscale)
 - Current energy or material efficiency policies are not up to the task (macroscale)
- Estimates of energy footprint decline itself are generally too optimistic [39]

[40] HALL, Charles A. S., et al., 2014. EROI of different fuels and the implications for society. DOI [10.1016/j.enpol.2013.05.049](https://doi.org/10.1016/j.enpol.2013.05.049).

B. Physics inevitability

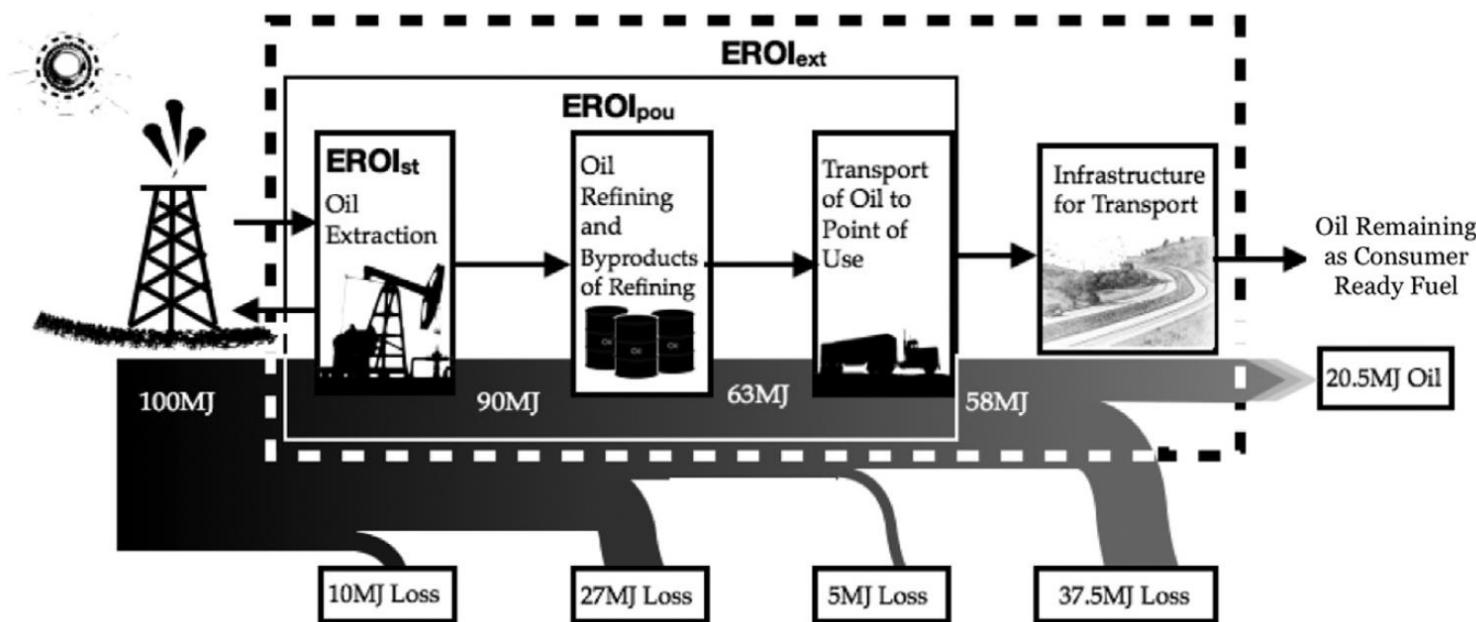
- Material & Energy flows will decline anyway due to the physics underlying the production peak
 - We've seen that the decline in ores's grade do lead to an exponential demand in energy for base metals extraction, and that a mineralogical barrier can happen for rarer metals
 - But oil itself needs energy to be extracted!
- Last notion of this course: ***EROI – Energy return on investment***
 - Ratio of energy delivered by a specific energy vector and the energy invested in the capture & delivery of this energy
 - Measures the relative quality of energy vectors
 - Varied possible choices of boundaries in systemic assessments, so as much particular EROI: standard ; point of use ; extended ; societal

[40] HALL, Charles A. S., et al., 2014. EROI of different fuels and the implications for society. DOI [10.1016/j.enpol.2013.05.049](https://doi.org/10.1016/j.enpol.2013.05.049).

B. Physics inevitability

Extracted from [40]

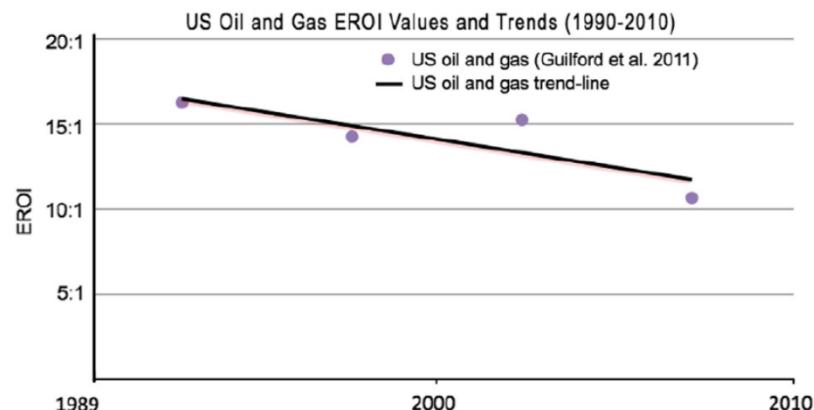
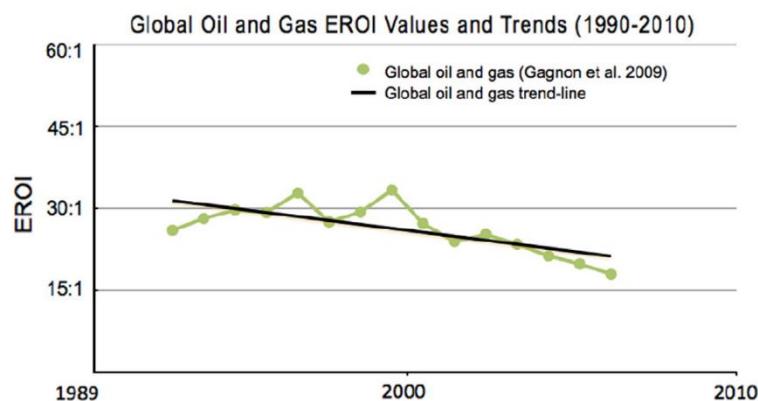
- Varied possible choices of boundaries in systemic assessments, so as much EROI calculations: standard ; point of use ; extended ; societal



[40] HALL, Charles A. S., et al., 2014. EROI of different fuels and the implications for society. DOI [10.1016/j.enpol.2013.05.049](https://doi.org/10.1016/j.enpol.2013.05.049).

B. Physics inevitability

- Is there a trend for oil already?
 - As oil is often extracted together with natural gas, calculations can be tricky
 - Complicated also by what we said about oil compagnies low level of transparency
 - But all estimates tend to show a progressive decrease in EROI for every place where data is available: ***here in USA***

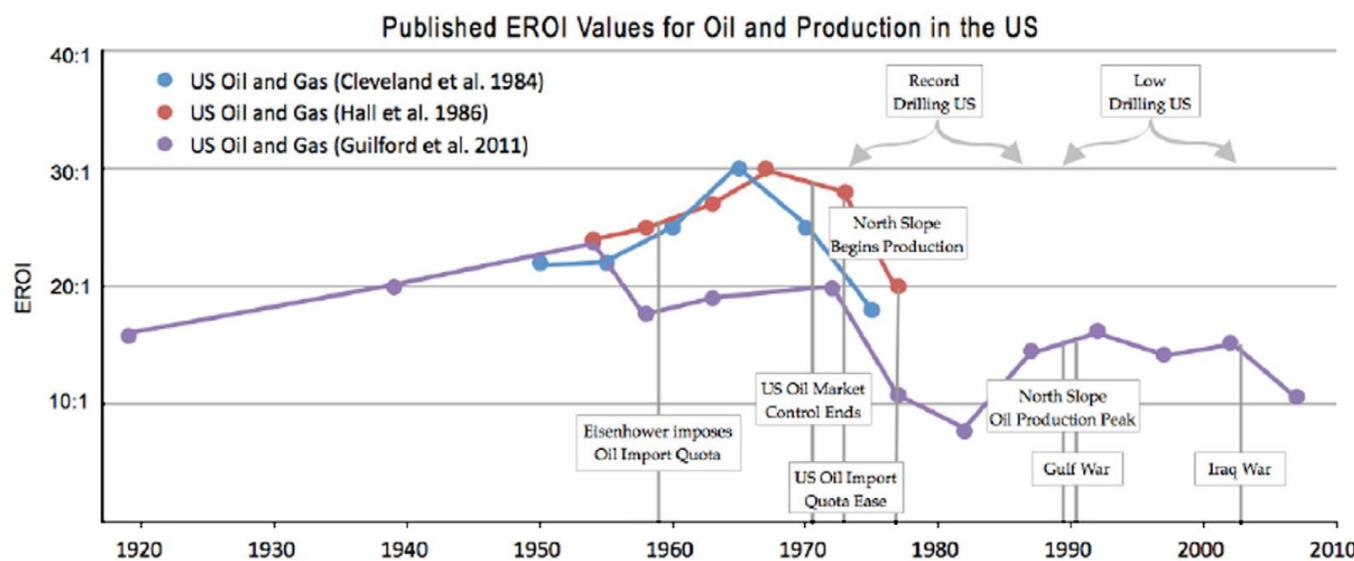


Extracted from [40]

[40] HALL, Charles A. S., et al., 2014. EROI of different fuels and the implications for society. DOI [10.1016/j.enpol.2013.05.049](https://doi.org/10.1016/j.enpol.2013.05.049).

B. Physics inevitability

- Is there a trend for oil already?
 - Seems so
 - All estimates tend to show a progressive decrease in EROI for every place where data is available: ***here in USA***

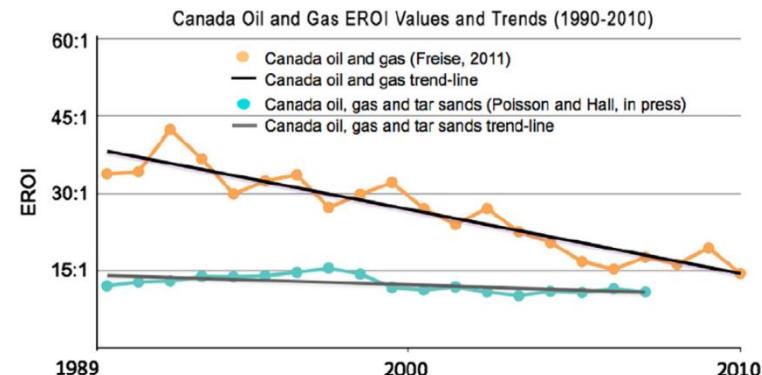
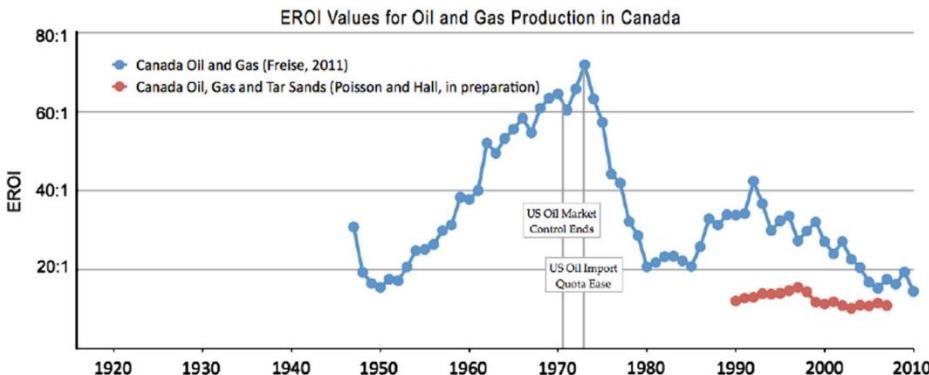


Extracted from [40]

[40] HALL, Charles A. S., et al., 2014. EROI of different fuels and the implications for society. DOI [10.1016/j.enpol.2013.05.049](https://doi.org/10.1016/j.enpol.2013.05.049).

B. Physics inevitability

- Is there a trend for oil already?
 - Pretty much so!
 - All estimates tend to show a progressive decrease in EROI for every place where data is available:
here in Canada

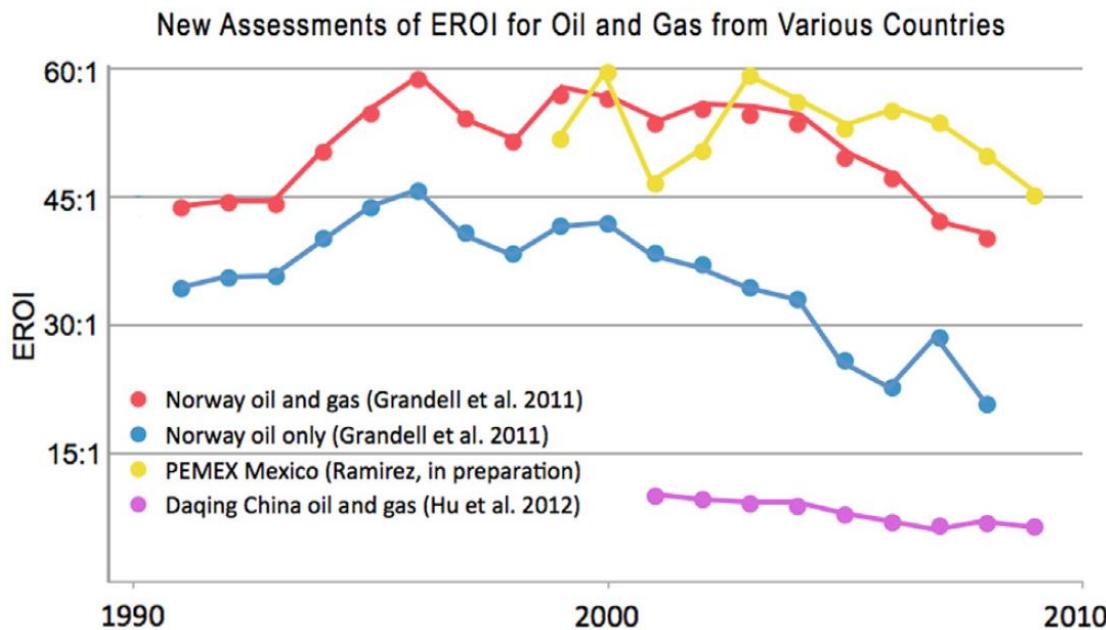


Extracted from [40]

[40] HALL, Charles A. S., et al., 2014. EROI of different fuels and the implications for society. DOI [10.1016/j.enpol.2013.05.049](https://doi.org/10.1016/j.enpol.2013.05.049).

B. Physics inevitability

- Is there a trend for oil already?
 - Undeniably so!
 - All estimates tend to show a progressive decrease in EROI for every place where data is available:
here in various other countries

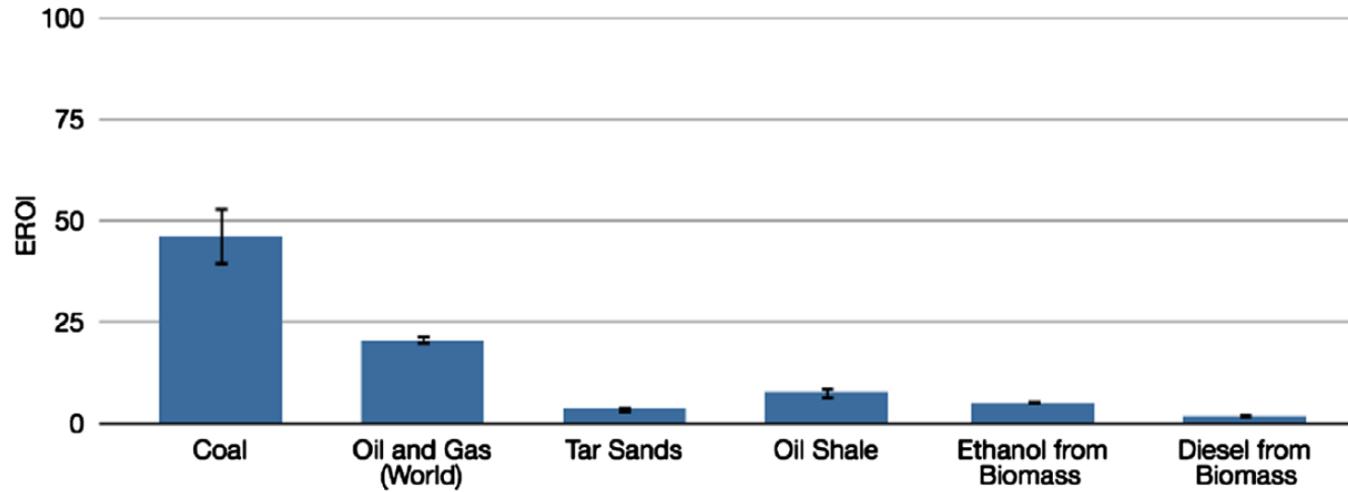


Extracted from [40]

[40] HALL, Charles A. S., et al., 2014. EROI of different fuels and the implications for society. DOI [10.1016/j.enpol.2013.05.049](https://doi.org/10.1016/j.enpol.2013.05.049).

B. Physics inevitability

- It is logical from what we've seen about the concentration of resources in general. But why does it especially matter here?
 - The decrease of the EROI of conventional oil means we'll need to set aside a growing share of the oil flows just to continue to have a flow
 - This share of oil « lost » will no longer be used to supply other sectors [36]
 - Non conventional oils have a base EROI quite lower than conventional (and will also decrease with their further exploitation) [40]



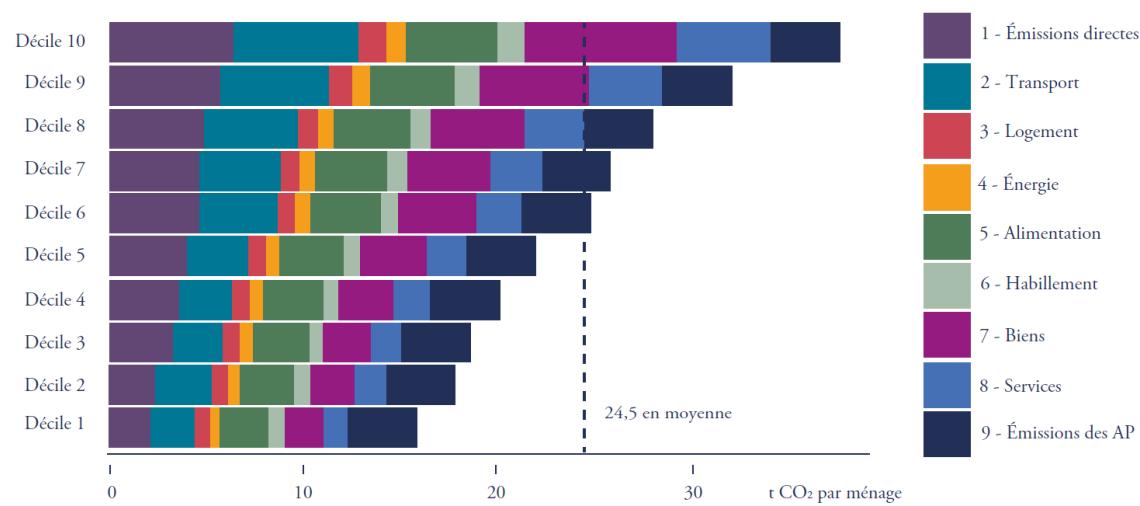
Extracted from [40]

[36] MITTEAU, Gilles, 2018. Economie et finance du pétrole - Heu?reka. [online].
 [40] HALL, Charles A. S., et al., 2014. EROI of different fuels and the implications for society. DOI [10.1016/j.enpol.2013.05.049](https://doi.org/10.1016/j.enpol.2013.05.049).
 [33] HCC, 2020. Rapport annuel - Redresser le cap, relancer la transition. Haut Conseil pour le Climat [online]. 2020.

C. Managing consequences, tackling causes

- As there is no absolute decoupling, a contraction & instability of economy and as we know it seems unavoidable in the medium-term, regardless of climate change [36] & [40]
 - By « economy », here, we mean that all socioeconomic & geopolitical relationships will be impacted
 - Social acceptability of dynamics created by contracting flows will be a key component of the success of mitigating policies [33]
- ➔ Ecological transition is also a social one

Figure 23 – Empreinte carbone par ménage,
décomposée par source et produit selon les déciles de niveau de vie



Source : Malliet et al. (2020) d'après EXIOBASE 3, INSEE BdF 2011 et SDES-CGDD - <http://carbonconsumptionsurvey.eu/>

[30] BIHOUIX, Philippe, 2014. *L'Age des low techs: vers une civilisation techniquement soutenable*. Seuil.

C. Managing consequences, tackling causes

- This is were we, as engineers, must at the very least inspire ourselves by the 7 principles of low-techs [30]
 1. Challenging needs
 2. Design and produce truly sustainable
 3. Orienting knowledge to resources' savings
 4. Striking a technical balance between performance & *conviviality*
 5. Relocalize without losing the right scale effects
 6. De-machinizing services
 7. Knowing to remain modest