Critical raw materials and their environmental impact

Prof. Alessandro Cavallo, PhD

GEORGIUS AGRICOLA

DE RE METALLICA

TRANSLATED FROM THE FIRST LATIN EDITION OF 1556

with

Biographical Introduction, Annotations and Appendices upon the Development of Mining Methods, Metallurgical Processes, Geology, Mineralogy & Mining Law from the earliest times to the 16th Century

BY

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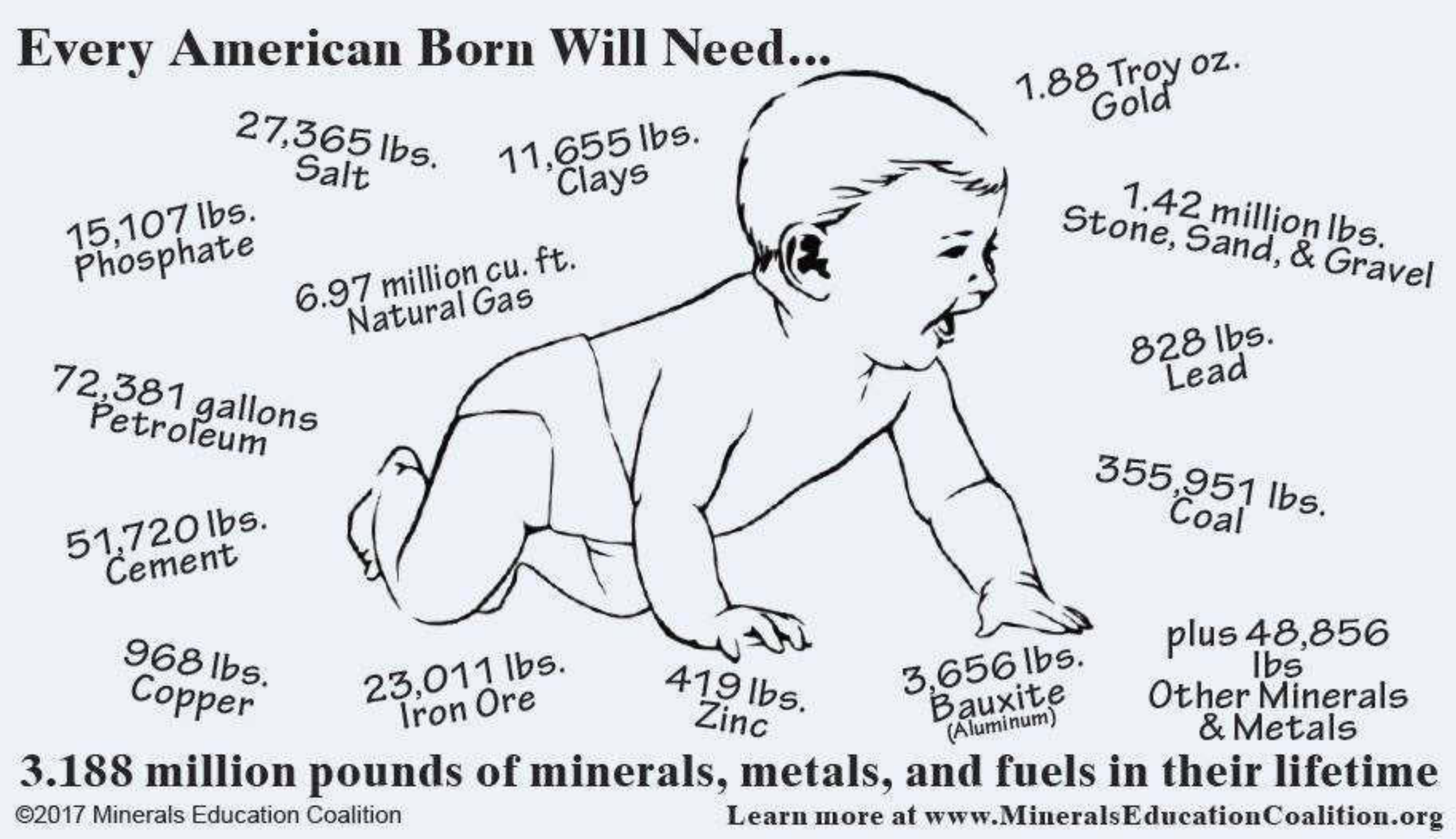
Ore, industrial & energy minerals



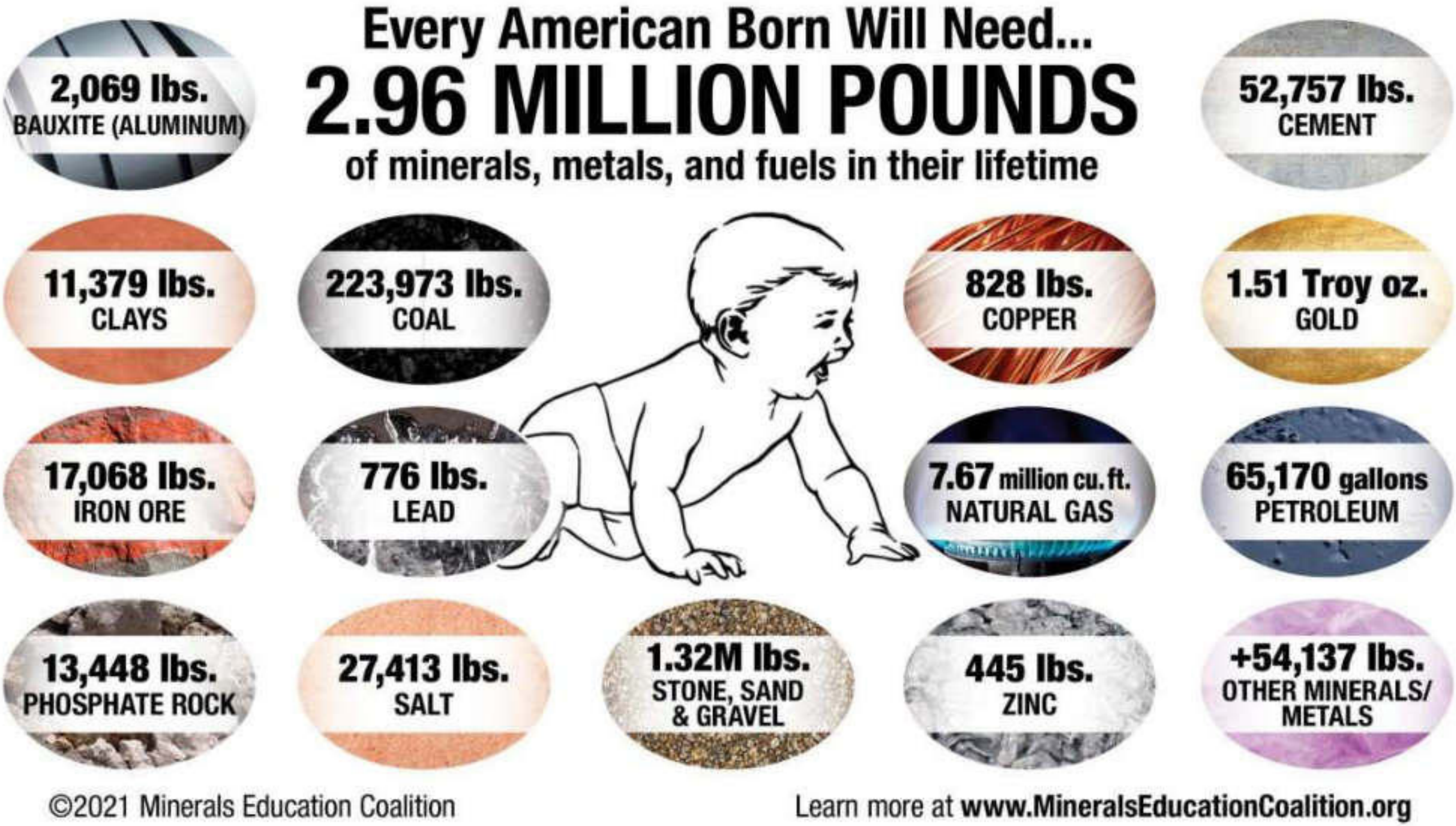
1 **lbs** = 0.453592 **kg**

1 **gallon** = 3.78541 **l**

1 **Troy oz.** = 31.1035 **g**

1 **cu ft.** = 28.3168 **l**

Ore, industrial & energy minerals



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1 **gallon** = 3.78541 **l**

1 **Troy oz.** = 31.1035 **g**

1 **cu ft.** = 28.3168 **l**

EVERY YEAR: 38,272 pounds of new minerals must be provided for every person in the United States to make the things we use daily

10,188 lbs.	**Stone** is used to make roads, buildings, bridges, landscaping and other construction uses, and for numerous chemical uses.
6,912 lbs.	**Sand and Gravel** are used to make concrete, asphalt, roads, blocks and bricks.
682 lbs.	**Cement** is used to make roads, sidewalks, bridges, buildings, schools and houses.
221 lbs.	**Iron Ore** is used to make steel for buildings, cars, trucks, planes, trains, and for other construction and containers.
355 lbs.	**Salt** is used in various chemicals, for highway deicing, and in food and agriculture.
174 lbs.	**Phosphate Rock** is used to make fertilizers to grow food and in animal feed supplements.
147 lbs.	**Clays** are used to make floor and wall tile, dinnerware, kitty litter, bricks, cement and paper.
27 lbs.	**Aluminum (from bauxite)** is used to make buildings, beverage containers, autos and airplanes.
11 lbs.	**Copper** is used in buildings, electrical and electronic parts, plumbing and in transportation.
10 lbs.	**Lead**—75% is used for transportation, and it is used in batteries, electrical equipment and in communications.
6 lbs.	**Zinc** is used to make metals rust-resistant, to make various metals and alloys, paints, rubber, and in skin creams, health care and nutritional supplements.
27 lbs.	**Soda Ash** is used in all kinds of glass, powdered detergents, medicines, as a food additive, and for water treatment.
3 lbs.	**Manganese** is used to make almost all steel for construction, and in machinery and transportation.
547 lbs.	**Other Nonmetals** are used in glass, chemicals, soaps, paper, computers, cell phones, and more.
20 lbs.	**Other Metals** are used in electronics, TV and video equipment, recreation equipment, and more.

Including These Energy Fuels

- 843 gallons of Petroleum
- 99,204 cu. ft. of Natural Gas
- 2,897 lbs. of Coal
- 0.15 lb. of Uranium

To generate the energy each person uses in one year—

MEC
Minerals Education Coalition

Raw materials per capita/year

N.B. 1 lbs = 0.45359 kg

ORE DEPOSIT

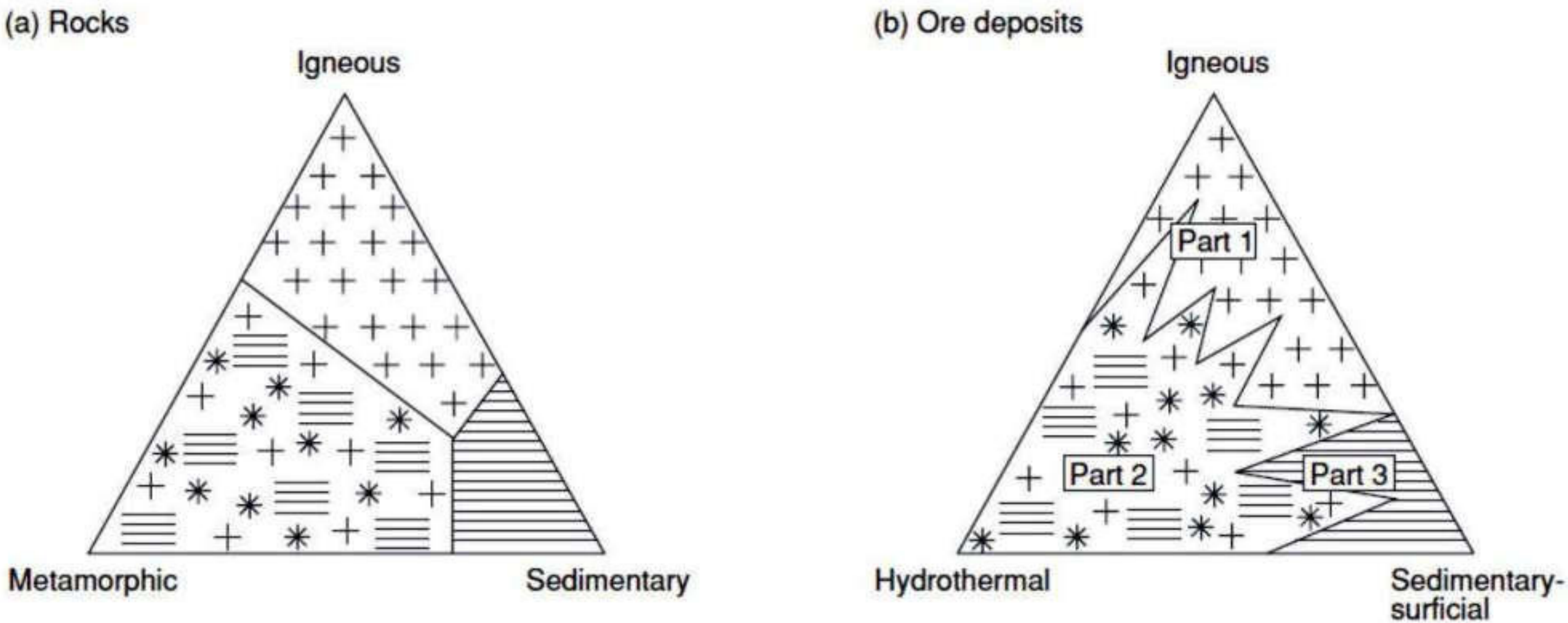
- **Mineral deposit**: a mass of naturally occurring mineral material, e.g. metal ores or nonmetallic minerals, usually of economic value, without regard to mode of origin. Accumulations of coal and petroleum may or may not be included; usage should be defined in context.

- **Orebody**: a continuous, well-defined mass of material of sufficient ore content to make extraction economically feasible.

- **Ore**: the naturally occurring material from which a mineral or minerals of economic value can be extracted at a reasonable profit. Also, the mineral(s) thus extracted. The term is generally but not always used to refer to **metalliferous material and** is often modified by the name of the valuable constituent, e.g., "iron ore".

- **Gangue**: the valueless rock or mineral aggregates in an ore; that part of an ore that is not economically desirable but cannot be avoided in mining. It is separated from the ore minerals during concentration. Syn: matrix

Ore forming processes



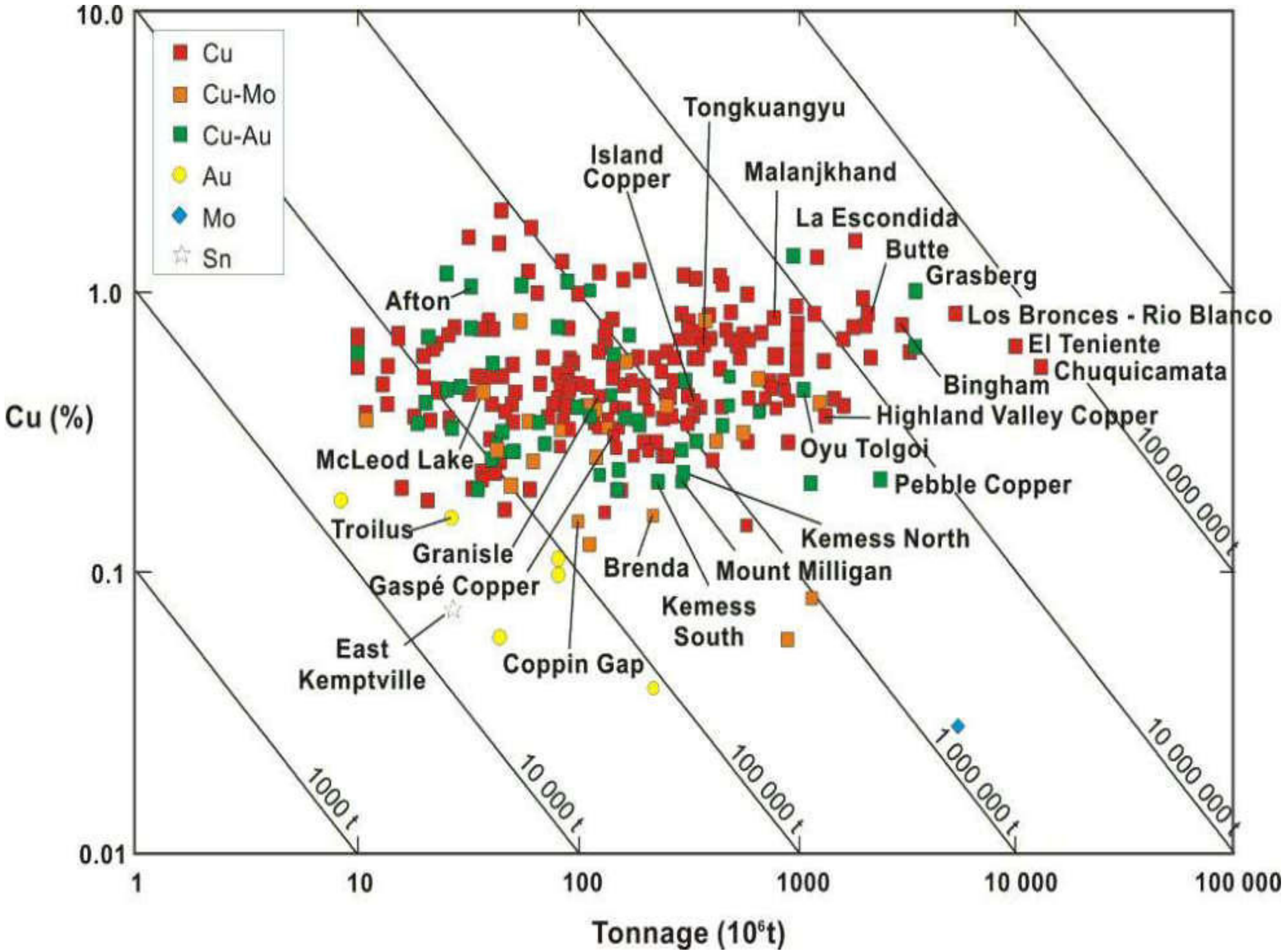
Average crustal abundances and concentration factors

Table 1 Average crustal abundances for selected metals and typical concentration factors that need to be achieved in order to produce a viable ore deposit

	Average crustal abundance	Typical exploitable grade	Approximate concentration factor
Al	8.2%	30%	×4
Fe	5.6%	50%	×9
Cu	55 ppm	1%	×180
Ni	75 ppm	1%	×130
Zn	70 ppm	5%	×700
Sn	2 ppm	0.5%	×2500
Au	4 ppb	$5\ g\ t^{-1}$	×1250
Pt	5 ppb	$5\ g\ t^{-1}$	×1000

Note: 1 ppm is the same as $1\ g\ t^{-1}$.

Grade and tonnage diagrams



ECONOMIC CLASSIFICATION OF METALS

a) Precious metals: **Au, Ag, PGE** (o PGM, Ru, Rh, Pd, Os, Ir, Pt; *Ir-group IPGEs*: Os, Ir, Ru; *Pd-group PPGEs*: Rh, Pt, Pd).

b) *Non ferrous metals*: **Cu-Pb-Zn-Sn** (*base metals*), **Al**.

c) *Iron and ferrous metals*: **Fe, Mn, Ni, Cr, Mo, W, V, Co**.

d) *Minor metals and non-metals*: **Sb, As, Be, Bi, Cd, Mg, Hg, REE, Nb, Ta, Se, Te, Ti, Zr**, ecc.

e) *Fissile metals*: **U, Th, (Ra).**

ORE & ORE MINERALS: some basic definitions

- **Ore**: *the naturally occurring material from which a mineral or minerals of economic value can be extracted at a reasonable profit. Also, the mineral(s) thus extracted. The term is generally but not always used to refer to metalliferous material and is often modified by the name of the valuable constituent, e.g., "iron ore". The German term is "Erz".*

- **Gangue**: *the valueless rock or mineral aggregates in an ore; that part of an ore that is not economically desirable but cannot be avoided in mining. It is separated from the ore minerals during concentration. Syn: matrix.*

- ***Grade***: *the relative quantity or the percentage of ore-mineral content in an orebody. Syn: tenor.*

- ***Cut-off grade*****:** *in economic geology, the lowest grade of mineralized material that qualifies as ore in a given deposit; ore of the lowest assay value that is included in an ore estimate.*

- ***Clarke***: *the average abundance of an element in the crust of the Earth. It is named in honour of F.W. Clarke. Syn: crustal abundance.*

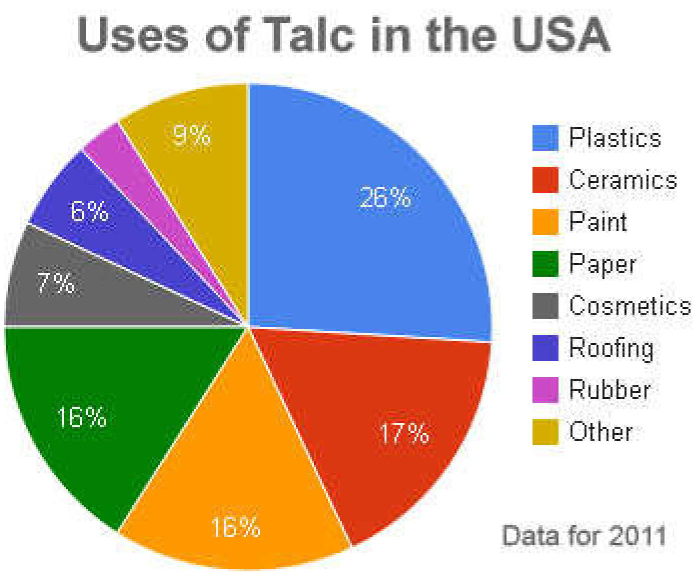
- ***Clarke of concentration***: *the concentration of an element in a mineral or rock relative to its crustal abundance. The term is applied to specific as well as average occurrences.*

Average concentration and enrichment factor

Element	Chemical symbol	Average concentration %	Quantity/km^3 (000 mt)	Typical ore grades %	Enrichment factor
Aluminum	Al	8.1	250,000	30	4
Iron	Fe	5.4	150,000	53	10
Titanium	Ti	0.5	15,000	0.7–15	2–40
Manganese	Mn	0.10	3000	31	310
Chromium	Cr	0.01	300	30	3000
Nickel	Ni	0.008	200	1	130
Zinc	Zn	0.007	190	4	570
Copper	Cu	0.005	135	0.5–4	100–800
Cobalt	Co	0.002	60	0.4–2	200–1000
Lead	Pb	0.001	35	5	3850
Uranium	U	0.0003	7	0.3	1100
Tin	Sn	0.0003	7	0.3	1200
Molybdenum	Mo	0.0002	4	0.2	1300
Tungsten	W	0.0001	3	0.7	5800
Silver	Ag	0.00001	0.2	0.01	1400
Gold	Au	0.0000003	0.01	0.001–0.0001	300–3000

INDUSTRIAL MINERALS

- **Industrial mineral**: any rock, mineral, or other naturally occurring substance of economic value, exclusive of metallic ores, mineral fuels, and gemstones; one of the nonmetallics.
- **Nonmetal**: in economic geology, any rock or mineral mined for its nonmetallic value, such as stone, sulfur, or salt. Syn: nonmetallic; industrial mineral.



ORE & INDUSTRIAL MINERAL: rutile TiO_2

Industrial mineral ↓

Ore mineral ↓

TITANIUM DIOXIDE TIO2	95%
Paint, varnishes, lacquers	60%
Paper	12%
Plastics	22%
Rubber/other	6%

TITANIUM SPONGE METAL	5%
Aerospace Applications (air frames, engine parts, landing gear, etc.)	73%
Other (armor, chemical processing, marine, medical, power generation, sporting goods)	27%

Ore processing

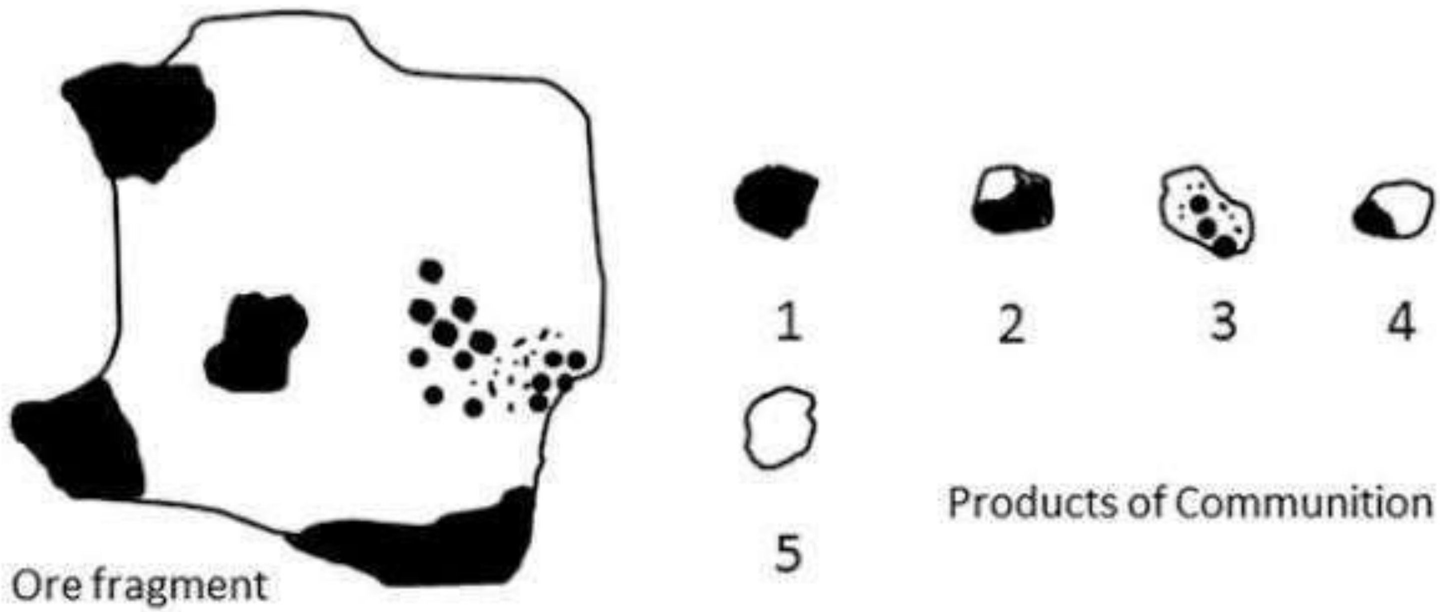


Fig. 4.2 Cross sections of ore particles, before (*left*) and after comminution (*right*). *Black* areas represent valuable mineral

Ore processing

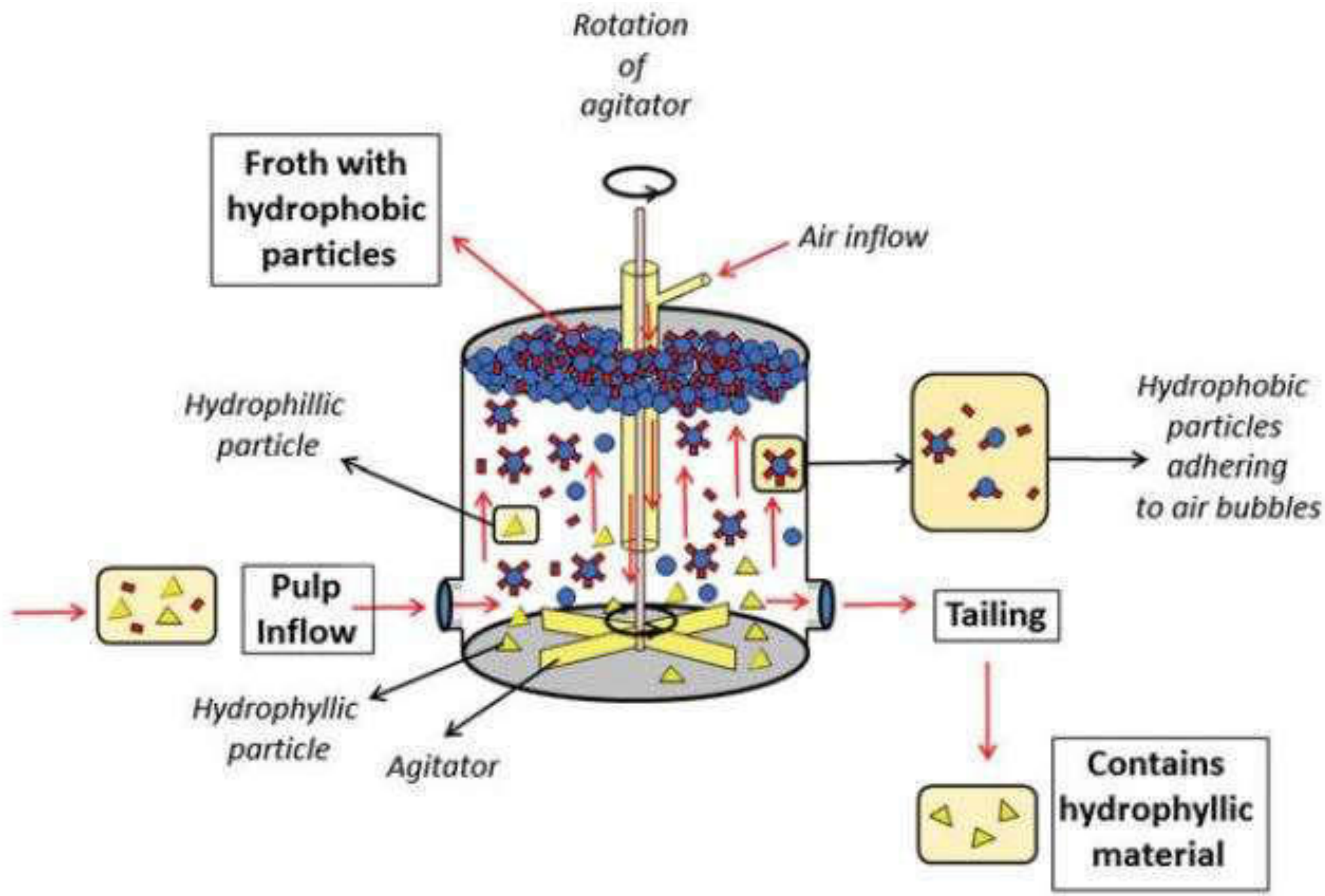


Fig. 4.3 The principle of froth flotation. Redrawn after Encyclopedia Brittanica (2015a)

MINING: depth vs. time

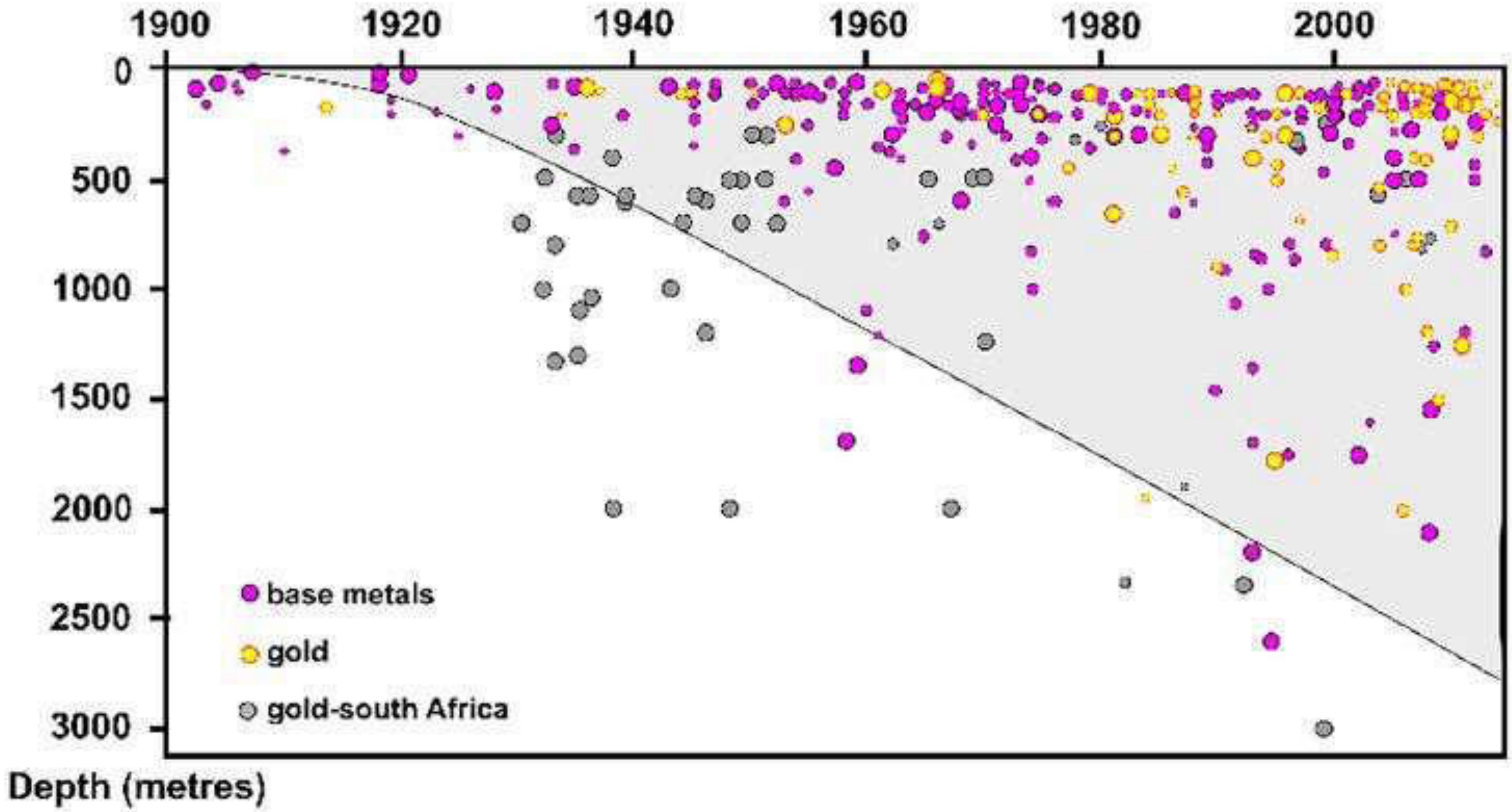


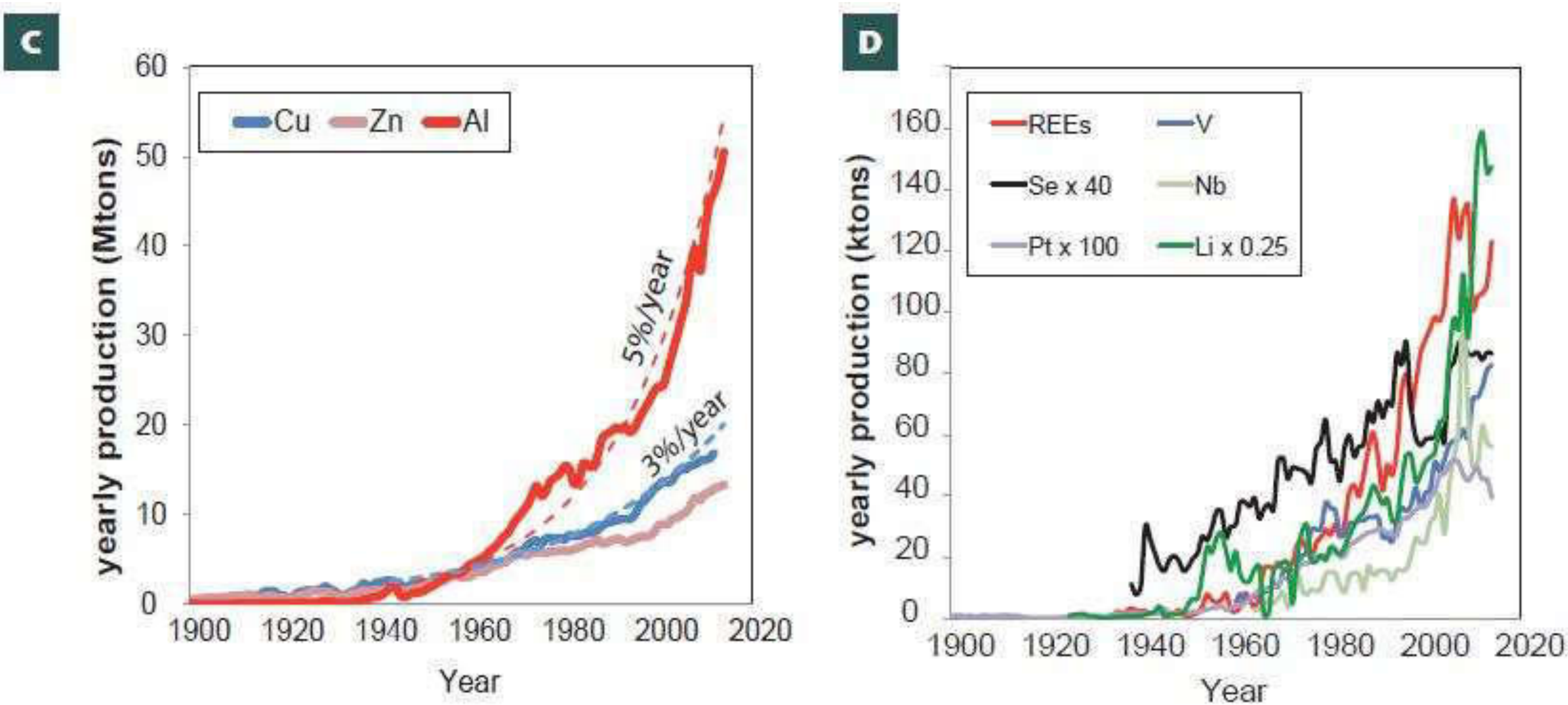
FIGURE 1 Depth of ore deposit versus discovery year, for gold and base-metal discoveries 1900–2016. The discovery of new and deep ore bodies requires significant improvements in geological models. Circle/dot sizes refer to moderate, major and giant discoveries. The triangular-shaped grey region in the figure represents the general tendancy. This figure excludes nickel laterites. DATA FROM MINEX CONSULTING (SCHODDE 2017).

World's largest mining companies

Table 2.1 World's largest mining companies by market capitalisation, mid-March 2013. (Data from author's estimates based on web sources.)

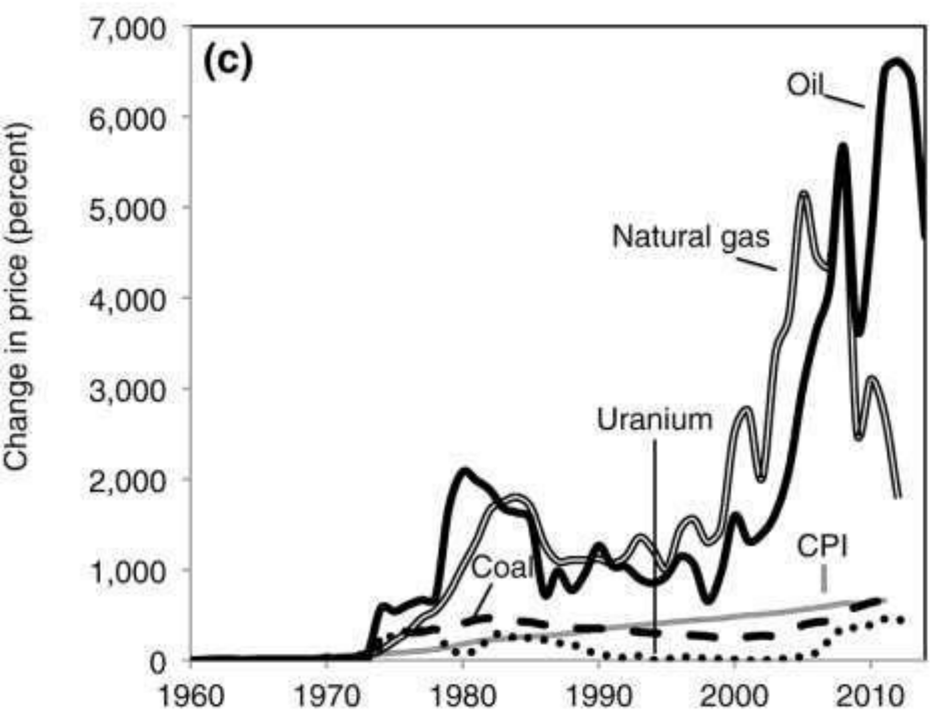
Rank	Company	Country	Market Cap $bn
1	BHP Billiton	Australia	190
2	Rio Tinto	UK	92
3	Vale	Brazil	90
4	Xstrata	Switzerland	51
5	Anglo American	UK	39
6	Freeport McMoRan	USA	34
7	Grupo Mexico	Mexico	32
8	Norilsk Nickel	Russia	32
9	Barrick Gold	Canada	29
10	Goldcorp	Canada	26
11	Newmont Mining	USA	20
12	Newcrest Mining	Australia	18
13	Teck Resources	Canada	17
14	Antofagasta	UK	16
15	Fresnillo	UK	16
16	AngloGold Ashanti	South Africa	13
17	Fortescue Metals Group	Australia	13
18	Yamana Gold	Canada	11
19	Impala Platinum	South Africa	9
20	Kinross Gold	Canada	9

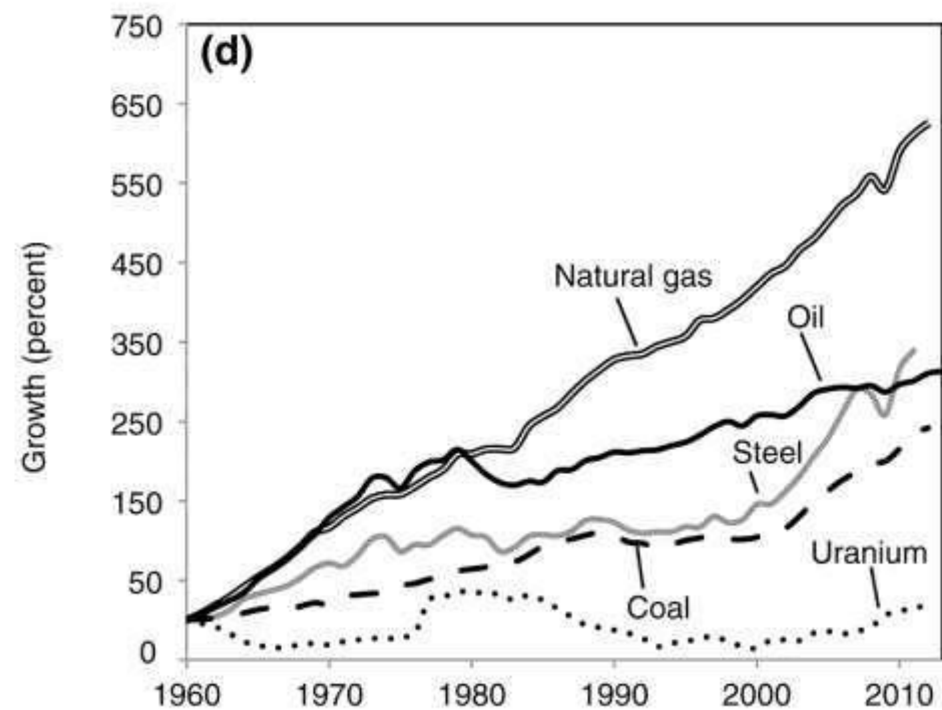
MINING: base metals vs. technology metals



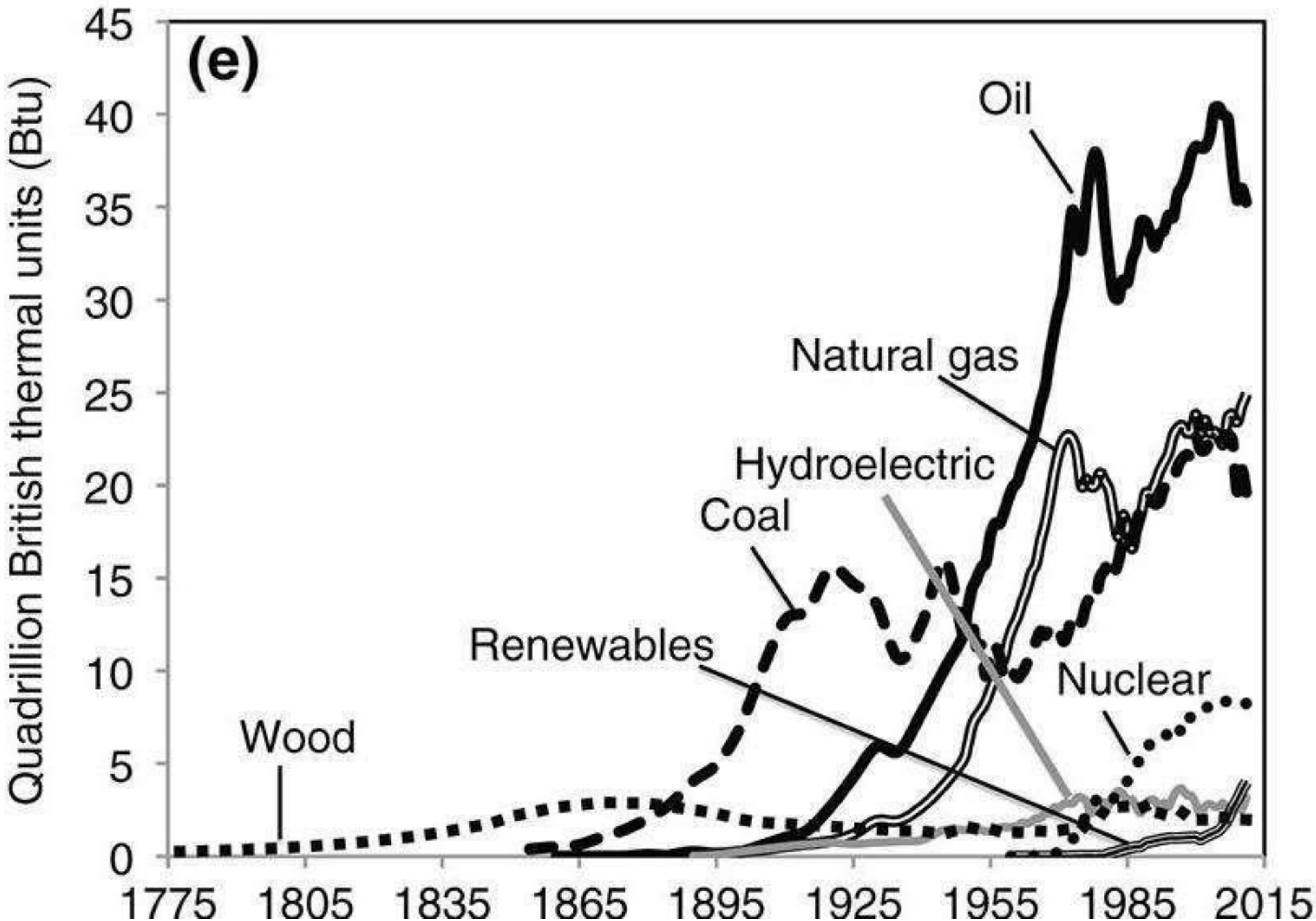
ENERGY MINERALS

ENERGY MINERALS (oil, gas, coal, uranium)

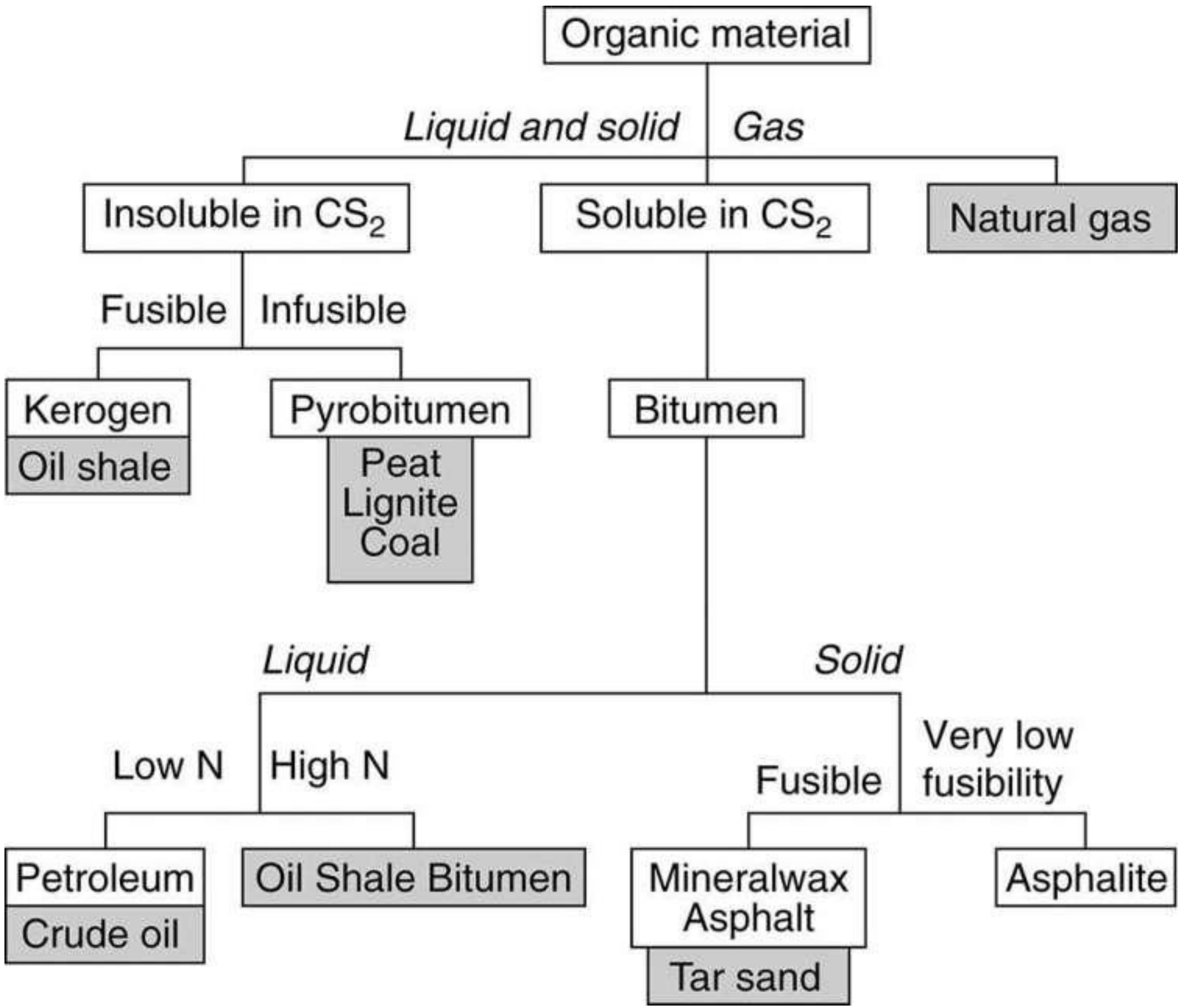




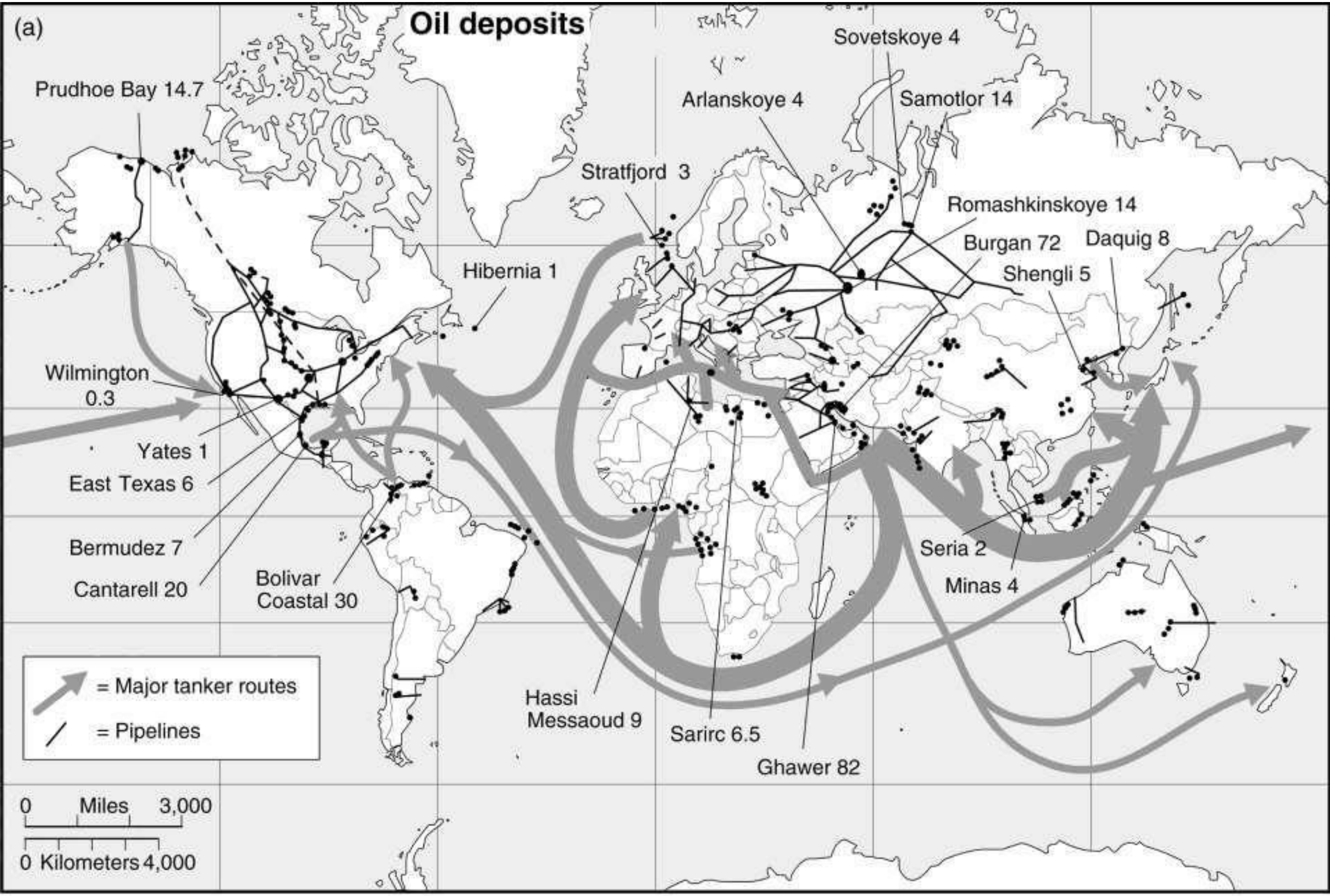
ENERGY MINERALS - energy generation



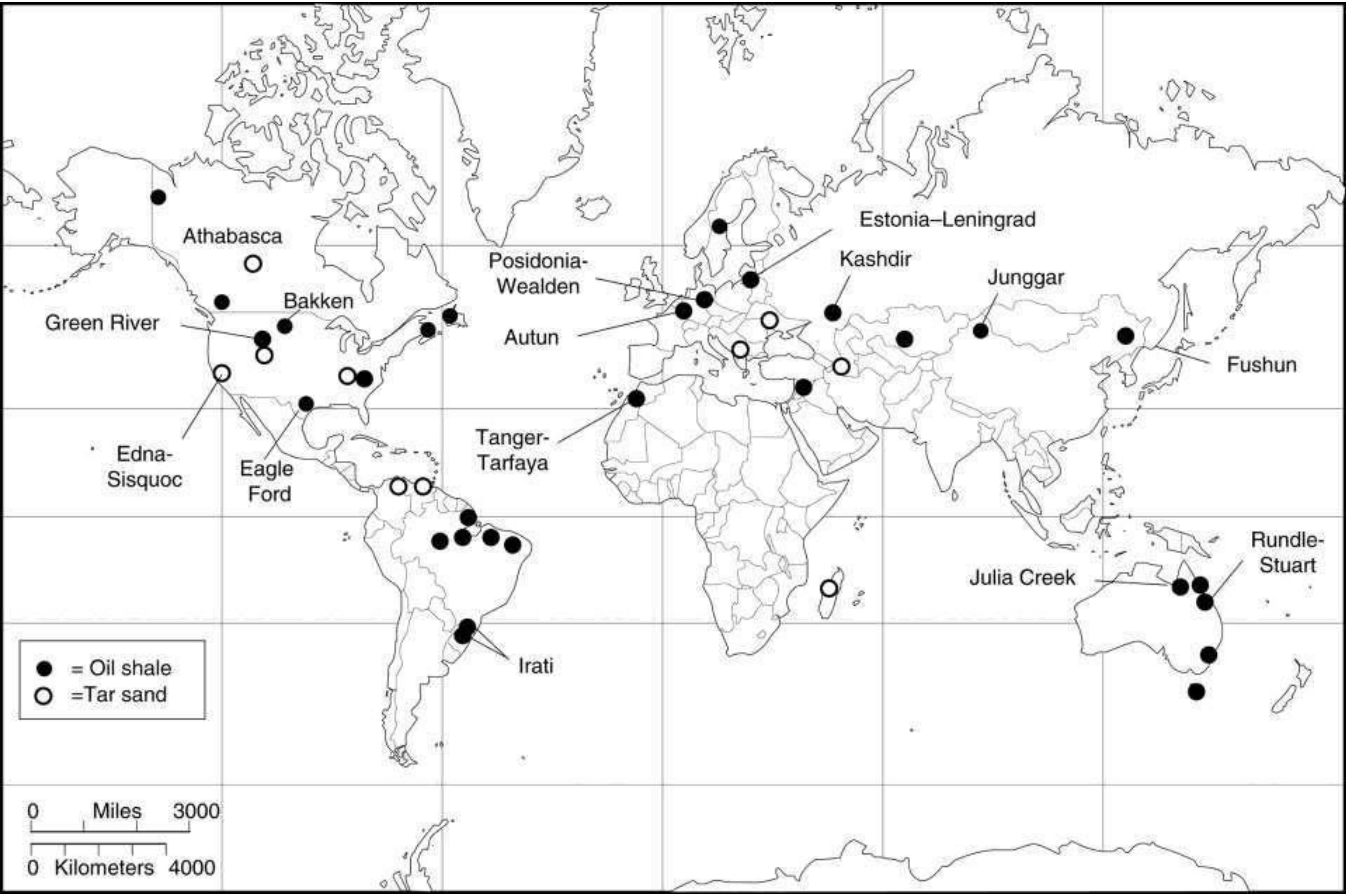
ENERGY MINERALS – organic matter



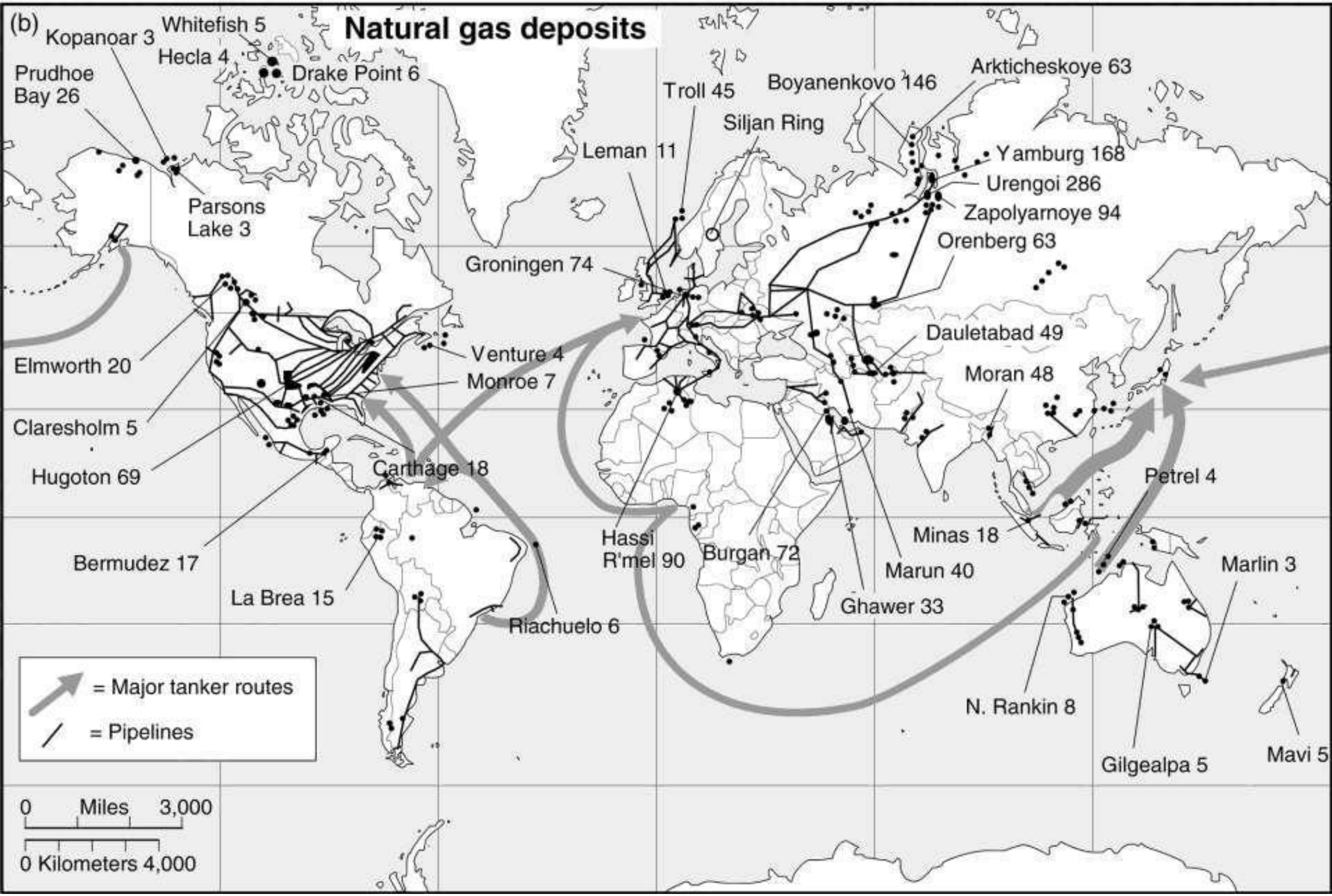
ENERGY MINERALS – oil deposits



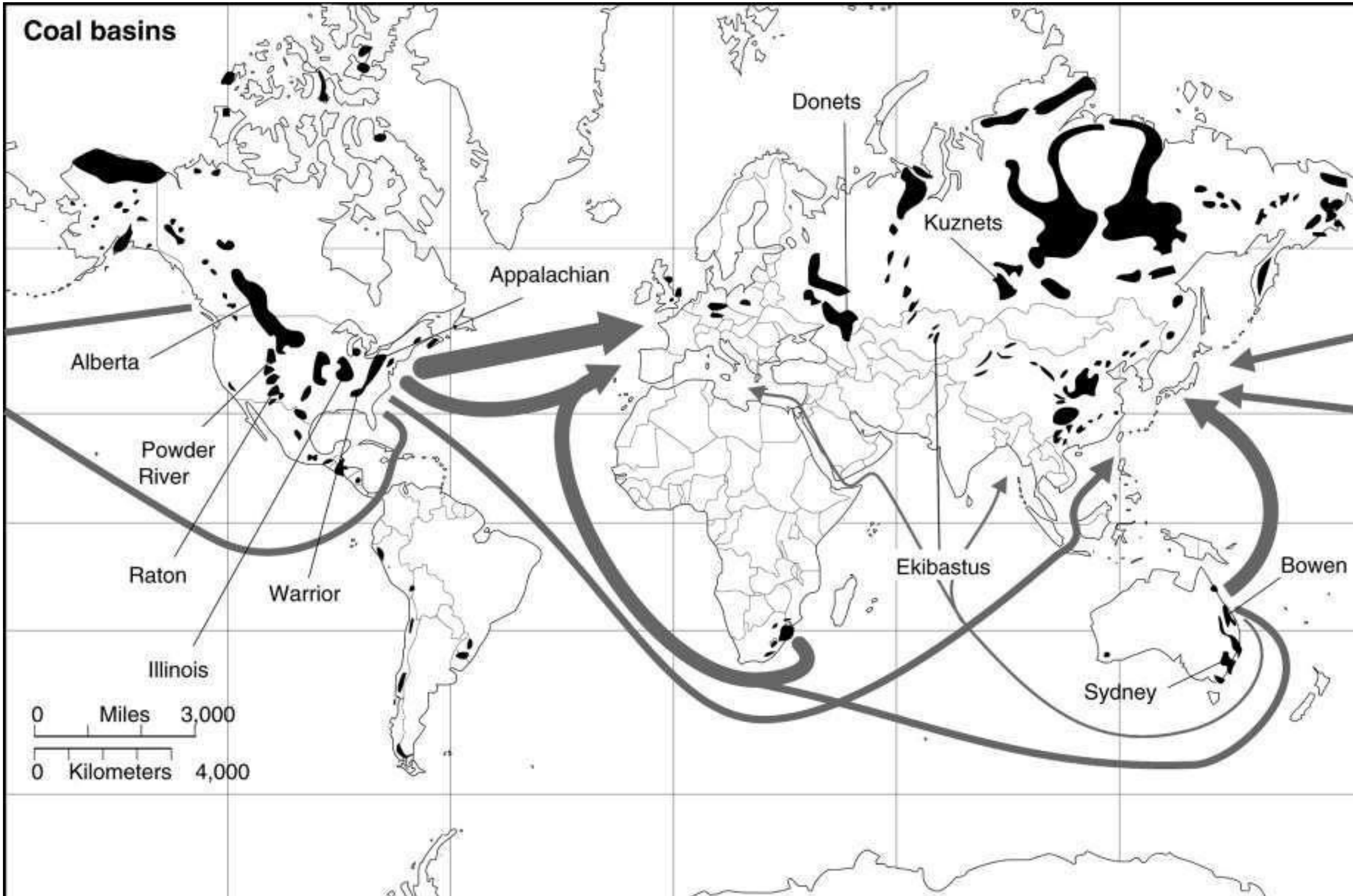
ENERGY MINERALS – non-conventional oil deposits



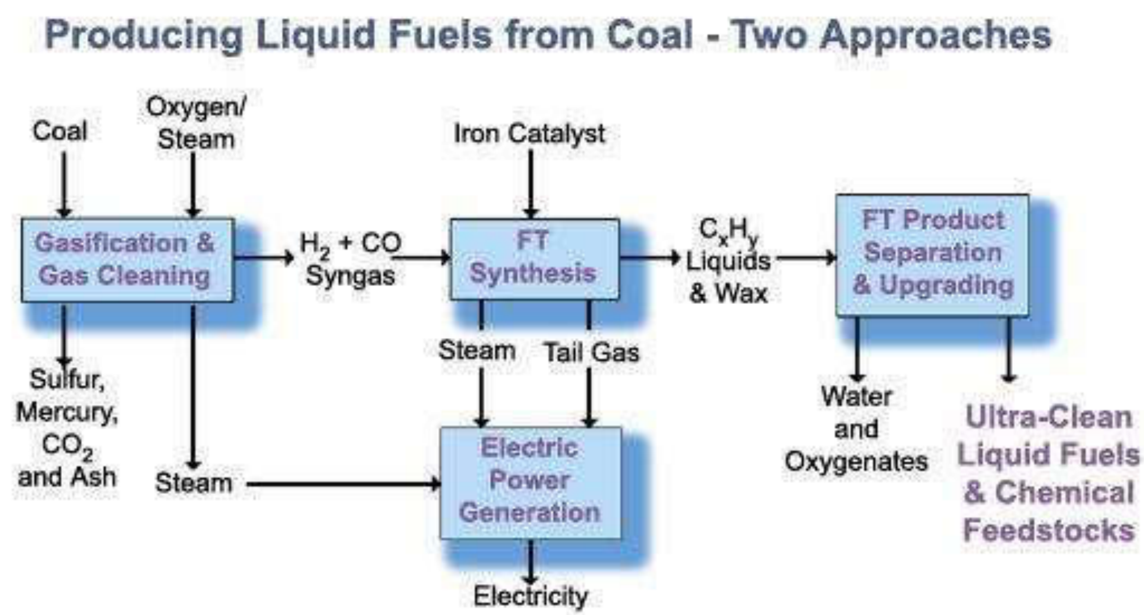
ENERGY MINERALS – gas



ENERGY MINERALS – coal

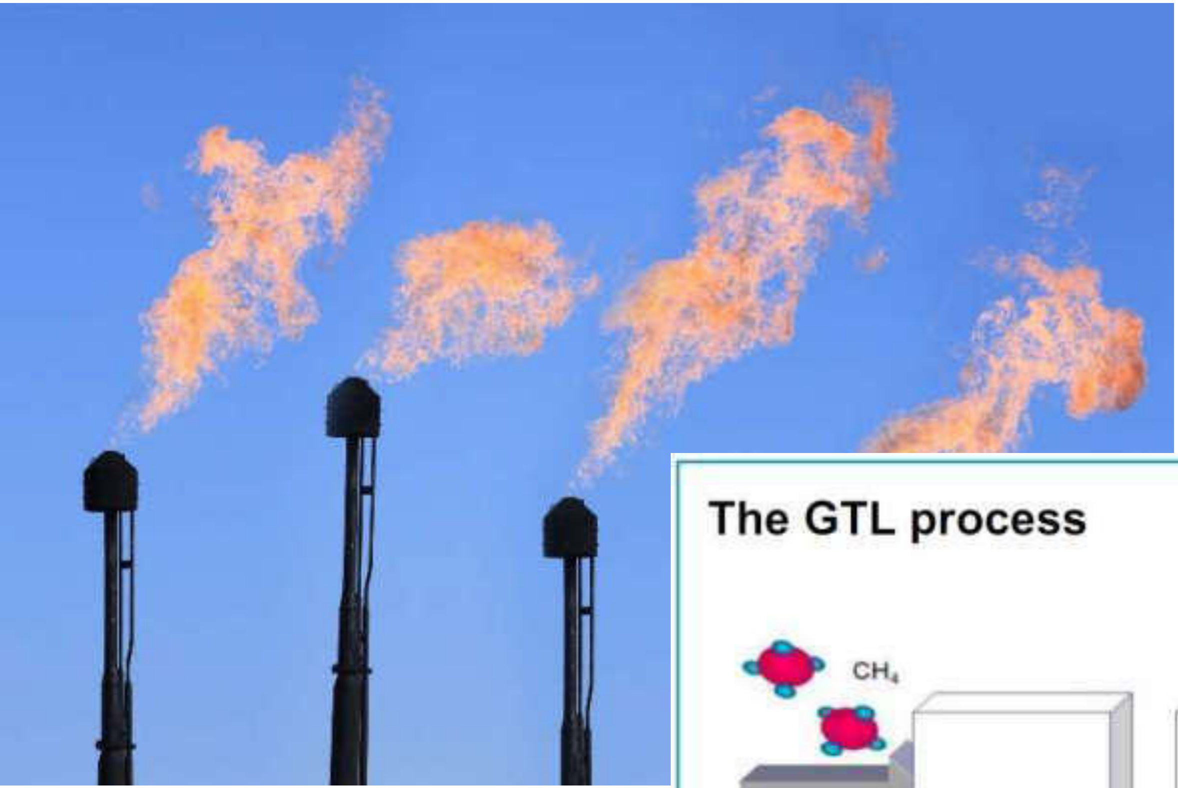


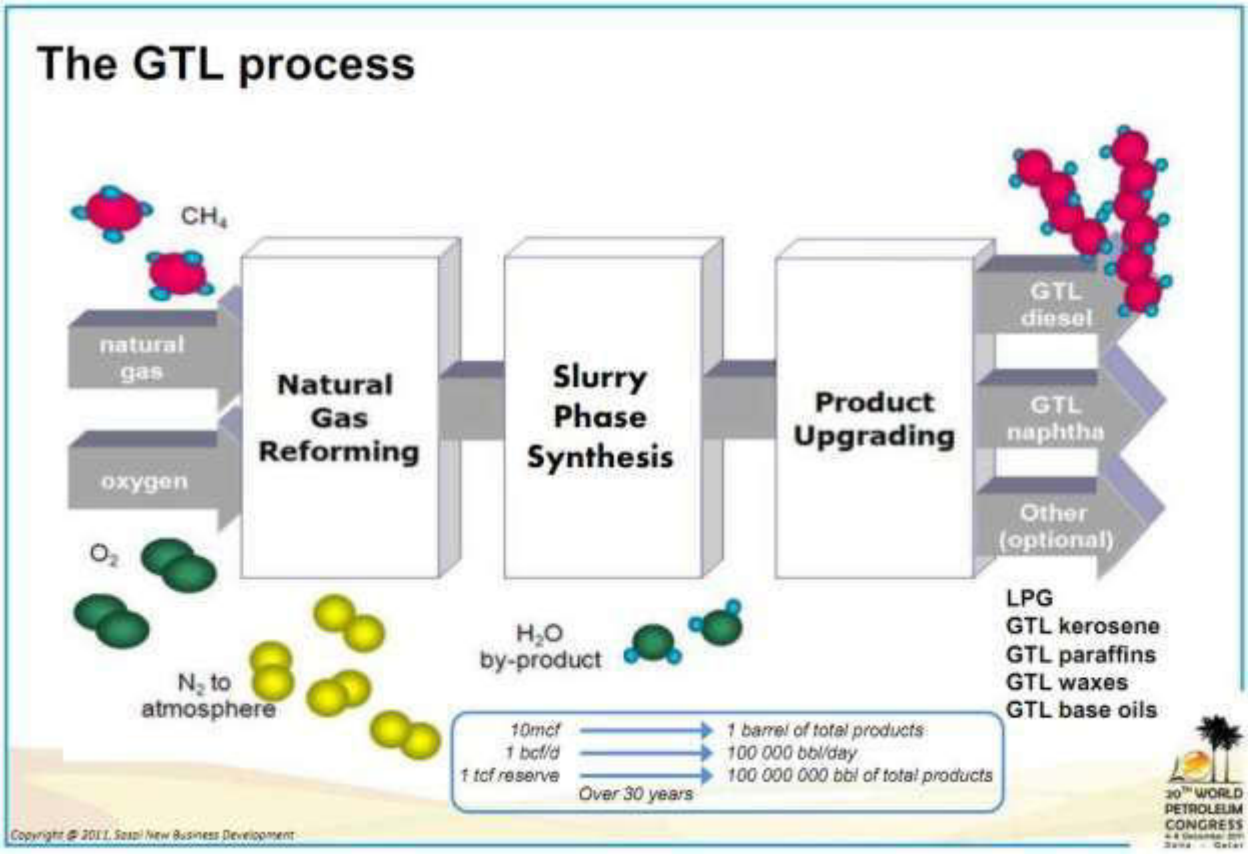
The Fischer-Tropsch process: liquid hydrocarbons from coal



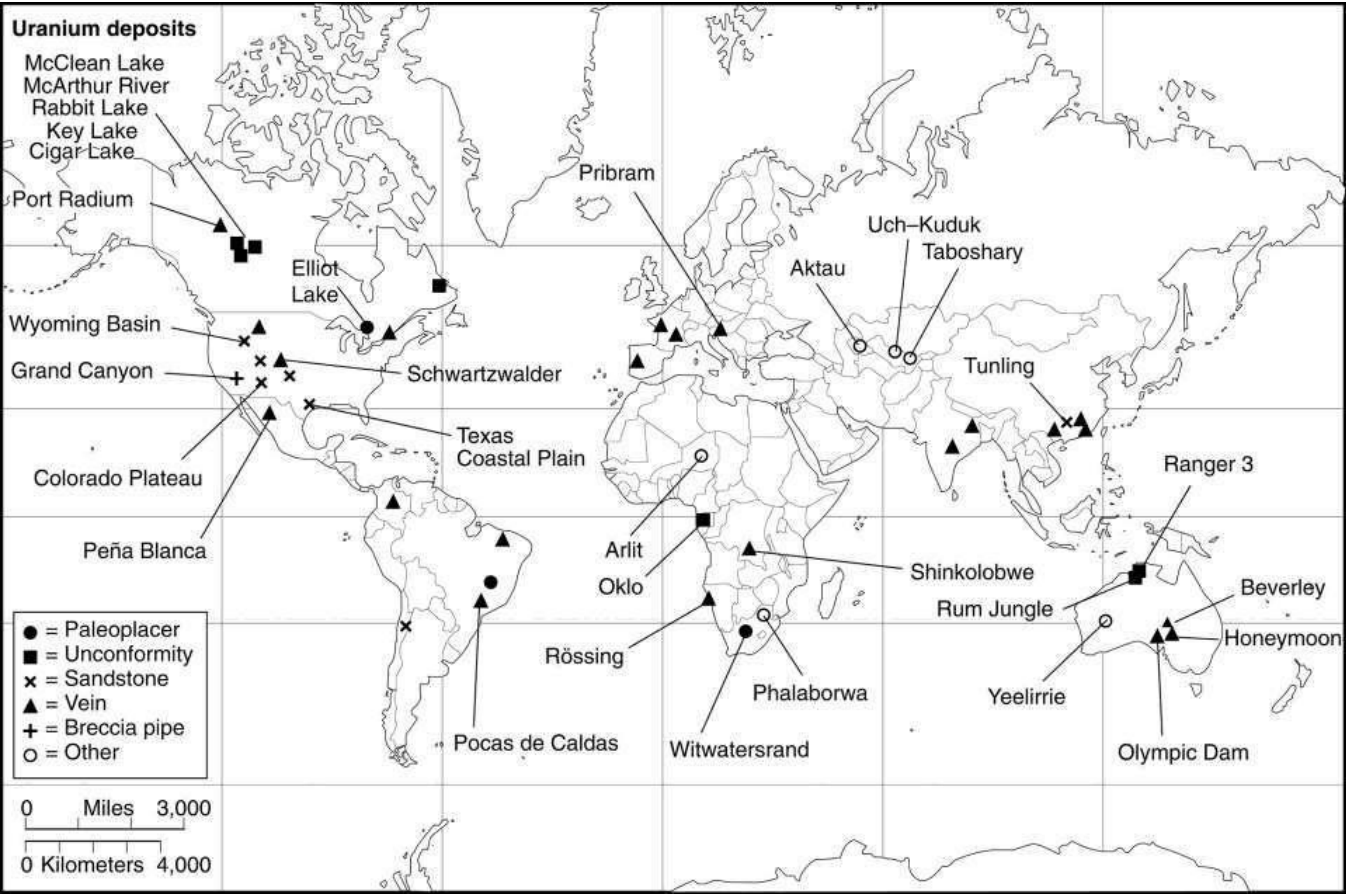
Fischer-Tropsch process

The GTL process: liquid hydrocarbons from methane

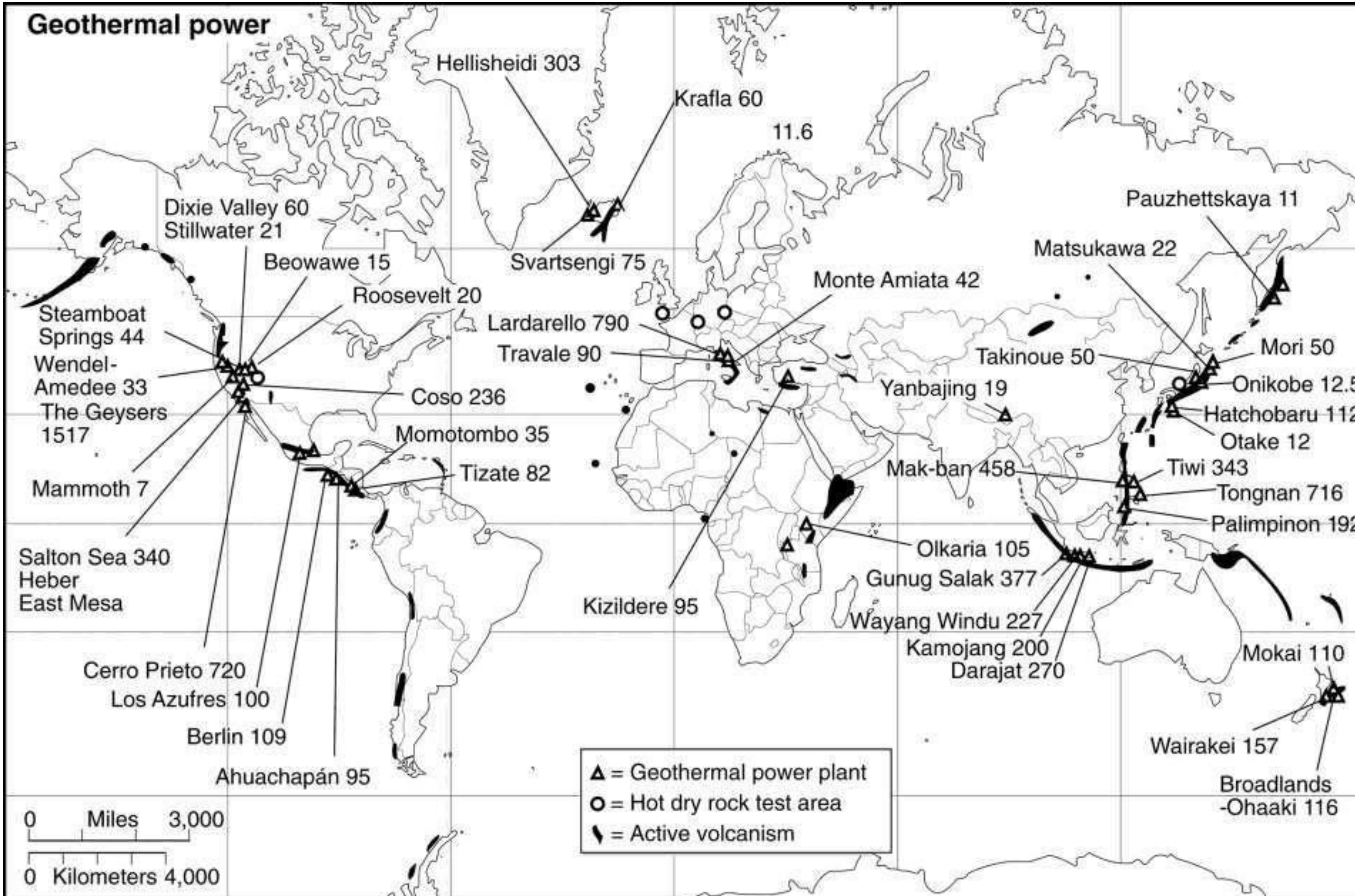




ENERGY MINERALS – uranium



ENERGY MINERALS – geothermal power

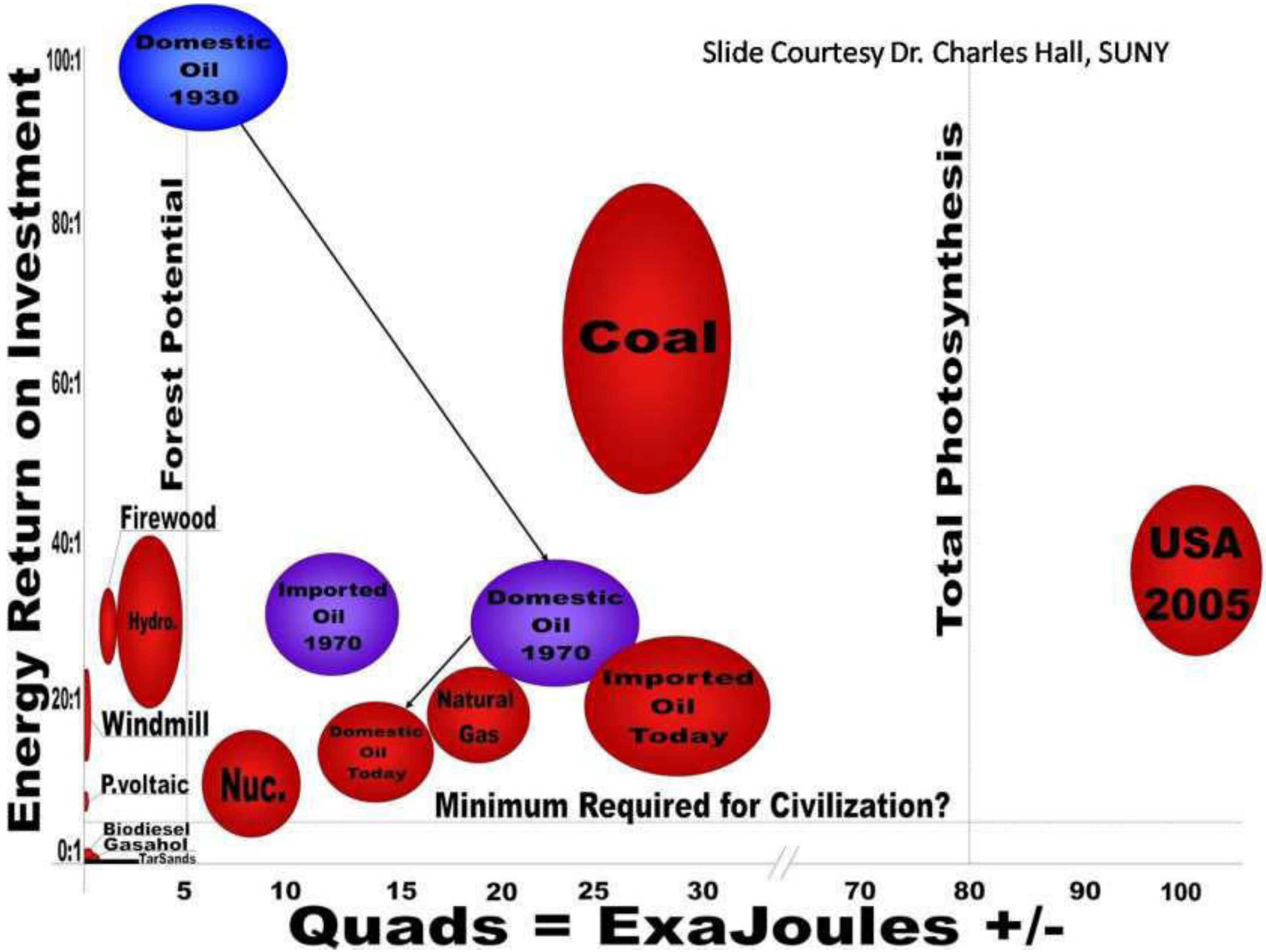


EROEI

BOX 7.6 | HOW MUCH ENERGY DOES IT TAKE TO PRODUCE ENERGY?

All of the energy resources used by society require energy to produce, and this is energy that is not available to the consumer. This includes not only energy used to produce oil, natural gas, corn-ethanol, but also energy to mine copper and rare-earth metals for turbines to produce electricity. The concept of "energy return on energy invested" (EROEI) compares the amount of energy necessary to extract a particular energy resource to the amount of energy actually available to society (Inman, 2013). For liquid fuels, gasoline refined from crude oil pumped from conventional reservoirs such as those in the Middle East returns 16 units of energy for every 1 unit required to produce the gasoline. Ethanol from sugarcane returns 9 units, soy biodiesel returns 5.5, oil from the Alberta tar sands returns 5 units, heavy oil from California returns 4, and ethanol from corn returns only 1.4. To understand the "at-the-pump" energy available to consumers from each of these resources, the distance driven by a car can be calculated for each fuel by multiplying the fuel economy of a car (miles per gallon) and the EROEI for each fuel, and then dividing this by the energy density of each fuel, expressed in gigajoules per gallon (Inman, 2013). Assuming 1 gigajoule of energy invested in the production of each fuel, a car can drive 3,600 miles using gasoline from conventional oil; 2,000 miles using ethanol from sugar cane; 1,400 miles using biodiesel from soy; 1,100 miles using gasoline from tar-sands oil; 900 miles using gasoline from heavy oil; and 300 miles using ethanol from corn. The same EROEI concept applied to electricity indicates that hydroelectric returns 40 units of energy for each unit invested, wind returns 20 units, coal 18 units, natural gas 7 units, photovoltaic solar 6 units, and nuclear 5 units.

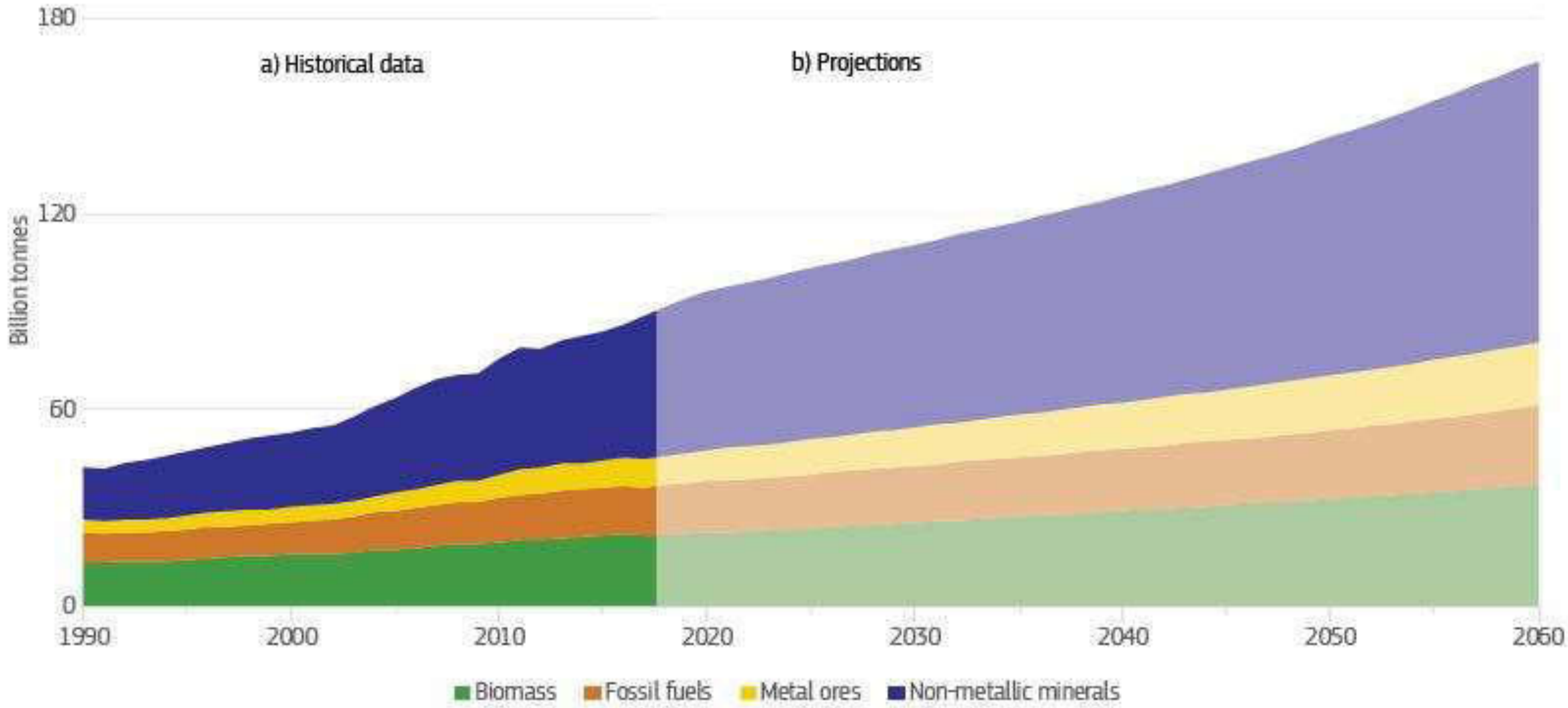
EROEI



Slide Courtesy Dr. Charles Hall, SUNY
Energy Return on Investment
100:1
80:1
60:1
40:1
20:1
0:1
Domestic Oil 1930
Forest Potential
Coal
Total Photosynthesis
USA 2005
Firewood
Hydro.
Imported Oil 1970
Domestic Oil 1970
Imported Oil Today
Natural Gas
Domestic Oil Today
Windmill
Nuc.
P.voltaic
Biodiesel
Gasahol
TarSands
Minimum Required for Civilization?
5
10
15
20
25
30
70
80
90
100
Quads = ExaJoules +/-

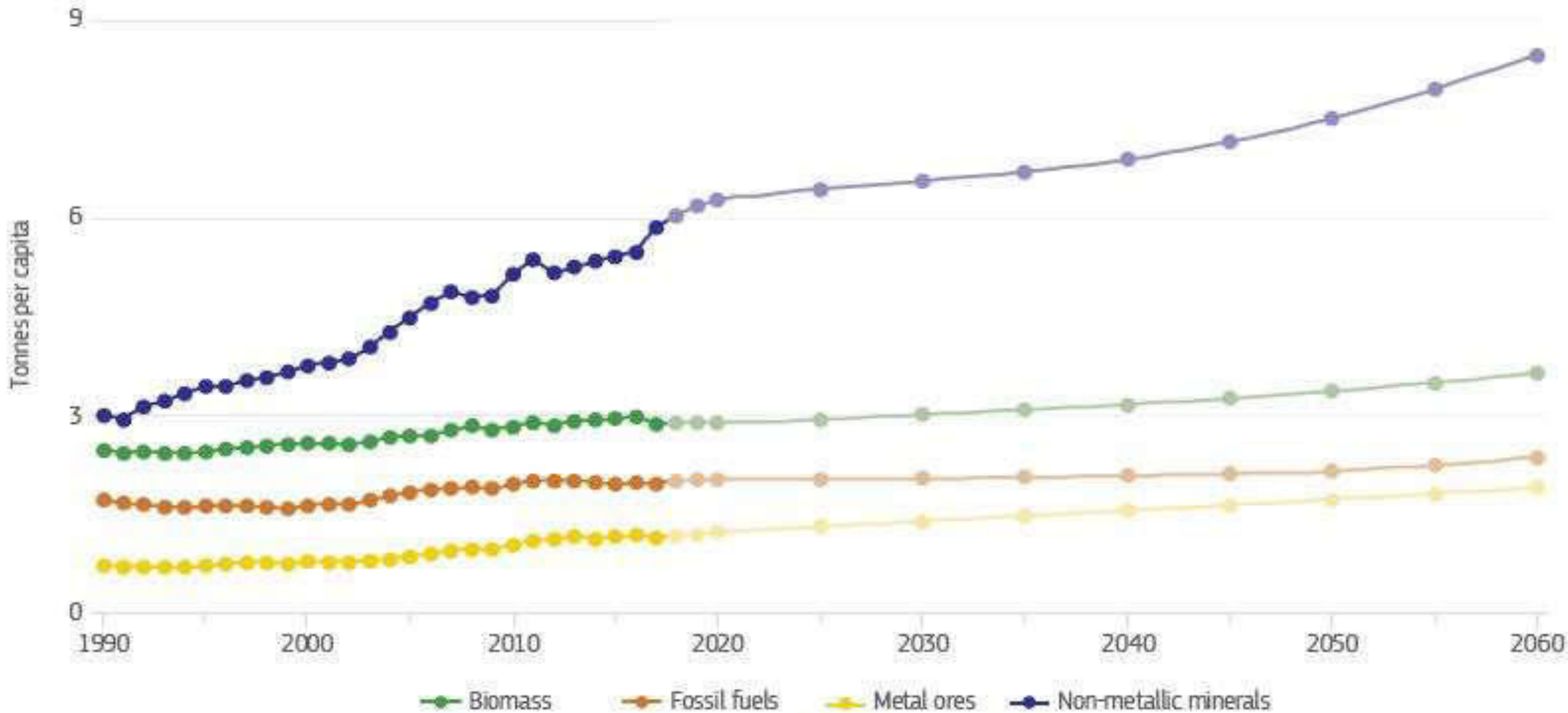
Global material use by resource type - projections

Figure 1: Global material use by resource type: a) historical data (world, 1990 - 2017) and b) projection (world, 2018 - 2060)[20]



Global material per capita use by resource type - projections

Figure 2: Global material use per capita by resource type: a) historical data (world, 1990-2017) and b) projection (world, 2018-2060)[21]



…green economy…

…eco-friendly…

…zero impact…

…circular economy…

…sustainability…

…green new deal…

+

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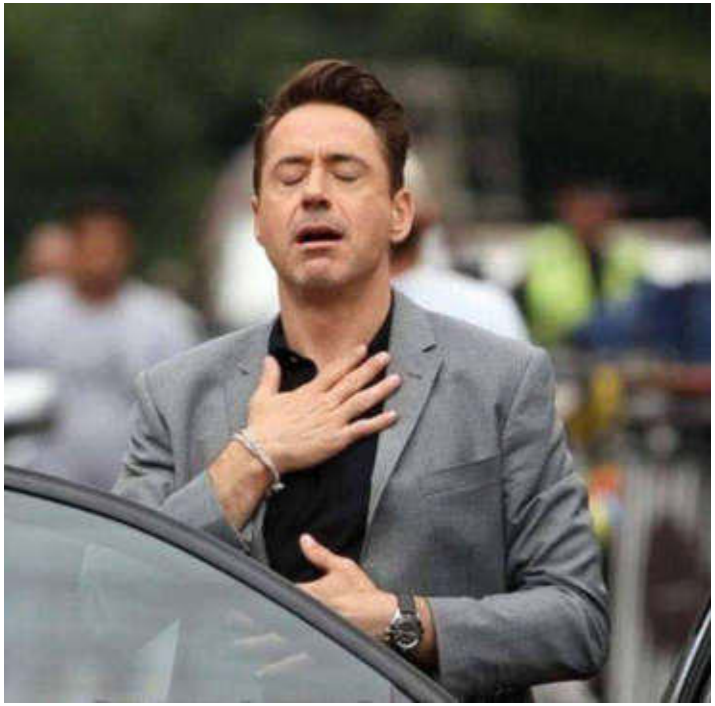
Green or greenwashing?



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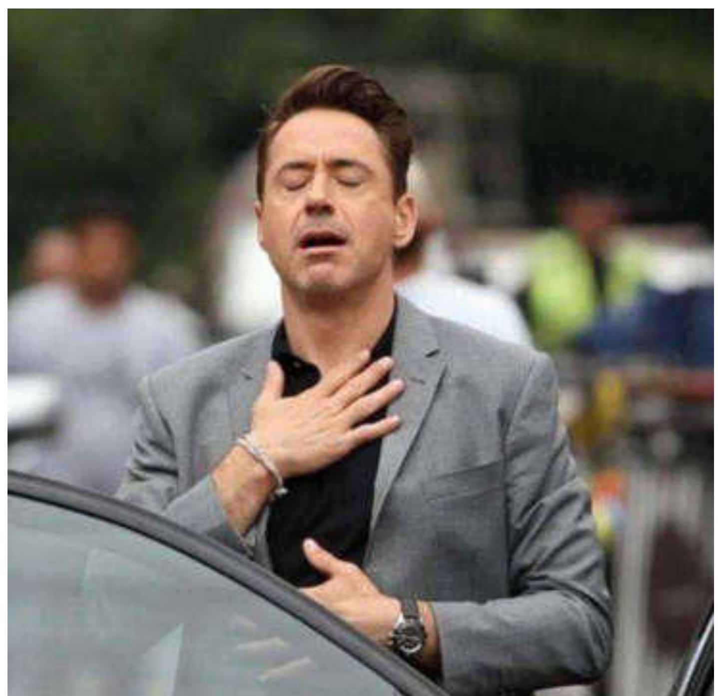
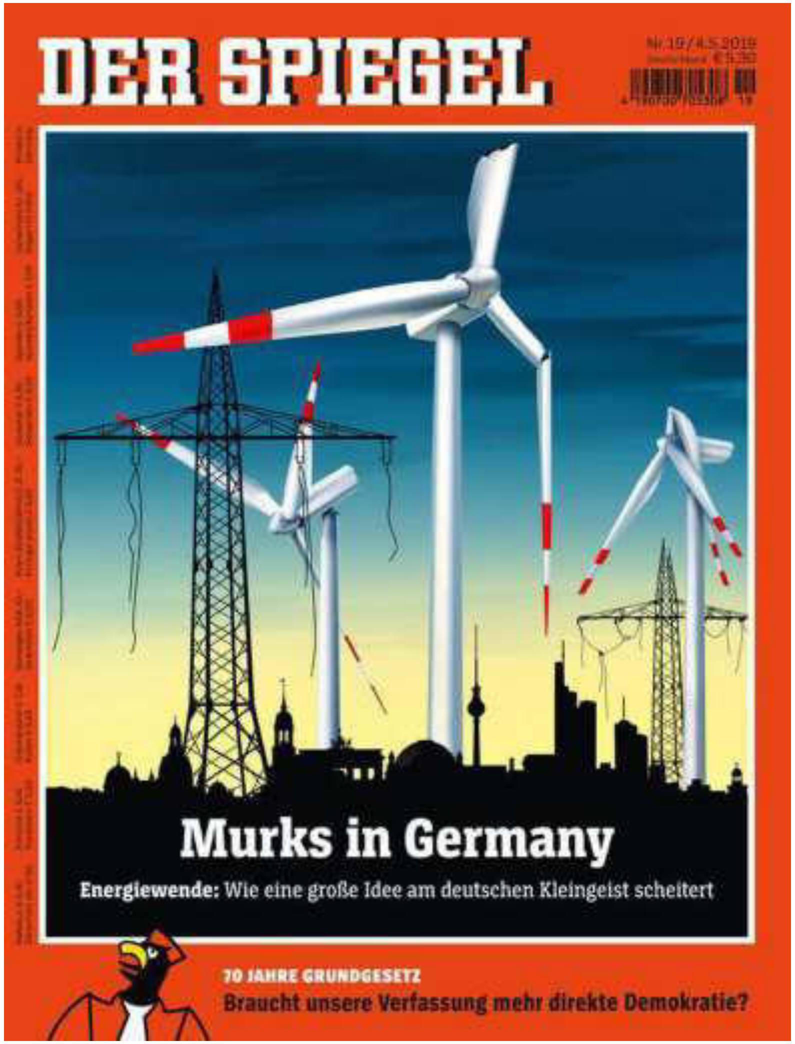
Green or greenwashing?

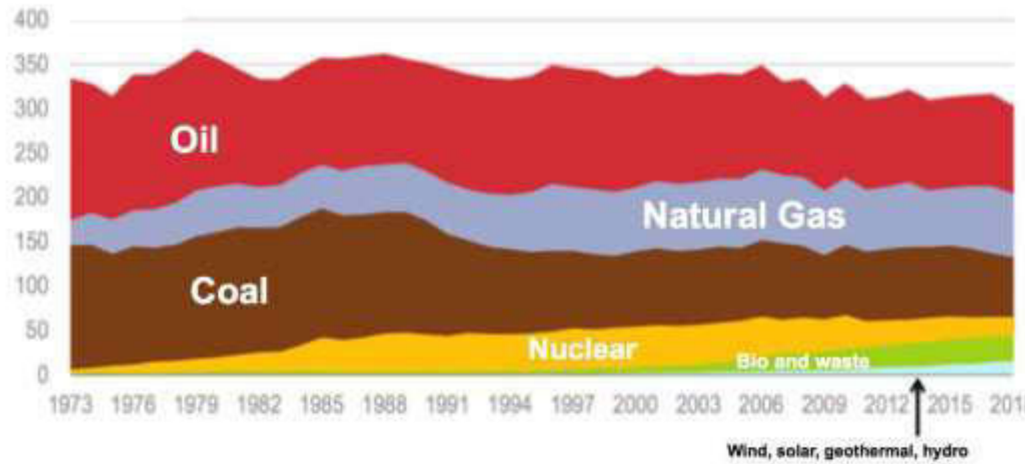


Wind + solar + electric cars = universal panacea?



Despite Spending Hundreds of Billions on Renewables, Wind and Solar Barely Register, and Germany is Still Overwhelmingly Fossil-Fuel Based

Total Primary Energy Supply: Million Tonnes of Oil Equivalent



Wind and PV:

- **Discontinuous production**
- **Need for storage**
- **Need for complex grids**
- **Short lifetime**

Population, economy & environment: limits of growth

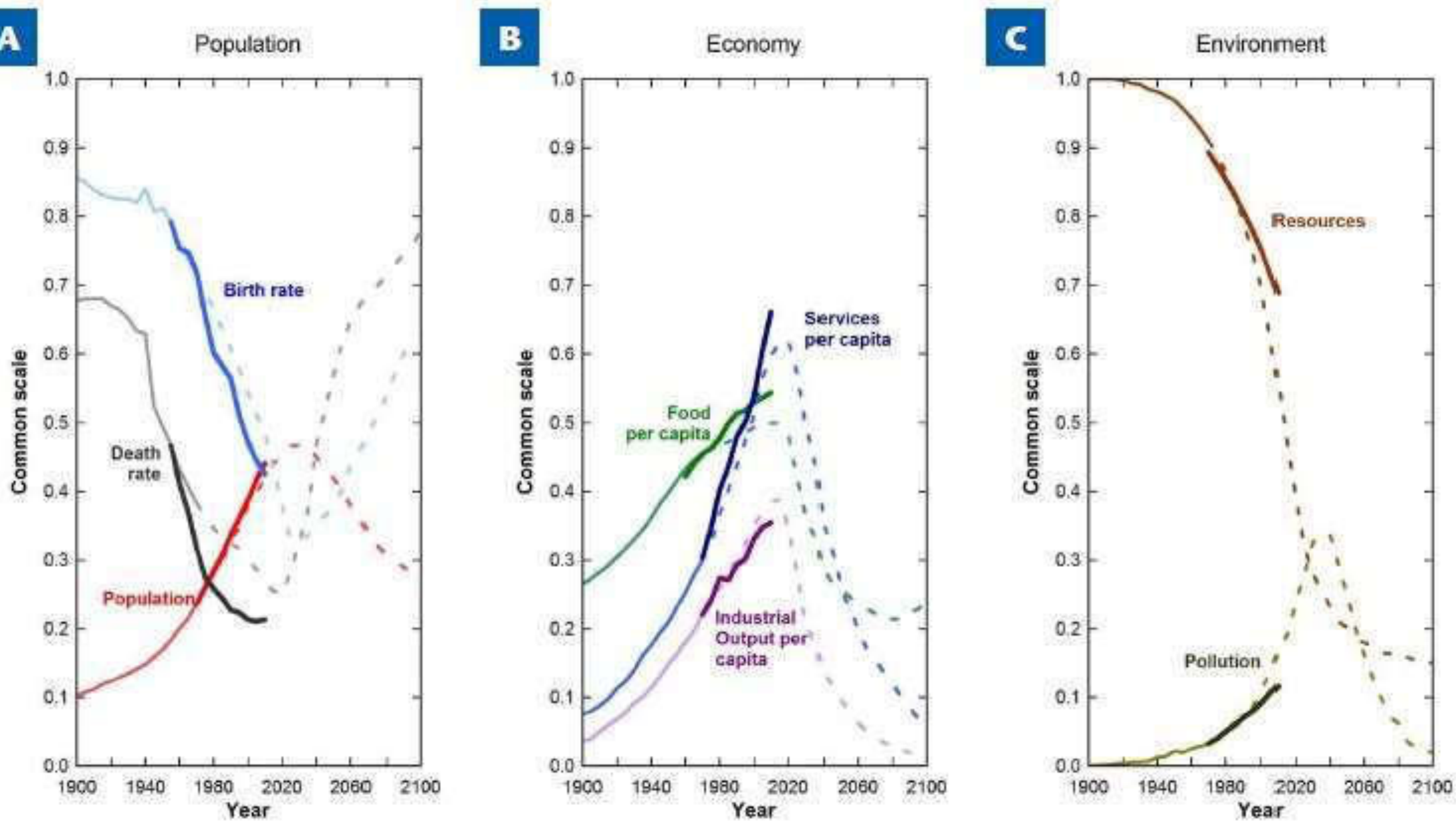


FIGURE 1 Projections of the standard model in *The Limits to Growth* (dashed lines) compared to pre-1970 data (light solid lines) and updated results (bold solid lines; Turner 2014). Shown are the projections out to 2100 for (**A**) population, (**B**) economy, and (**C**) natural resources. FIGURES FROM TURNER AND ALEXANDER (2014), COURTESY OF *THE GUARDIAN* UK

Global material extraction

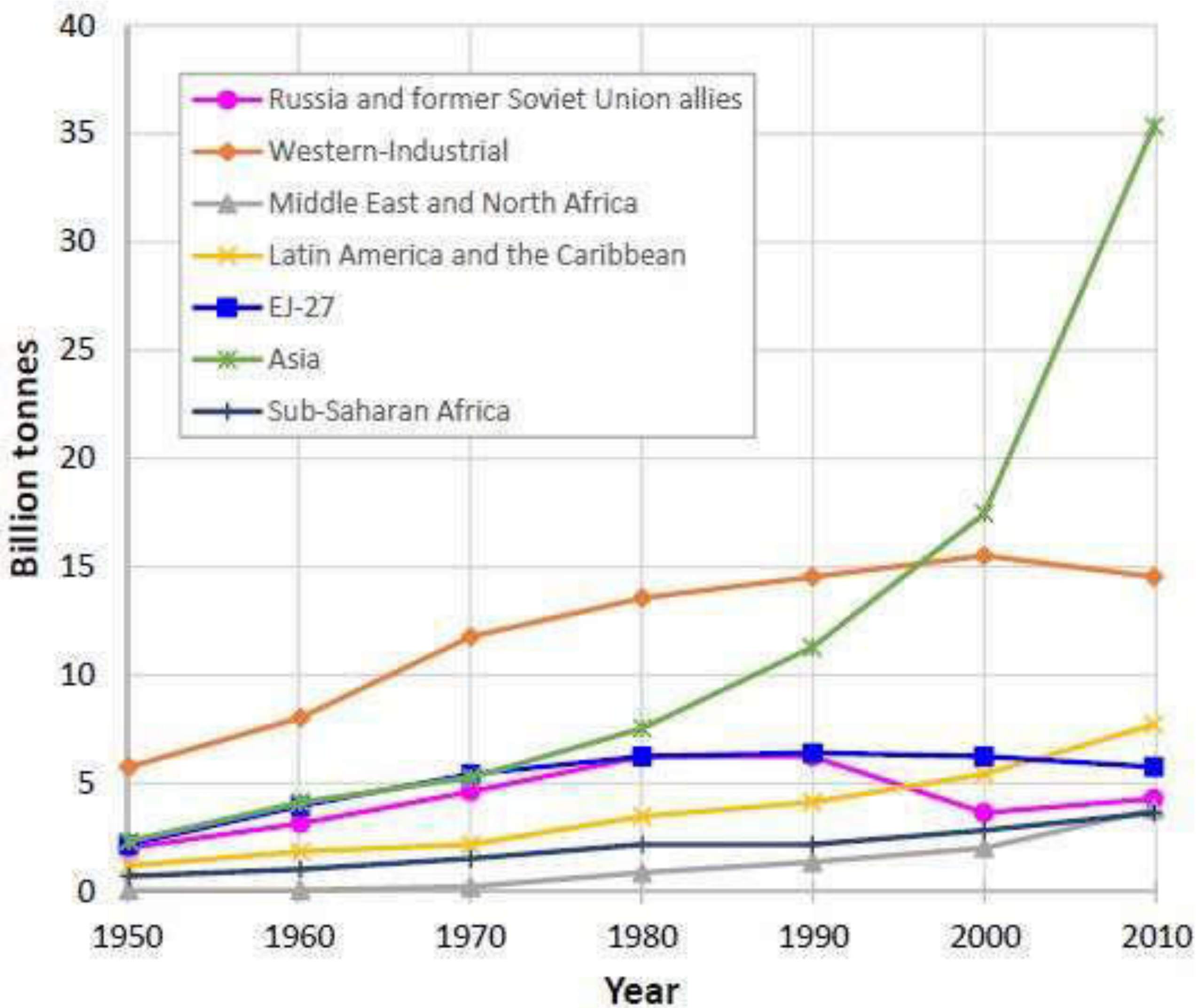
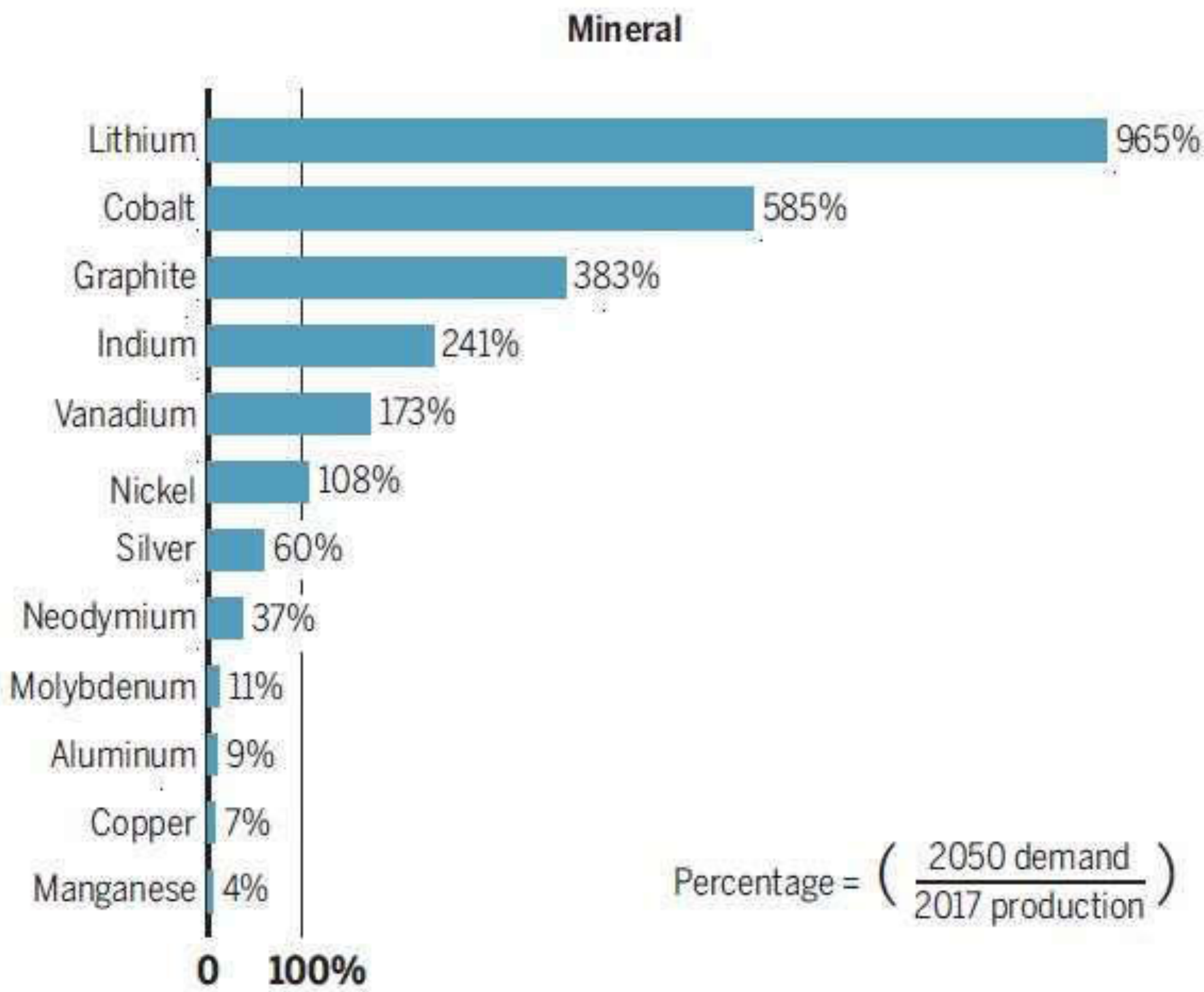


FIGURE 1 Global material extraction by resource type (1950–2010). REPRODUCED WITH PERMISSION FROM EUROPEAN COMMISSION (2016).

Growth in mineral needs for low-carbon energy technology



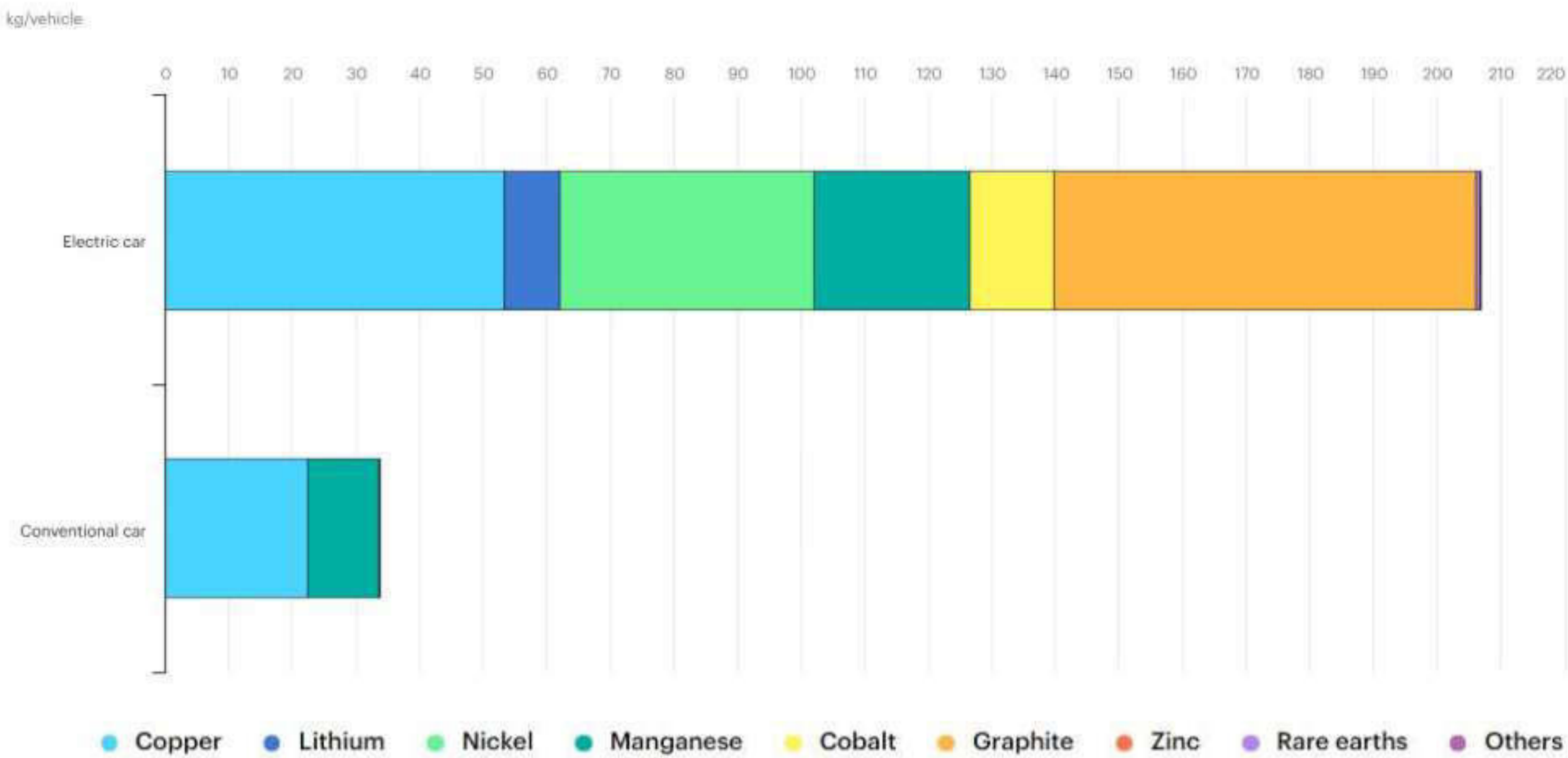
$$\text{Percentage} = \left(\frac{\text{2050 demand}}{\text{2017 production}} \right)$$

Mineral	Production (kilo–metric tons) 2017	Demand (kilo–metric tons) 2050
Lithium	43	415
Cobalt	110	644
Graphite	1200	4590
Indium	0.72	1.73
Vanadium	80	138
Nickel	2100	2268
Silver	25	15
Neodymium	23	8.4
Molybdenum	290	33
Aluminum	60,000	5583
Copper	19,700	1378
Manganese	16,000	694

EVs vs. conventional cars

Minerals used in electric cars compared to conventional cars

Last updated 26 Oct 2022



Raw materials for wind and solar energy

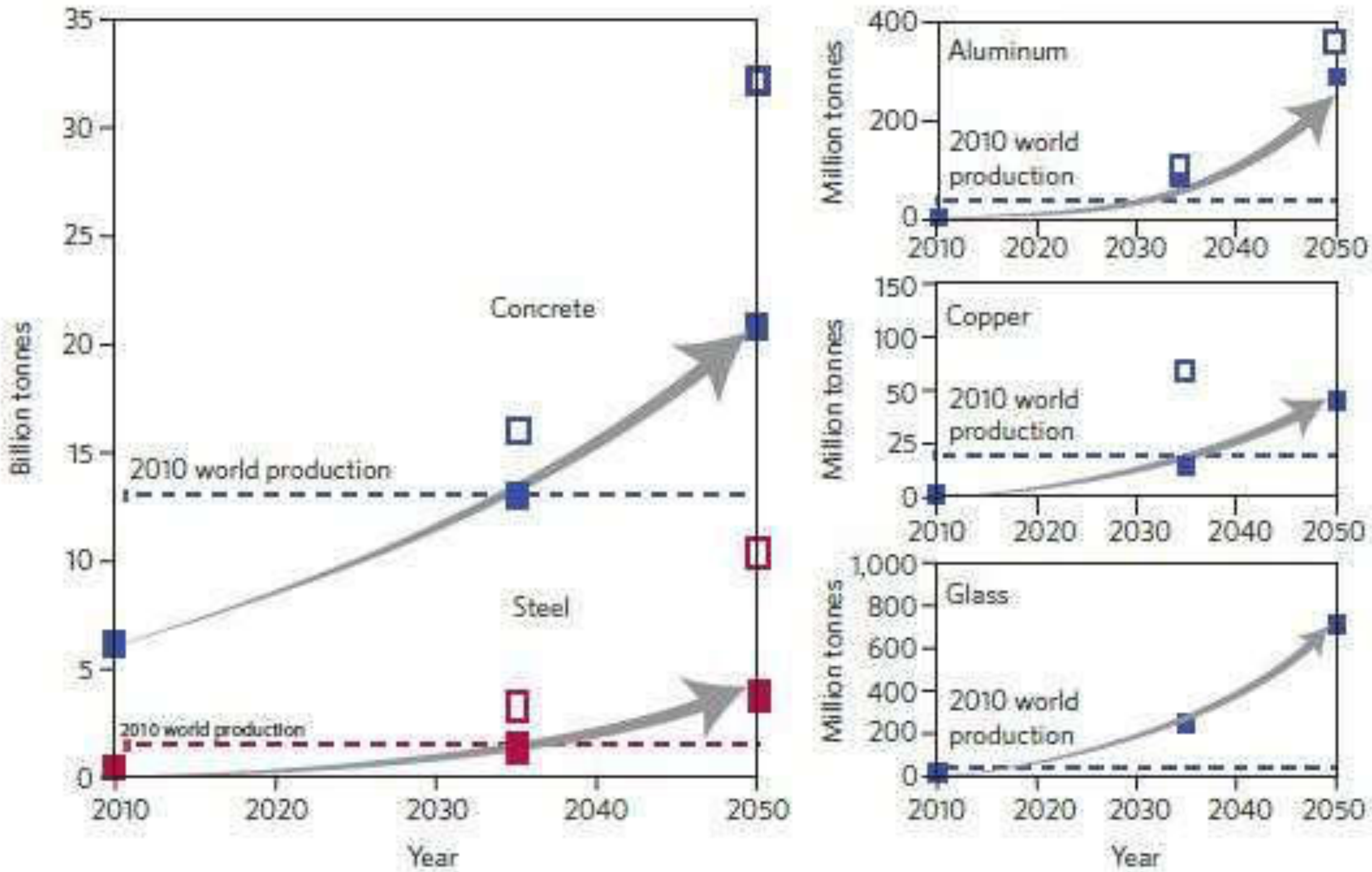
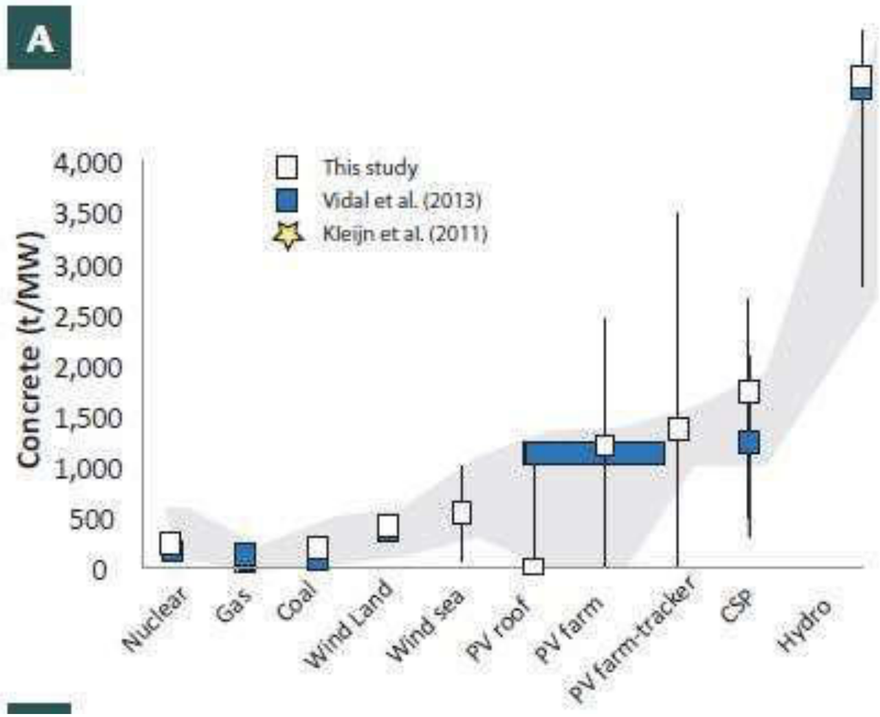
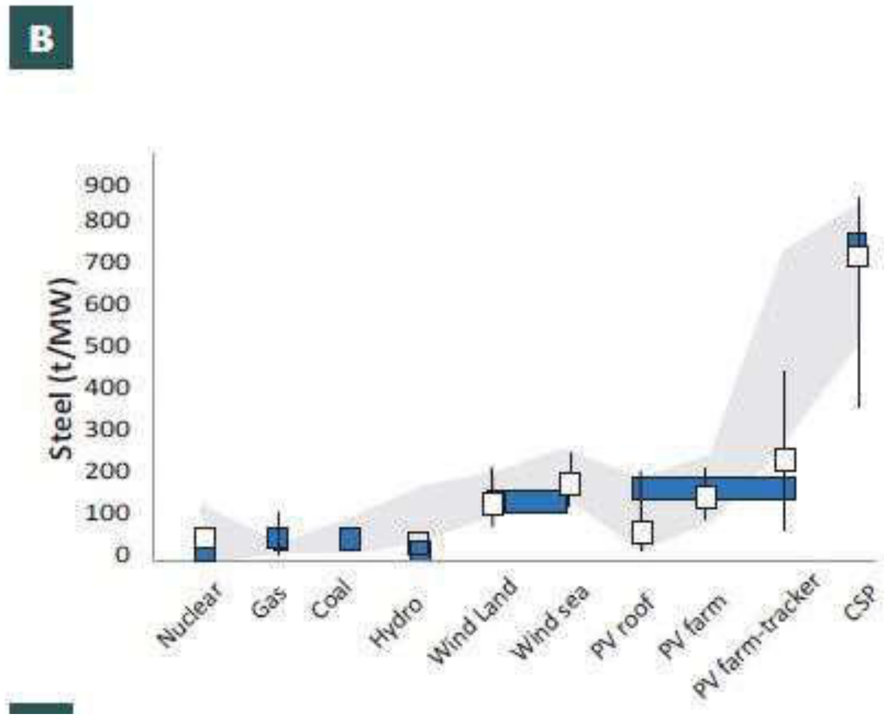


Figure 2 | Increasing global consumption of raw materials. The World Wide Fund for Nature (WWF) predicts that the contribution from wind and solar energy to global energy production will rise to 25,000 TWh in 2050[7]. To meet this demand, the global production of raw materials such as concrete, steel, aluminium, copper and glass will need to significantly increase. Open and filled symbols correspond to different volumes of raw material required to construct different types of photovoltaic panels (PV1 and PV2, respectively, in Supplementary Table 1).

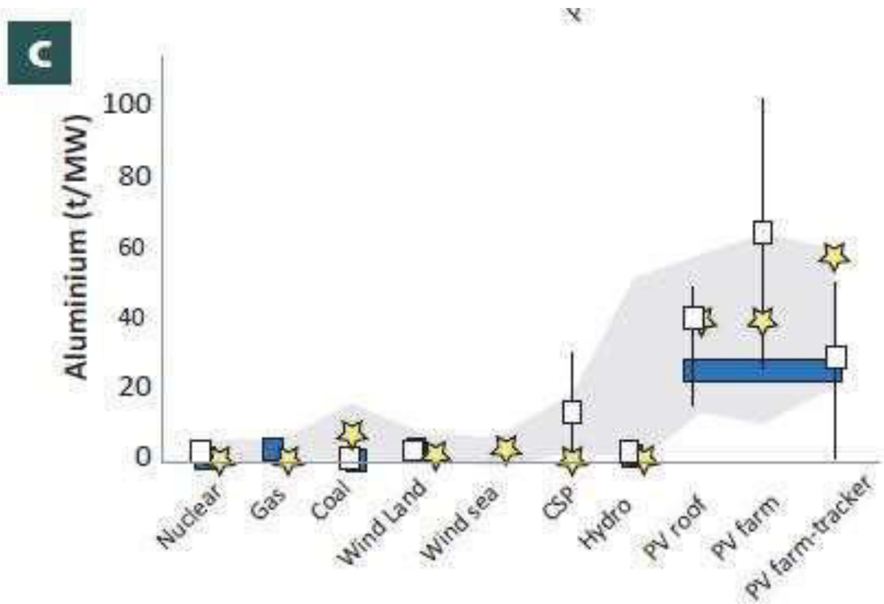
Concrete and steel for energy production

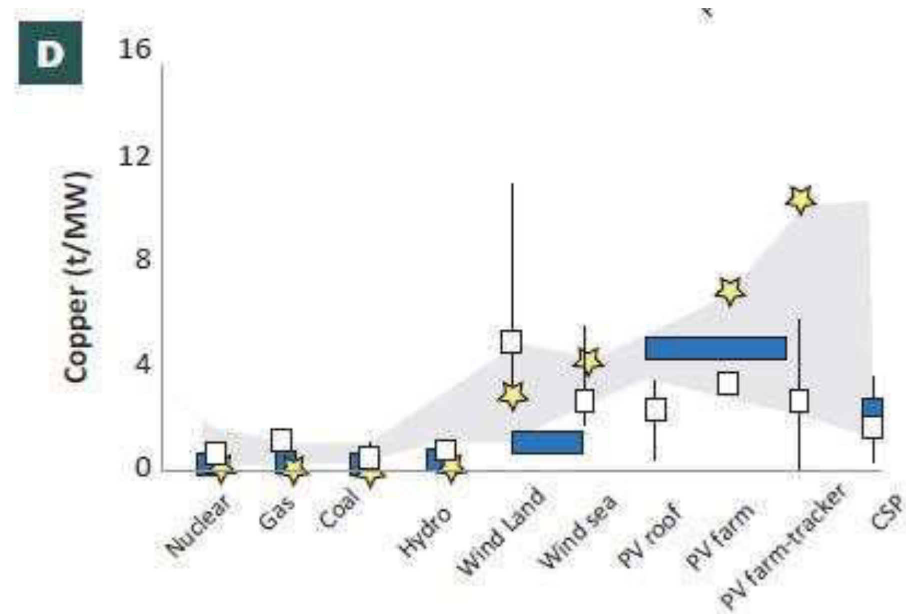




PV: photovoltaic cell
CSP: concentrated solar power

Aluminum and copper for energy production





PV: photovoltaic cell
CSP: concentrated solar power

Steel, aluminum & copper: mining & recycling

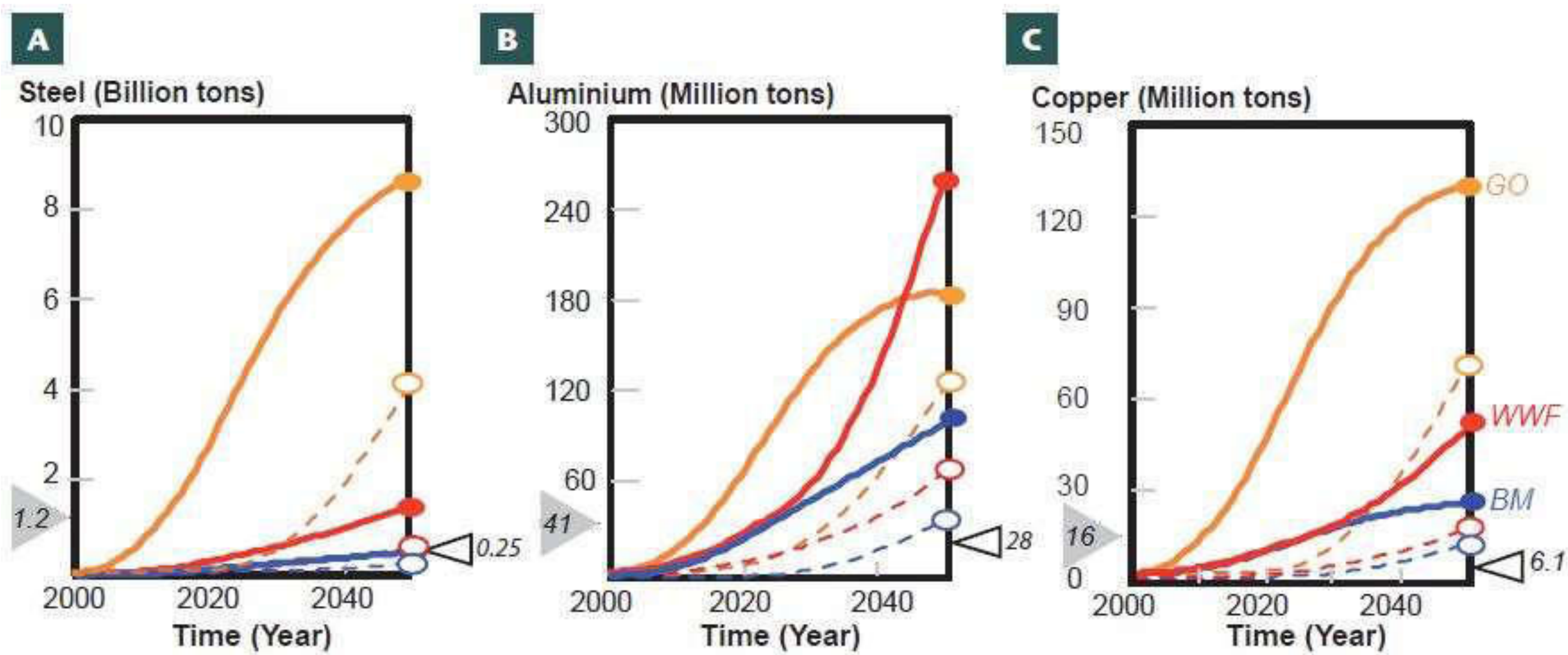
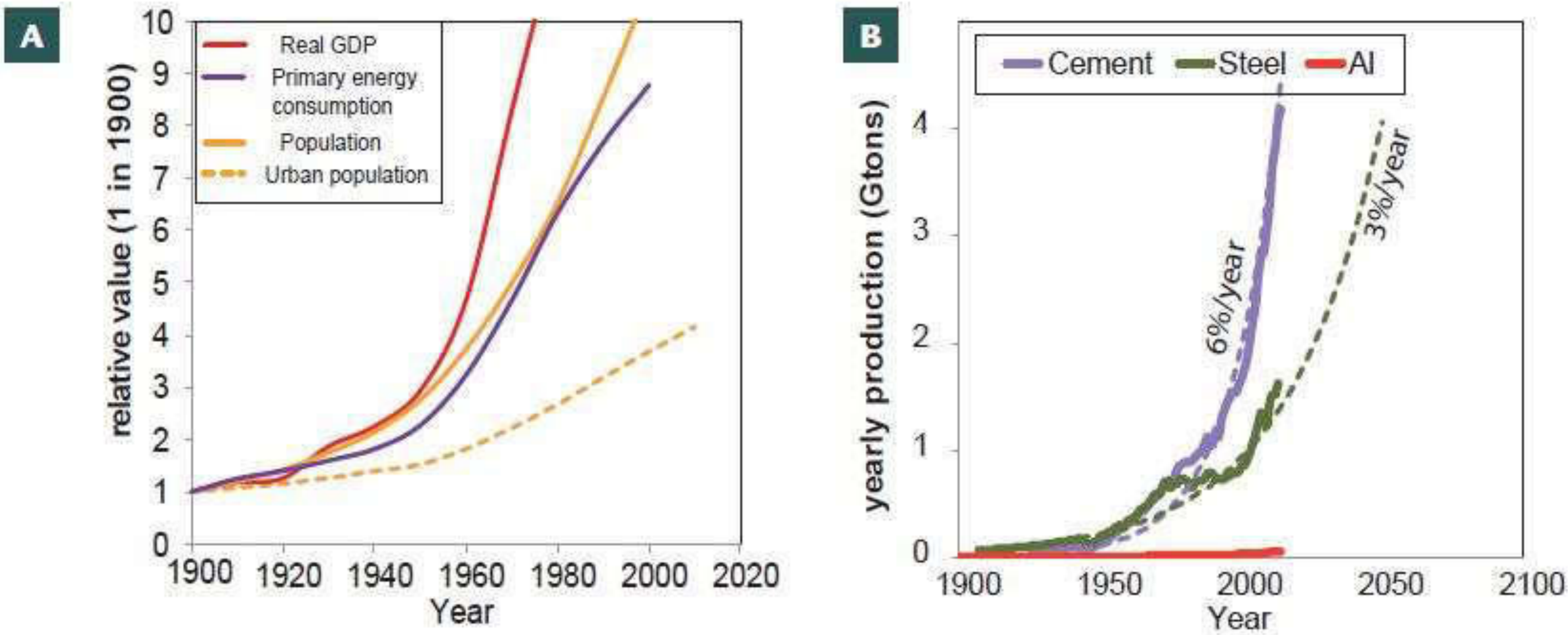


FIGURE 3 Cumulative amounts of three key metals that will be primary mined (continuous lines) and recycled (dashed lines), as projected between the years 2000 and 2050 and that are, or will be, used to build the infrastructure of energy generation: (**A**) steel, (**B**) aluminium, and (**C**) copper. Abbreviations refer to reference sources used: GO = Garcia-Olivares et al. (2012); BM = bluemap of IEA (2010); WWF = World Wildlife Fund and Ecofys of Deng et al. (2011). The grey-filled and open triangles show the 2010 global supply of primary and recycled metals, respectively.

Prosperity, cement, steel & aluminum



Price vs. dilution in ore deposits

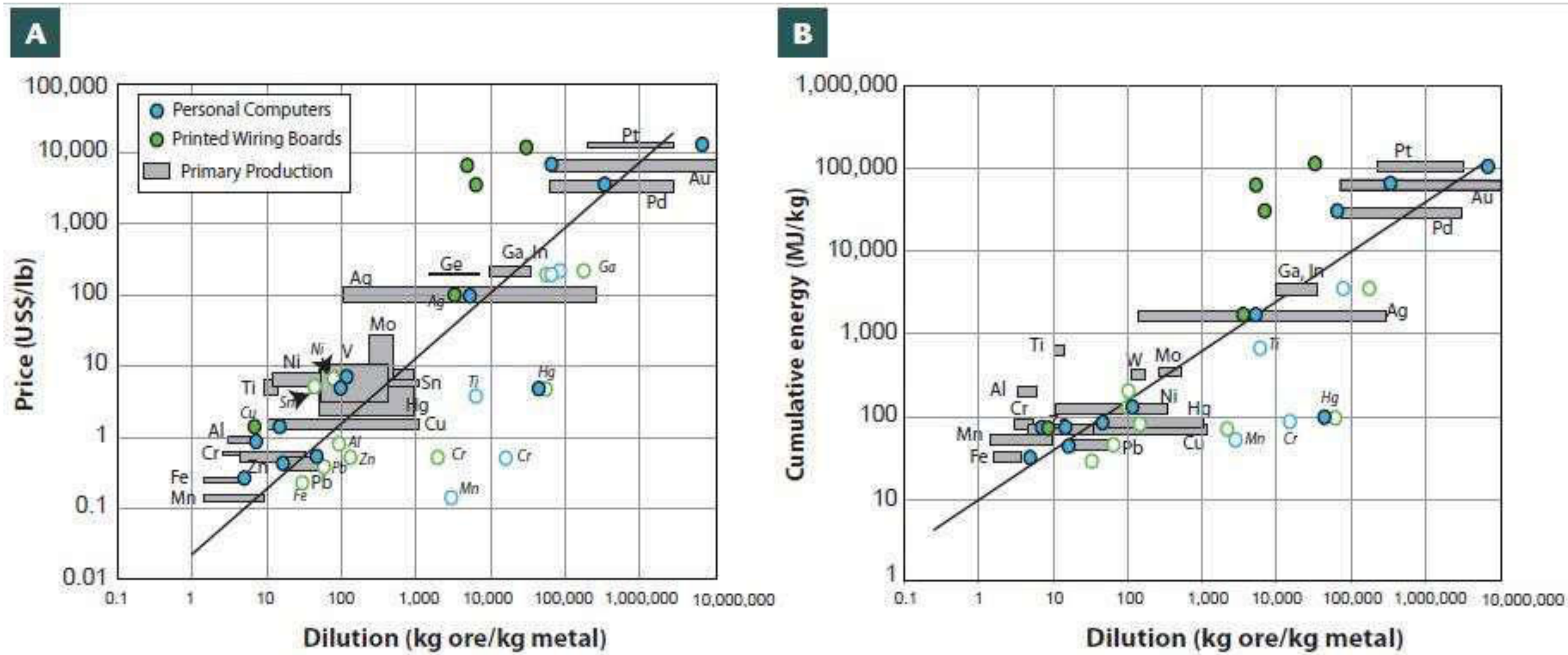


FIGURE 4 (**A**) Graph of price (in US$ per pound of metal) in terms of the dilution of that metal in its ore deposit (grey boxes) and that metal in personal computers (filled blue circles) and in printed circuit boards (filled green circles). Black line defines the average price vs dilution relationship obtained from primary metal production. Filled circles above this line are metals predominantly recycled; those metals below the black line (signified by empty circles) are too diluted compared to their concentration in ore deposits to be recycled at affordable price and energy cost. A noticeable exception of this trend is Hg, which is recycled for regulation reasons. (**B**) Graph of cumulative energy of metal production (E_{cum},) versus metal dilution in original ore body. Symbols as for 4A. DATA FROM PHILLIPS AND EDWARDS (1976), GUTOWSKI ET AL. (2013), AND KELLY ET AL. (2017).

CRITICAL RAW MATERIALS

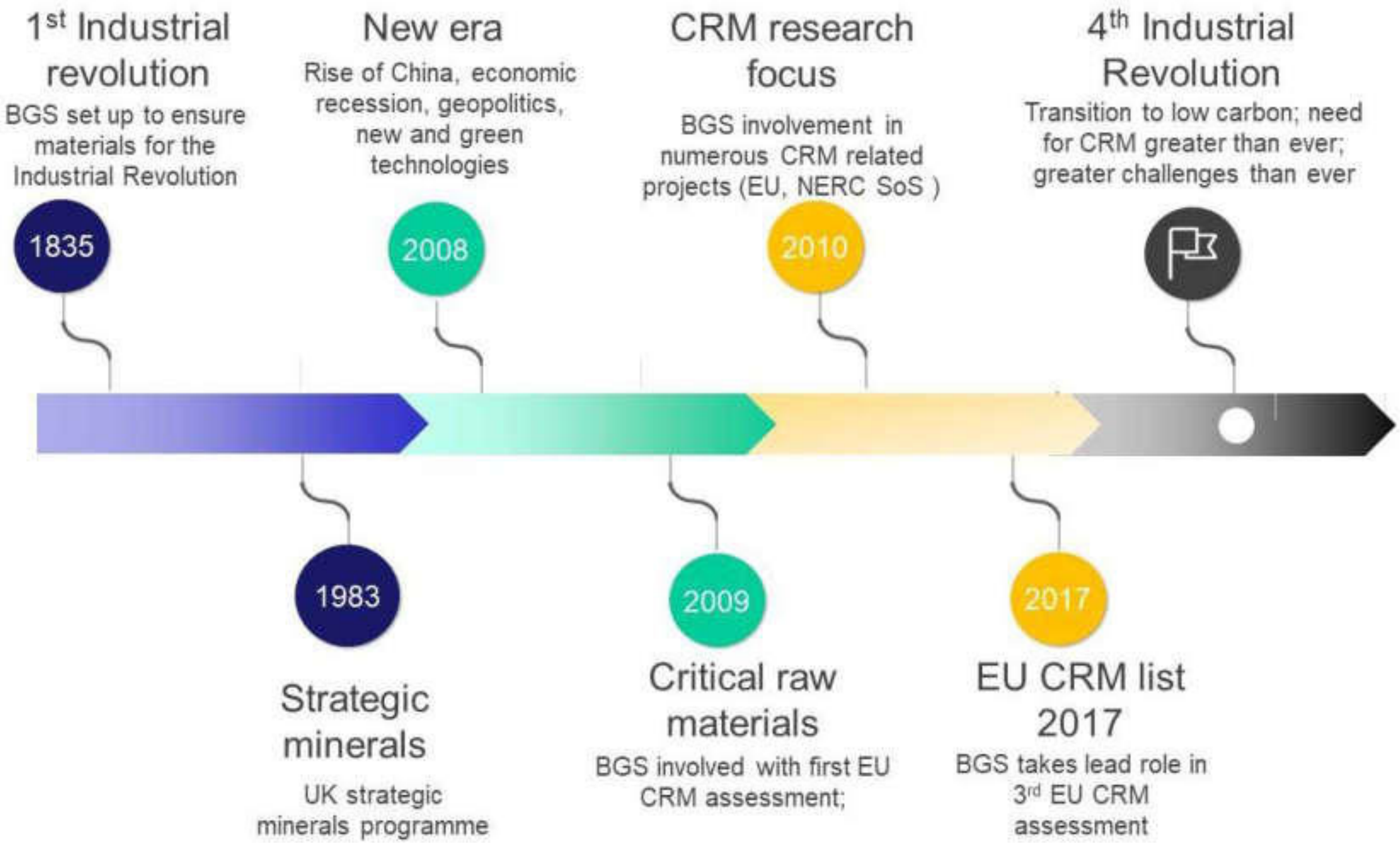
Critical raw materials

EU Supply	>20%	<20%	<10%	<3%	<1%
Non-Critical Raw Materials	Clays (& Kaolin) Diatomite Feldspar Hafnium Limestone Perlite Sawn Softwood Silica sand Tellurium	Bentonite Gypsum Potash Pulpwood Selenium Talc	Aluminium Copper Rhenium Silver Zinc	Barytes Bauxite Iron Ore Nickel	Gold Manganese Molybdenum Natural Rubber Scandium Tantalum Tin Titanium Vanadium
Critical Raw Materials		Gallium Magnesite	Silicon Metal Coking coal Fluorspar Germanium Indium	Chromium Lithium Tungsten	Antimony Beryllium Borate Cobalt Magnesium Natural Graphite Niobium PGMs Phosphate Rock REEs (Heavy) REEs (Light)

Critical raw materials for the EU

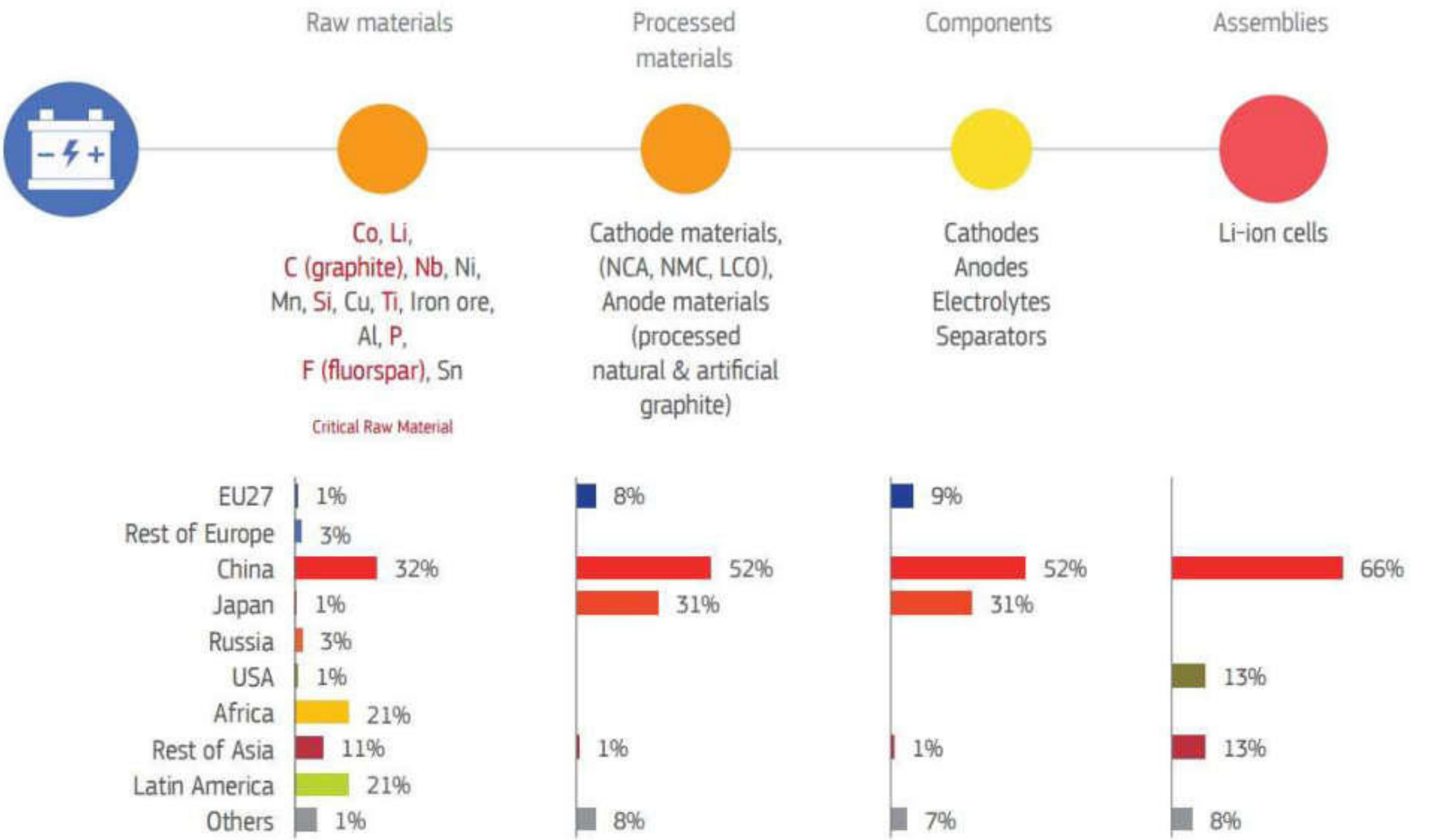
Industrial and construction minerals	Iron and ferro-alloy metals	Precious metals	Rare earths	Other non-ferrous metals	Bio and other materials
Aggregates	Chromium	Gold	Heavy rare earths	Aluminum	Natural cork
Baryte	Cobalt	Silver	Light rare earths	Antimony	Natural rubber
Bentonite	Manganese	Platinum Group Metals	Scandium	Arsenic	Natural teak wood
Borates	Molybdenum			Beryllium	Sapele wood
Diatomite	Nickel			Bismuth	Coking coal
Feldspar	Niobium			Cadmium	Hydrogen
Fluorspar	Tantalum			Copper	Helium
Gypsum	Titanium			Gallium	
Kaolin clay	Tungsten			Germanium	
Limestone	Vanadium			Hafnium	
Magnesite				Indium	
Natural graphite				Lead	
Perlite				Lithium	
Phosphate rock				Magnesium	
Phosphorus				Rhenium	
Potash				Selenium	
Silica sand				Silicon metal	
Sulphur				Strontium	
Talc				Tellurium	
				Tin	
				Zinc	
				Zirconium	

Raw materials and challenges of the future



Raw materials and challenges of the future

Figure 8. Li-ion batteries: an overview of supply risks, bottlenecks and key players along the supply chain. (See the Glossary for the acronyms used)



European Critical Raw Materials Act (16 marzo 2023)

European Critical Raw Materials Act (16 marzo 2023)

European Critical Raw Materials Act (16 marzo 2023)

Lithium

- **Net-zero use includes:**
  electrical vehicles
- **Projected increase in global demand:**
  x57 in 2050
- **Foreseen EU trade action:**
  - Special focus on raw materials in trade agreements in Latin America
  - Strategic raw materials partnerships with countries with important reserves

*Source: JRC Science for Policy Report Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study

European Critical Raw Materials Act (16 marzo 2023)

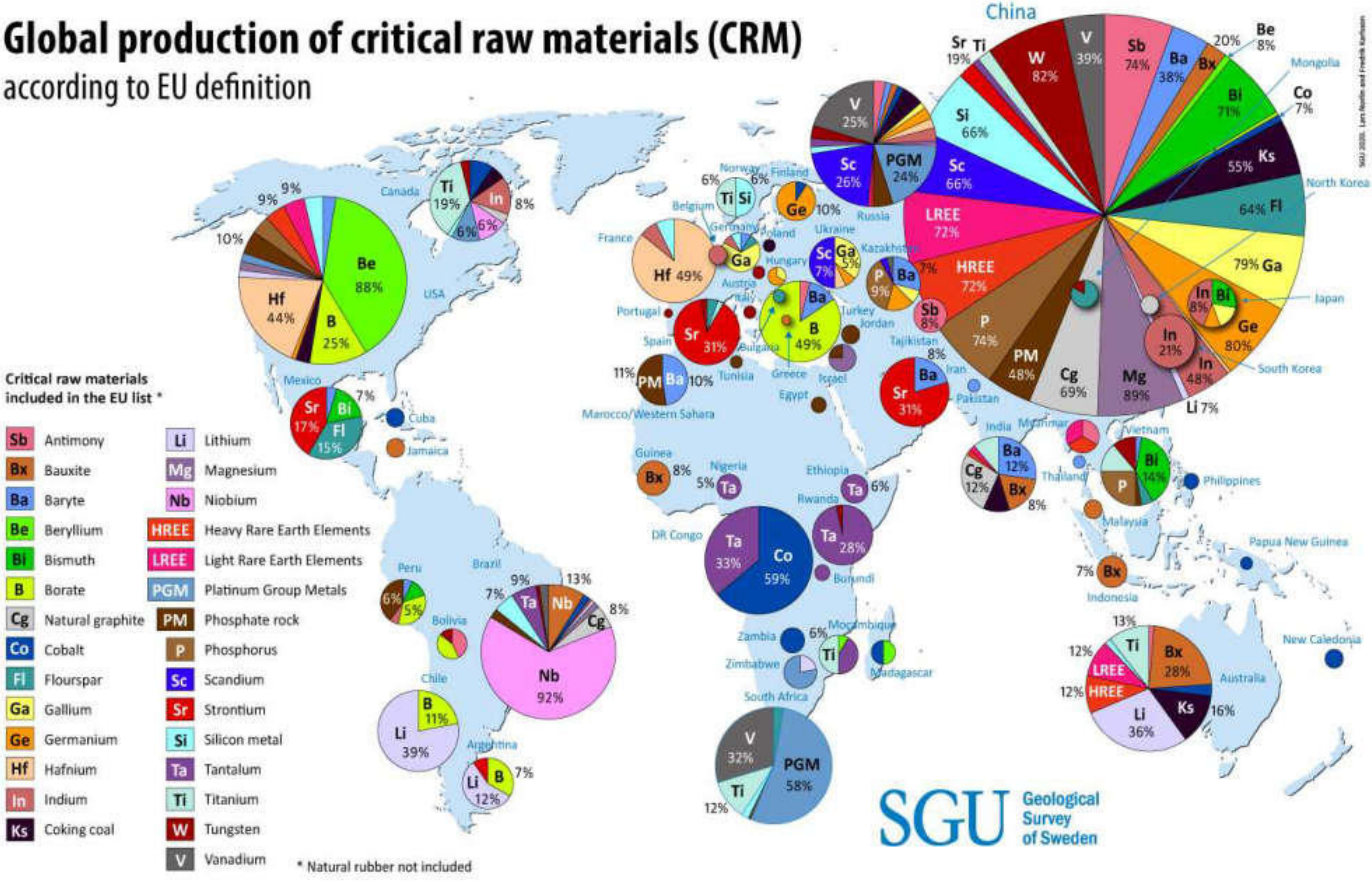
European Critical Raw Materials Act (16 marzo 2023)

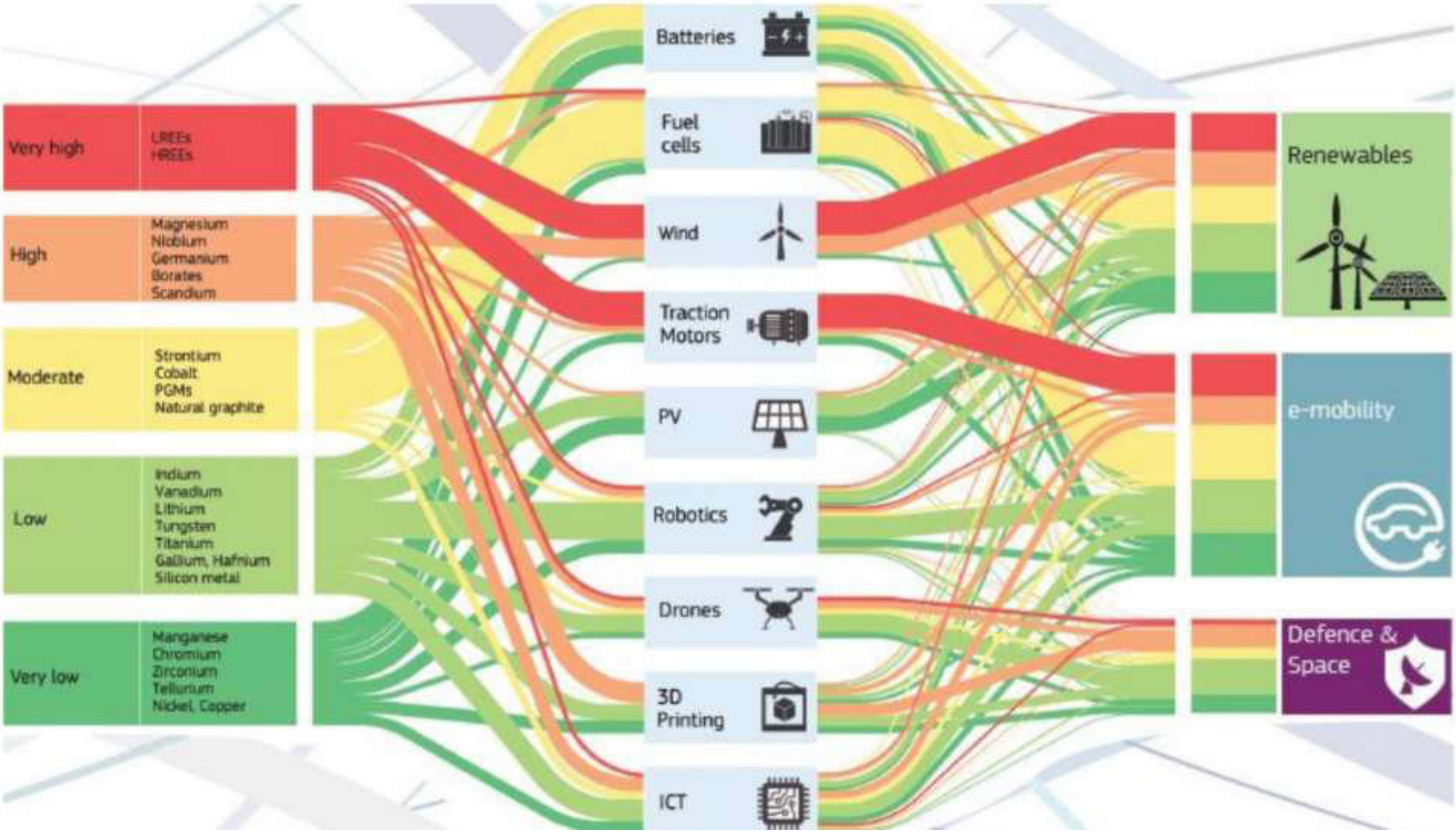
Platinum Group Metals

- **Net-zero use includes:** hydrogen fuel cells
- **Projected increase in global demand:** x970 in 2050
- **Foreseen EU trade action:**
  - Work with South Africa for more predictable legal environment for trade and investment
  - Strategic raw materials partnership with countries with important reserves
  - Support investments in South African energy infrastructure

Global production of critical raw materials (CRM)

according to EU definition

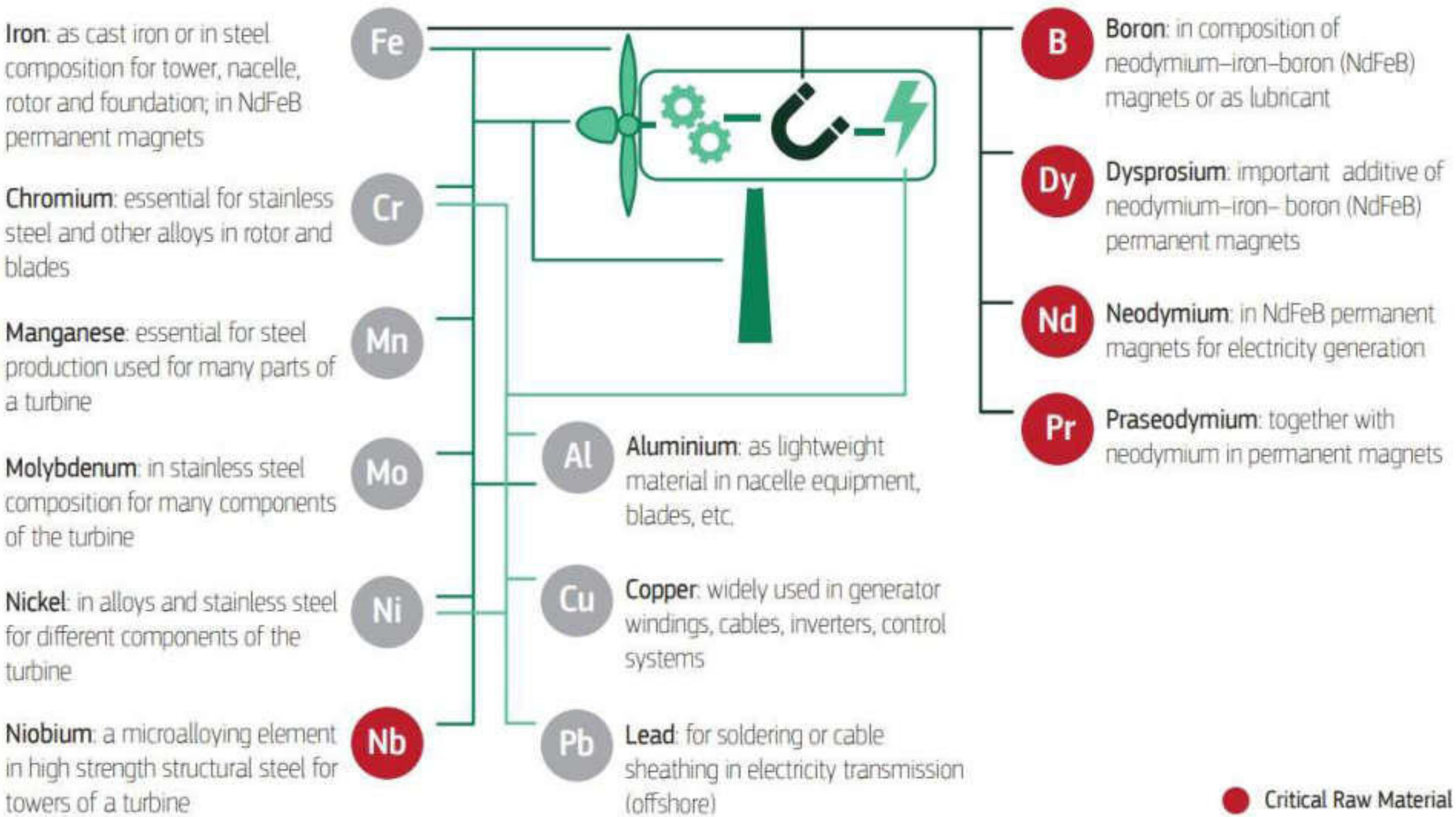




Very high
LREEs
HREEs
High
Magnesium
Niobium
Germanium
Borates
Scandium
Moderate
Strontium
Cobalt
PGMs
Natural graphite
Low
Indium
Vanadium
Lithium
Tungsten
Titanium
Gallium, Hafnium
Silicon metal
Very low
Manganese
Chromium
Zirconium
Tellurium
Nickel, Copper
Batteries
Fuel cells
Wind
Traction Motors
PV
Robotics
Drones
3D Printing
ICT
Renewables
e-mobility
Defence & Space

Critical metals – wind turbines

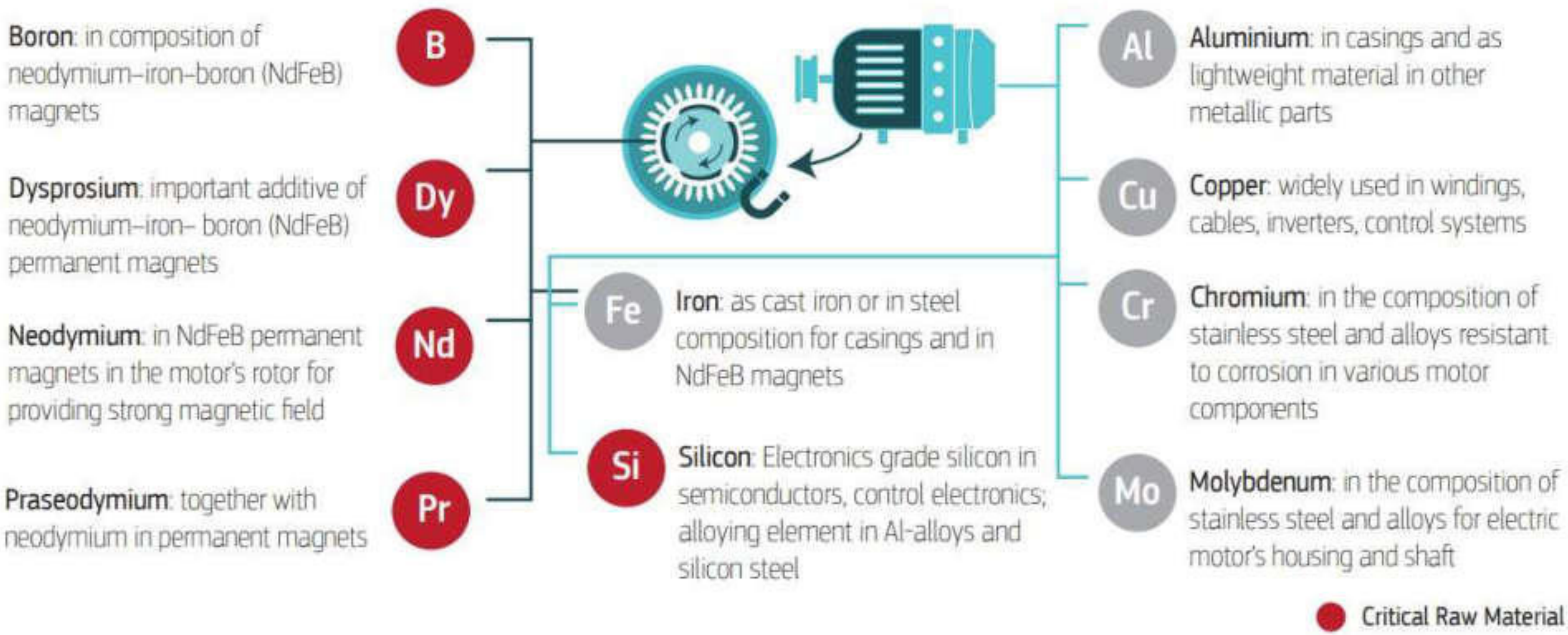
Figure 18. Raw materials used in wind turbines



Critical metals – traction motors (permament magnets)

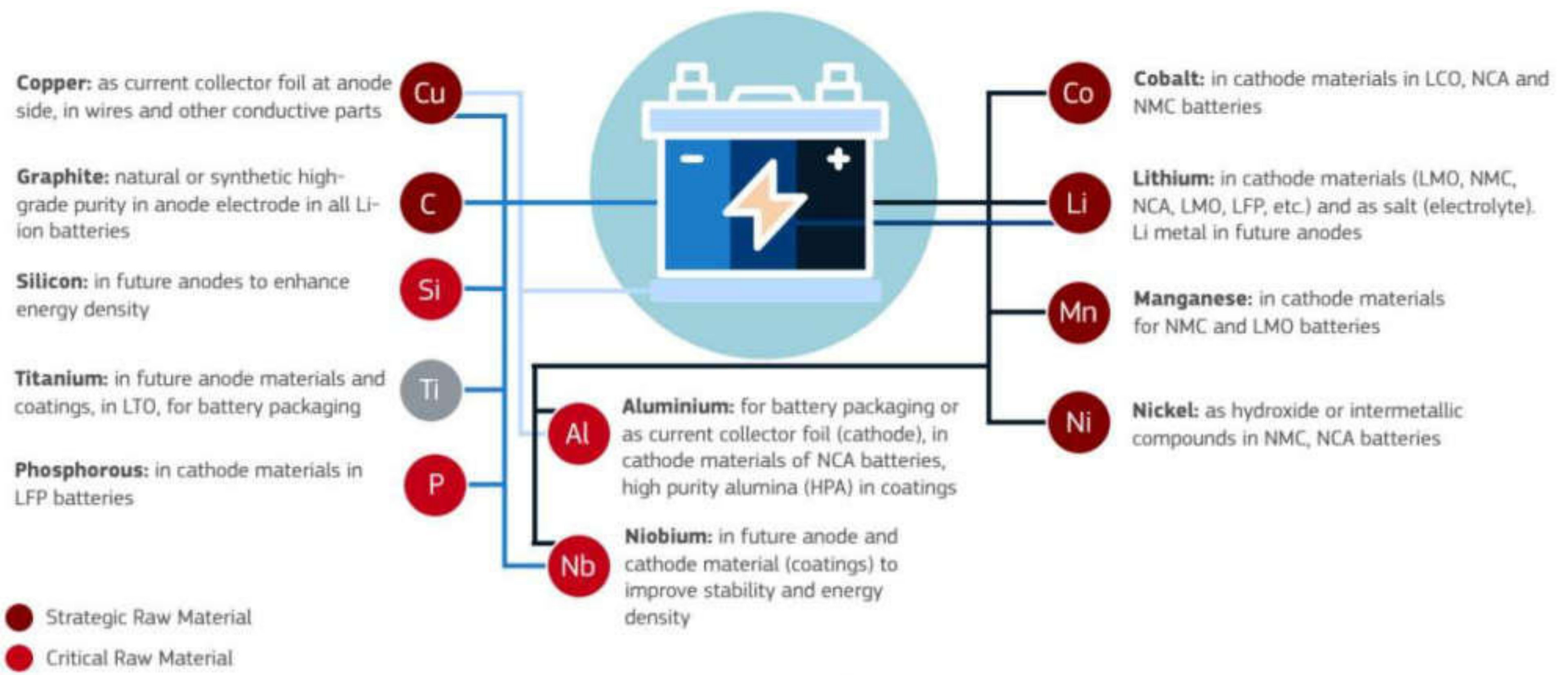
2.4 Traction motors (permanent magnets)

Figure 23. Raw materials in traction motors



Critical metals – Li-ion batteries

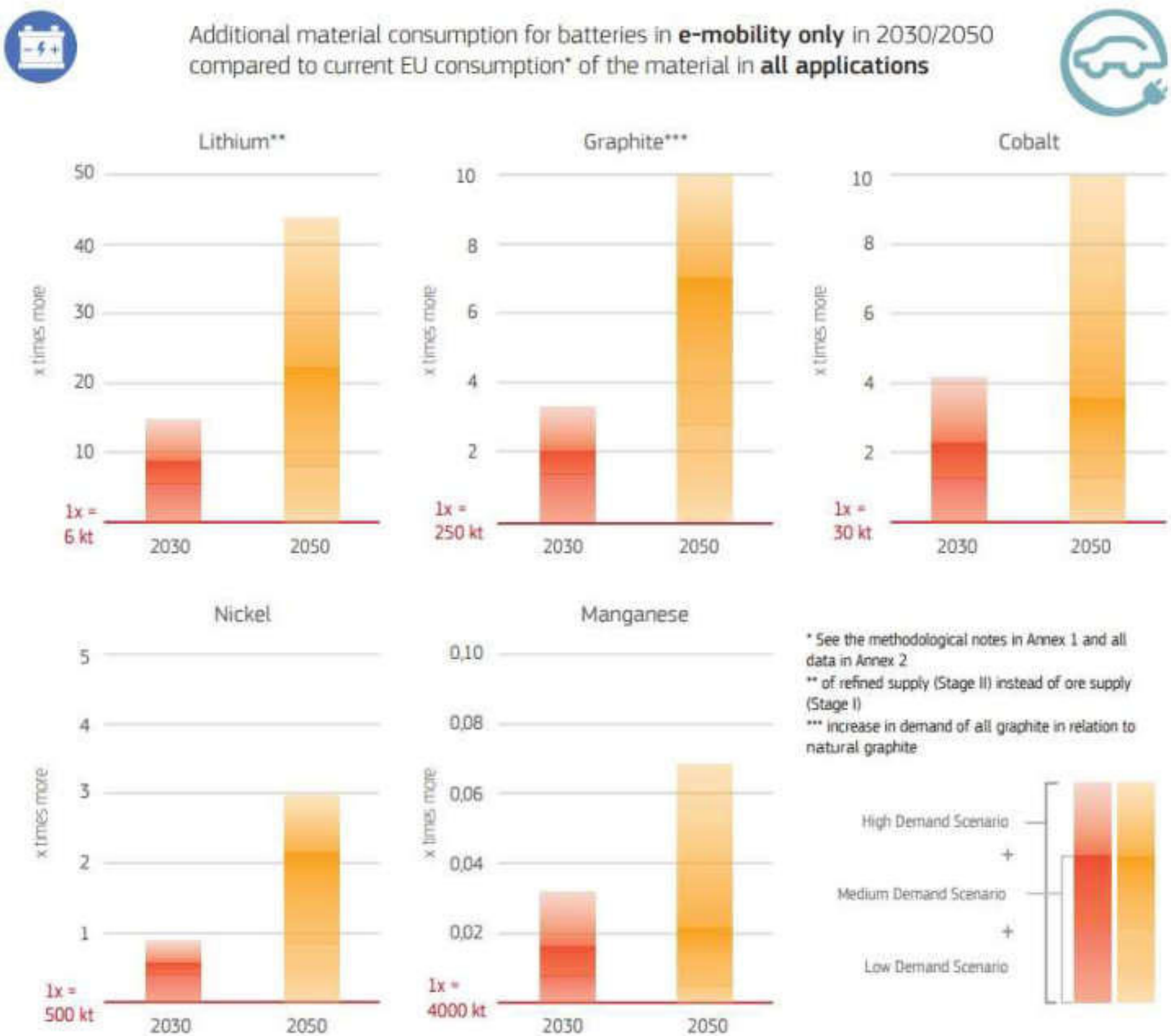
Figure 7. Selection of raw materials used in Li-ion batteries and their function



Source: JRC analysis.

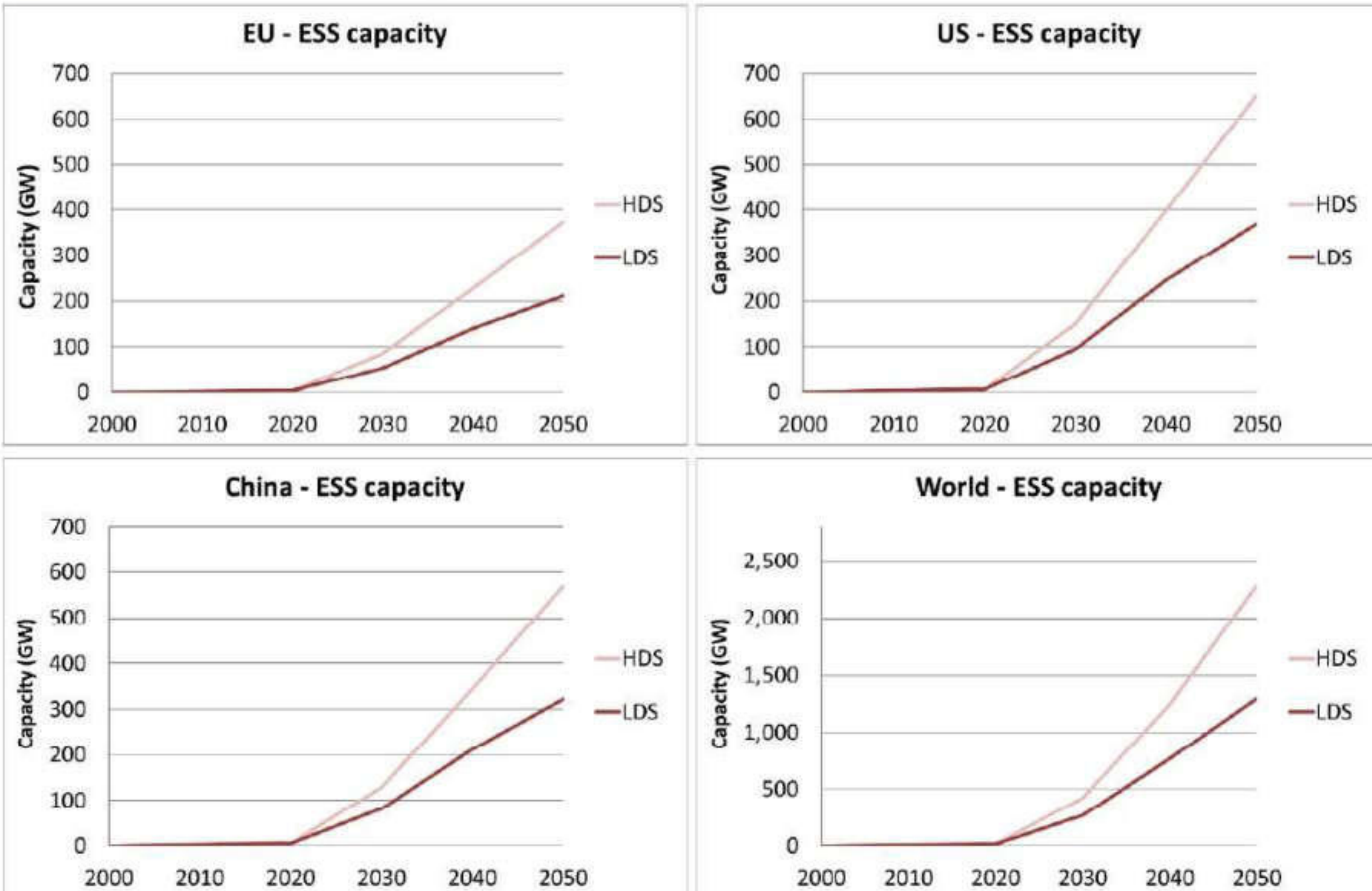
Critical metals – EU annual material demand for EVs

Figure 10. EU annual material demand for batteries in EVs in 2030 and 2050



Critical metals – Battery Energy Storage System (ESS)

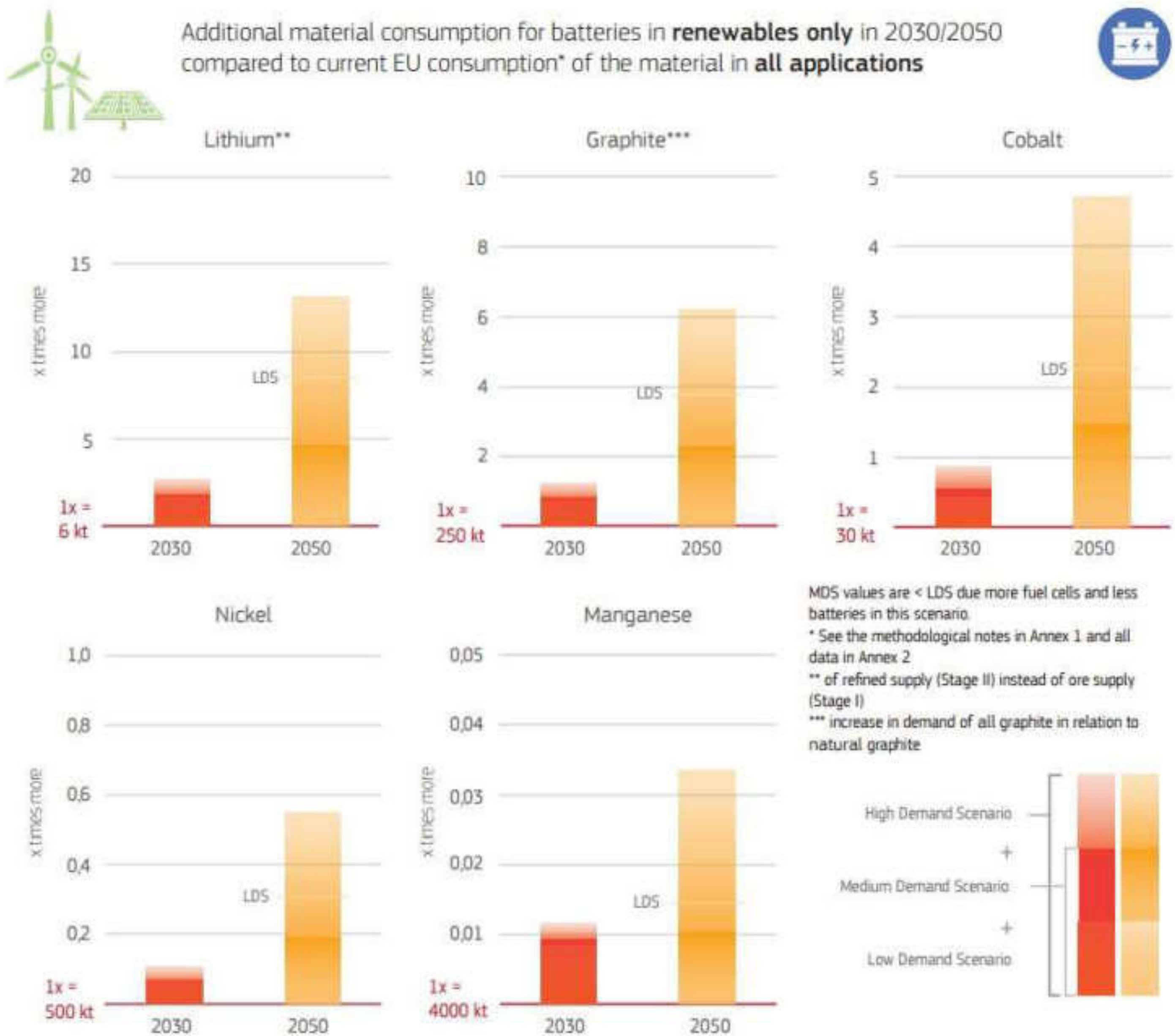
Figure 11. Battery Energy Storage System (ESS) capacity in the EU, US, China, and globally in the two explored scenarios



Source: JRC analysis based JRC, 2021b.

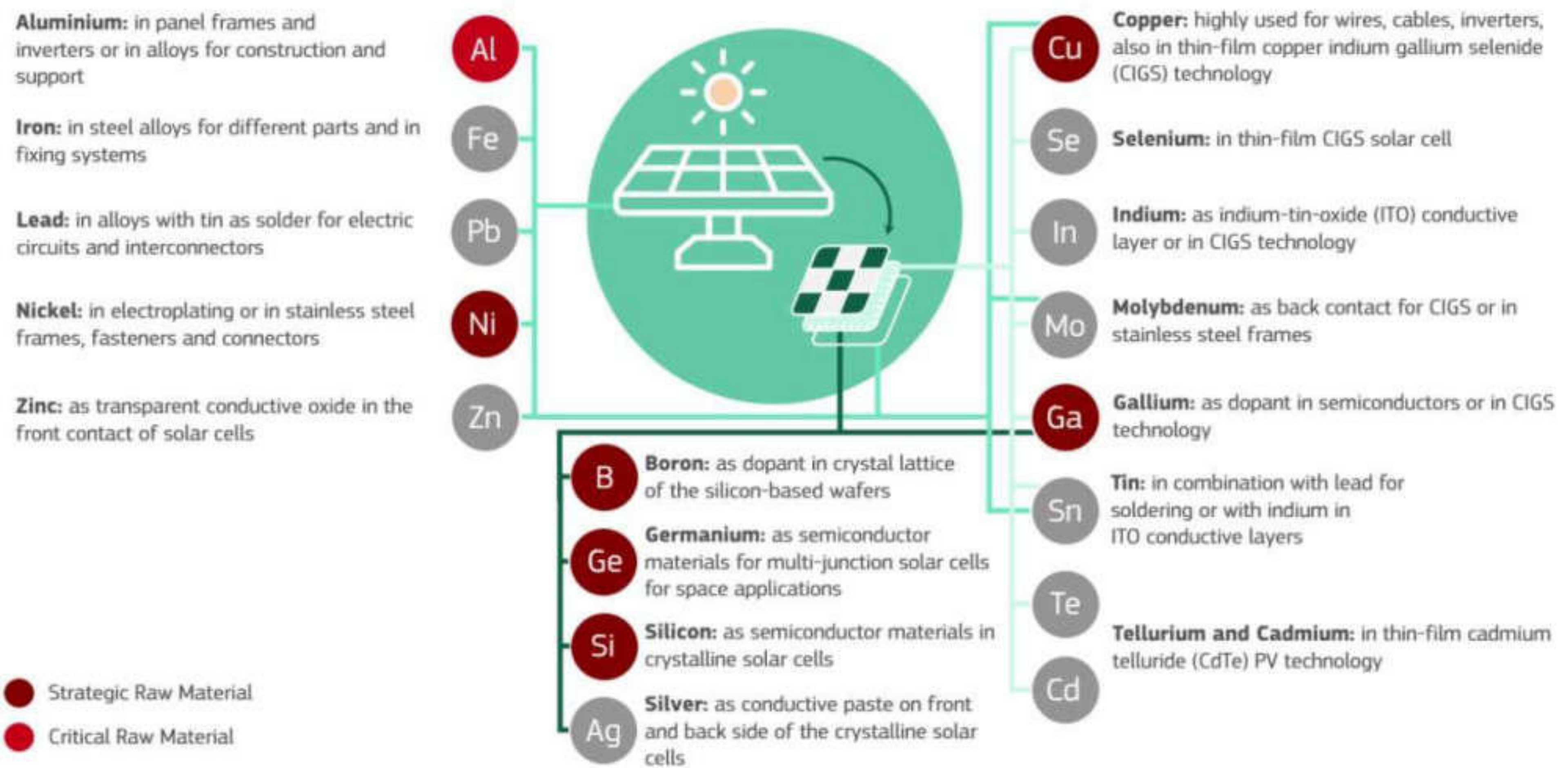
Critical metals – ESS storage

Figure 12. EU annual material demand for ESS batteries in 2030 and 2050



Critical metals – solar PV

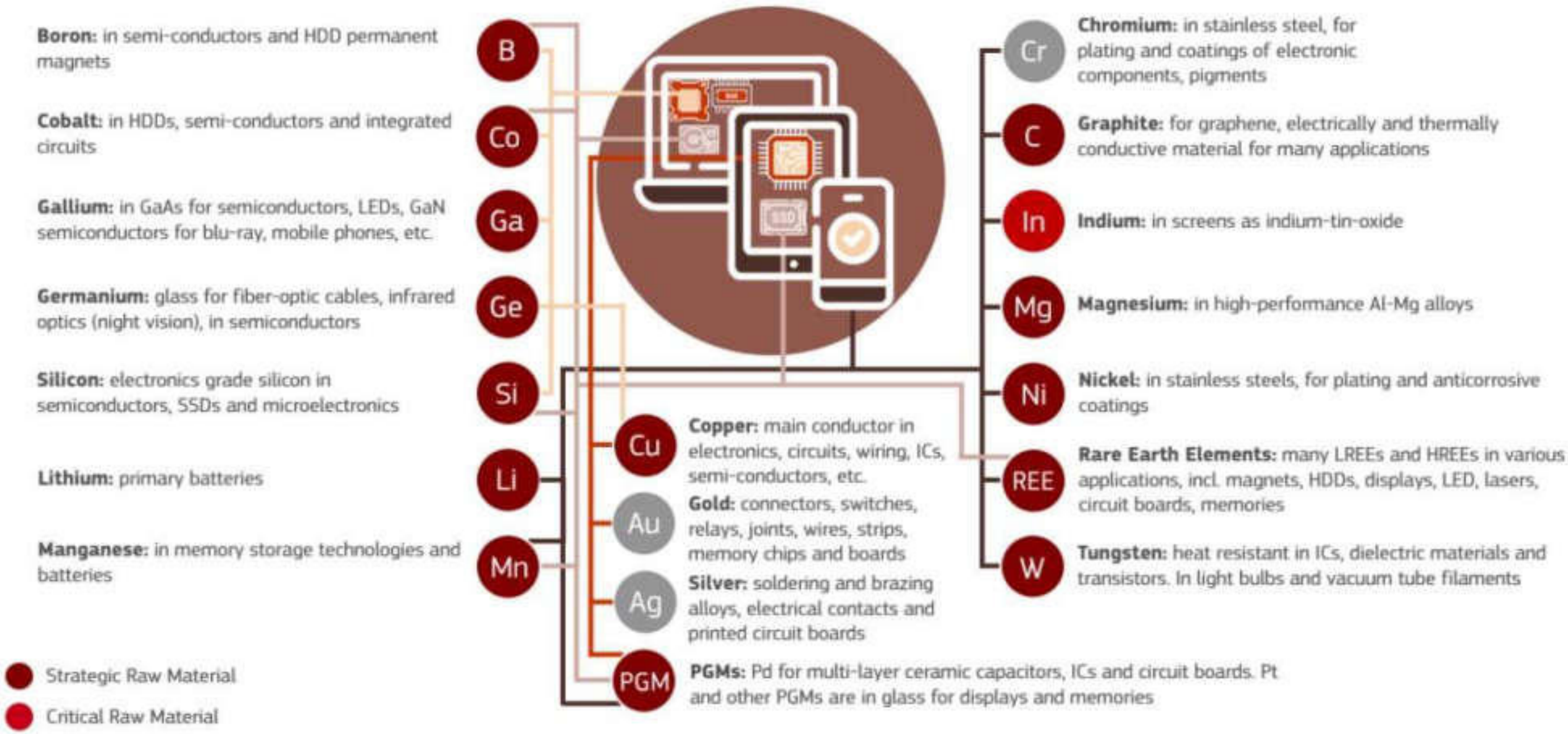
Figure 40. Selection of raw materials used in solar PV and their function



Source: JRC analysis.

Critical metals – smartphones, tablets and laptops

Figure 64. Selection of raw materials used in smartphones, tablets and laptops and their function



Source: JRC analysis.

Critical raw materials for Italy?

2019		2020	
Elemento	Import	Elemento	Import
Bauxite	5.212.993.876,00 €	Gold	8.560.722.438,00 €
Gold	4.680.632.383,00 €	Bauxite	4.312.041.650,00 €
Silver	2.138.900.607,00 €	Silver	2.361.905.036,00 €
Copper	1.723.395.332,00 €	Platinum Group Metals	2.217.336.784,00 €
Platinum Group Metals	1.266.548.688,00 €	Copper	1.658.825.442,00 €
Zinc	927.174.977,00 €	Nickel	788.937.506,00 €
Nickel	898.328.371,00 €	Zinc	710.223.080,00 €
Coking coal	634.599.094,00 €	Titanium	508.287.863,00 €
Titanium	534.504.097,00 €	Coking coal	332.363.732,00 €
Manganese	319.481.868,00 €	Manganese	265.928.061,00 €
Molybdenum	268.993.494,00 €	Molybdenum	164.435.590,00 €
Tin	120.124.937,00 €	Tin	88.096.349,00 €
Feldspar	100.478.866,00 €	Feldspar	80.592.015,00 €
Kaolin clay	91.847.854,00 €	Kaolin clay	71.211.712,00 €
Fluorspar	85.850.598,00 €	Others precious metals	67.078.270,00 €
Magnesium	85.819.846,00 €	Fluorspar	64.368.505,00 €
Vanadium	66.269.426,00 €	Magnesium	62.742.616,00 €
Natural teak wood	66.226.141,00 €	Antimony	57.373.450,00 €
Antimony	64.049.197,00 €	Natural teak wood	53.456.859,00 €
Baryte	63.623.250,00 €	Baryte	51.335.127,00 €

CRITICAL RAW MATERIALS

- **Aluminum** (bauxite), used in almost all sectors of the economy
- **Antimony**, used in batteries and flame retardants
- **Arsenic**, used in lumber preservatives, pesticides, and semi-conductors
- **Barite $BaSO_4$**, used in cement and petroleum industries
- **Beryllium**, used as an alloying agent in aerospace and defense industries
- **Bismuth**, used in medical and atomic research
- **Cesium**, used in research and development
- **Chromium**, used primarily in stainless steel and other alloys
- **Cobalt**, used in rechargeable batteries and superalloys

CRITICAL RAW MATERIALS

- **Fluorspar CaF_2**, used in the manufacture of aluminum, gasoline, and uranium fuel
- **Gallium**, used for integrated circuits and optical devices like LEDs
- **Germanium**, used for fiber optics and night vision applications
- **Graphite** (natural), used for lubricants, batteries, and fuel cells
- **Hafnium**, used for nuclear control rods, alloys, and high-temperature ceramics
- **Helium**, used for MRIs, lifting agent, and research
- **Indium**, mostly used in LCD screens
- **Lithium**, used primarily for batteries

CRITICAL RAW MATERIALS

- **Magnesium**, used in furnace linings for manufacturing steel and ceramics
- **Manganese**, used in steelmaking
- **Niobium**, used mostly in steel alloys
- **Platinum group metals (PGM)**, used for catalytic agents
- **Potash (K compounds and K-bearing materials)**, primarily used as a fertilizer
- **Rare earth elements (REE)**, primarily used in batteries and electronics
- **Rhenium**, used for lead-free gasoline and superalloys
- **Rubidium**, used for research and development in electronics

CRITICAL RAW MATERIALS

- **Scandium**, used for alloys and fuel cells
- **Strontium**, used for pyrotechnics and ceramic magnets
- **Tantalum**, used in electronic components, mostly capacitors
- **Tellurium**, used in steelmaking and solar cells
- **Tin**, used as protective coatings and alloys for steel
- **Titanium**, overwhelmingly used as a white pigment or metal alloys
- **Tungsten**, primarily used to make wear-resistant metals
- **Uranium**, mostly used for nuclear fuel
- **Vanadium**, primarily used for titanium alloys
- **Zirconium**, used in the high-temperature ceramics industries

A smartphone contains more than 60 elements!

ELEMENTS OF A SMARTPHONE

ELEMENTS COLOUR KEY: ALKALI METAL · ALKALI EARTH METAL · TRANSITION METAL · GROUP 13 · GROUP 14 · GROUP 15 · GROUP 16 · HALOGEN · LANTHANIDE

SCREEN

49 In Indium · 8 O Oxygen · 50 Sn Tin

Indium tin oxide is a mixture of indium oxide and tin oxide, used in a transparent film in the screen that conducts electricity. This allows the screen to function as a touch screen.

13 Al Aluminium · 14 Si Silicon · 8 O Oxygen · 19 K Potassium

The glass used on the majority of smartphones is an aluminosilicate glass, composed of a mix of alumina (Al_2O_3) and silica (SiO_2). This glass also contains potassium ions, which help to strengthen it.

39 Y Yttrium · 57 Ln Lanthanum · 65 Tb Terbium · 59 Pr Praseodymium · 63 Eu Europium · 66 Dy Dysprosium · 64 Gd Gadolinium

A variety of Rare Earth Element compounds are used in small quantities to produce the colours in the smartphone's screen. Some compounds are also used to reduce UV light penetration into the phone.

ELECTRONICS

29 Cu Copper · 47 Ag Silver · 79 Au Gold · 73 Ta Tantalum

Copper is used for wiring in the phone, whilst copper, gold and silver are the major metals from which microelectrical components are fashioned. Tantalum is the major component of micro-capacitors.

28 Ni Nickel · 66 Dy Dysprosium · 59 Pr Praseodymium · 65 Tb Terbium · 60 Nd Neodymium · 64 Gd Gadolinium

Nickel is used in the microphone and other electrical connections. Praseodymium, gadolinium and neodymium compounds are used in the magnets in the speaker and microphone. Neodymium, terbium and dysprosium compounds are used in the vibration unit.

14 Si Silicon · 8 O Oxygen · 51 Sb Antimony · 33 As Arsenic · 15 P Phosphorus · 31 Ga Gallium

Pure silicon is used to manufacture the chip in the phone. It is oxidised to produce non-conducting regions, then other elements are added in order to allow the chip to conduct electricity.

50 Sn Tin · 82 Pb Lead

Tin & lead are used to solder electronics in the phone. Newer lead-free solders use a mix of tin, copper and silver.

BATTERY

3 Li Lithium · 27 Co Cobalt · 8 O Oxygen · 6 C Carbon · 13 Al Aluminium

The majority of phones use lithium ion batteries, which are composed of lithium cobalt oxide as a positive electrode and graphite (carbon) as the negative electrode. Some batteries use other metals, such as manganese, in place of cobalt. The battery's casing is made of aluminium.

CASING

6 C Carbon · 12 Mg Magnesium · 35 Br Bromine · 28 Ni Nickel

Magnesium compounds are alloyed to make some phone cases, whilst many are made of plastics. Plastics will also include flame retardant compounds, some of which contain bromine, whilst nickel can be included to reduce electromagnetic interference.

Abundance of chemical elements in the Earth's upper continental crust

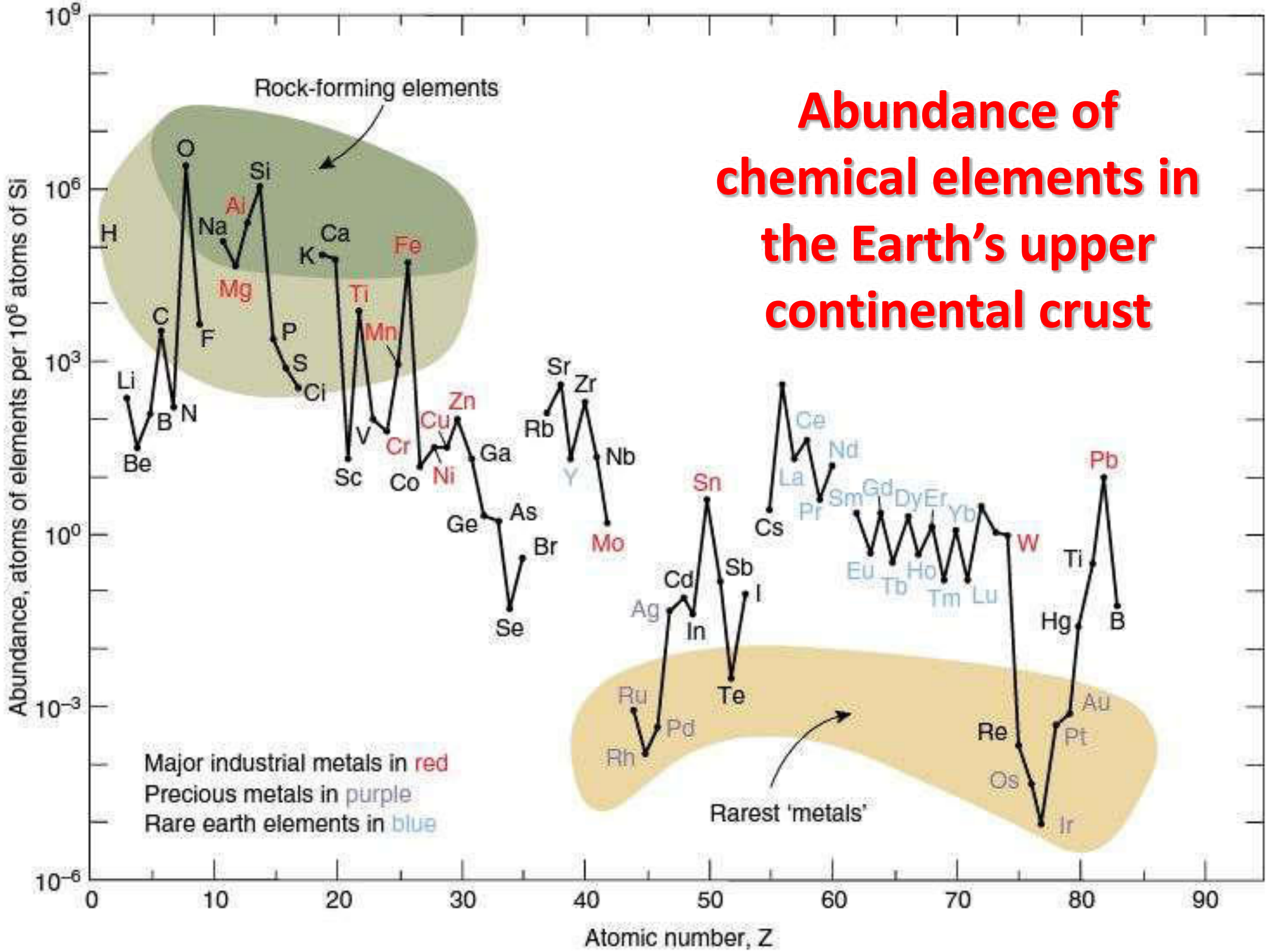
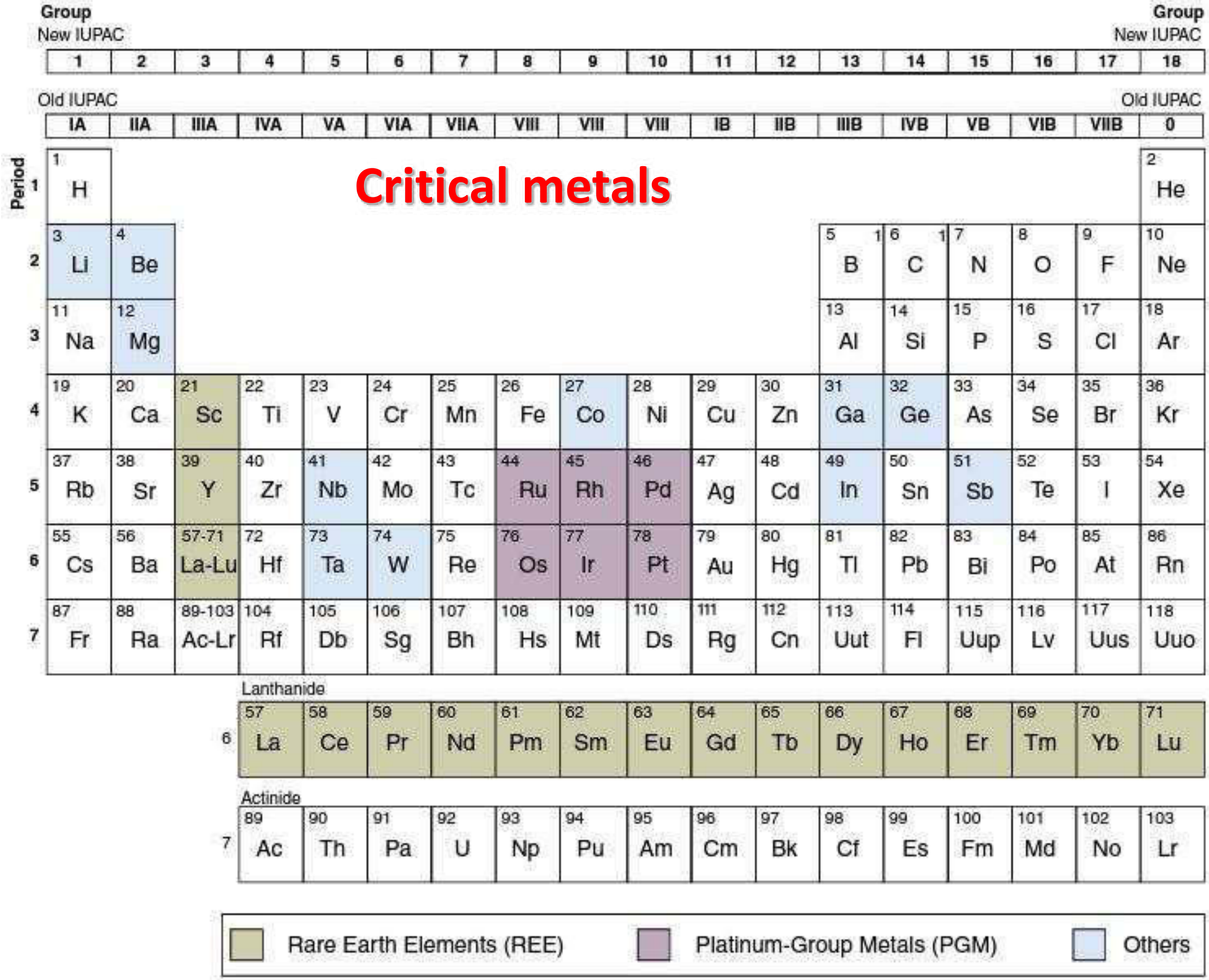
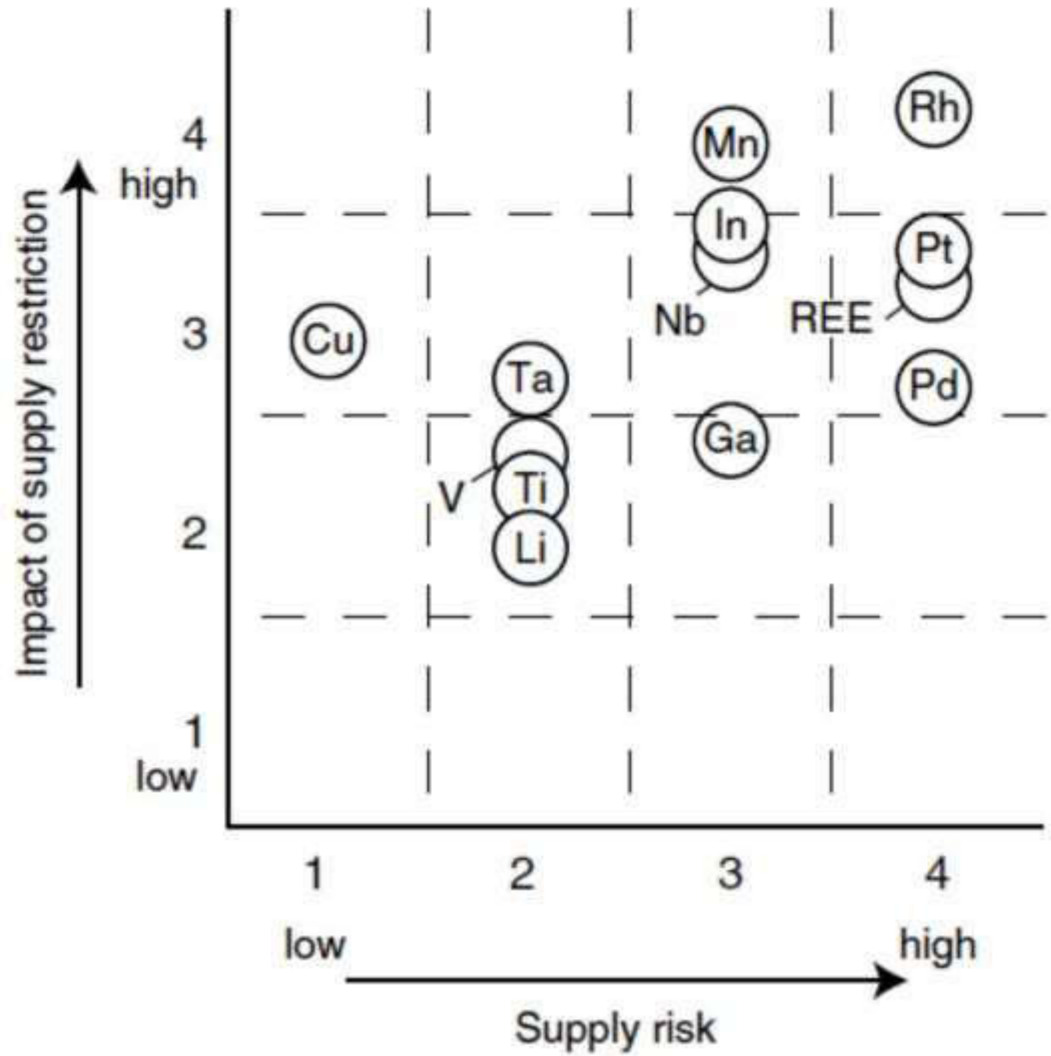


Figure 1.1 The abundance of the chemical elements in the Earth's upper continental crust as a function of atomic number. Many of the elements may be classified into partially overlapping categories. (Modified from USGS, 2002.)

Critical metals

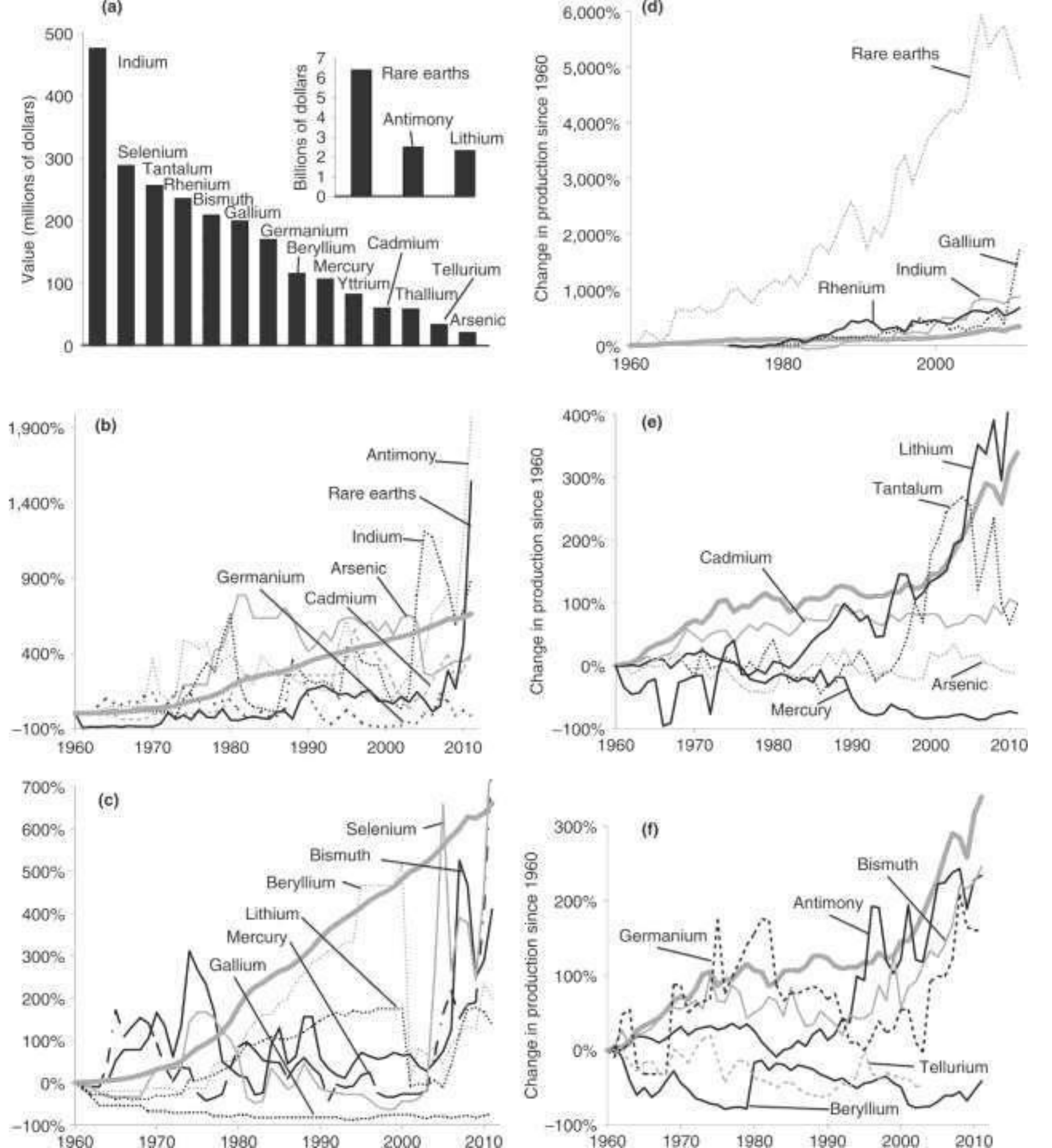


Critical metals – *criticality index*

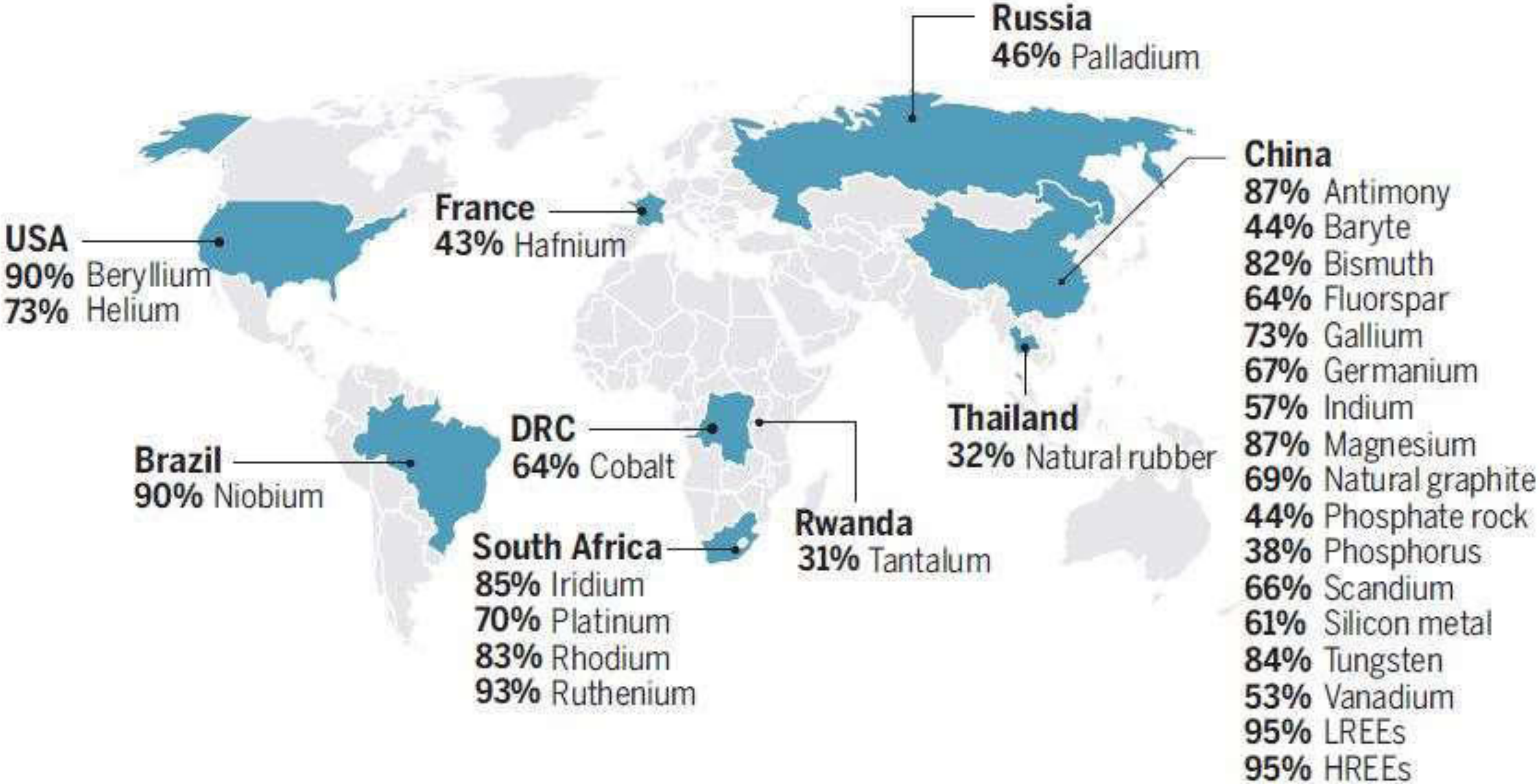


The USGS criticality index

Critical metals – value and production



Countries accounting for the largest share of critical raw materials

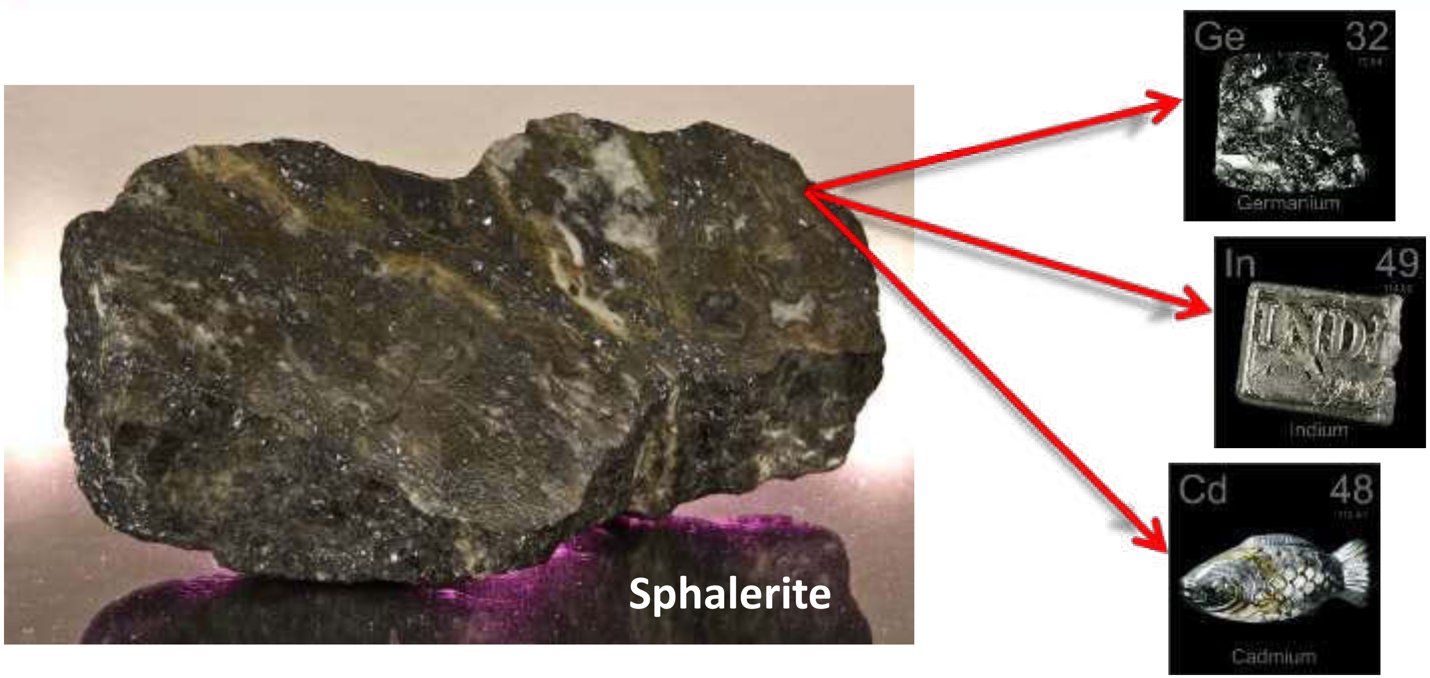


DRC, Democratic Republic of Congo; LREEs, light rare earth elements; HREEs, heavy rare earth elements. Figure modified from European Commission, "Third list of critical raw materials for the EU of 2017" (European Commission, 2017); https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en.

Critical metals and by-products

Table 1.1 By-product metals derived from the production of selected major industrial metals (top row, bold). Those metals shown in italics may also be produced from their own ores. (PGM, platinum-group metals; REE, rare earth elements.)

Copper	**Zinc**	**Tin**	**Nickel**	**Platinum**	**Aluminium**	**Iron**	**Lead**
Cobalt	Indium	*Niobium*	*Cobalt*	Palladium	Gallium	*REE*	*Antimony*
Molybdenum	Germanium	*Tantalum*	*PGM*	Rhodium		*Niobium*	Bismuth
PGM	Cadmium	Indium	Scandium	Ruthenium		Vanadium	Thallium
Rhenium				Osmium			
Tellurium				Iridium			
Selenium							
Arsenic							



Critical metals and by-products

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Copper	**Zinc**	**Tin**	**Nickel**	**Platinum**	**Aluminium**	**Iron**	**Lead**
Cobalt	Indium	*Niobium*	*Cobalt*	Palladium	Gallium	*REE*	*Antimony*
Molybdenum	Germanium	*Tantalum*	*PGM*	Rhodium		*Niobium*	Bismuth
PGM	Cadmium	Indium	Scandium	Ruthenium		Vanadium	Thallium
Rhenium				Osmium			
Tellurium				Iridium			
Selenium							
Arsenic							

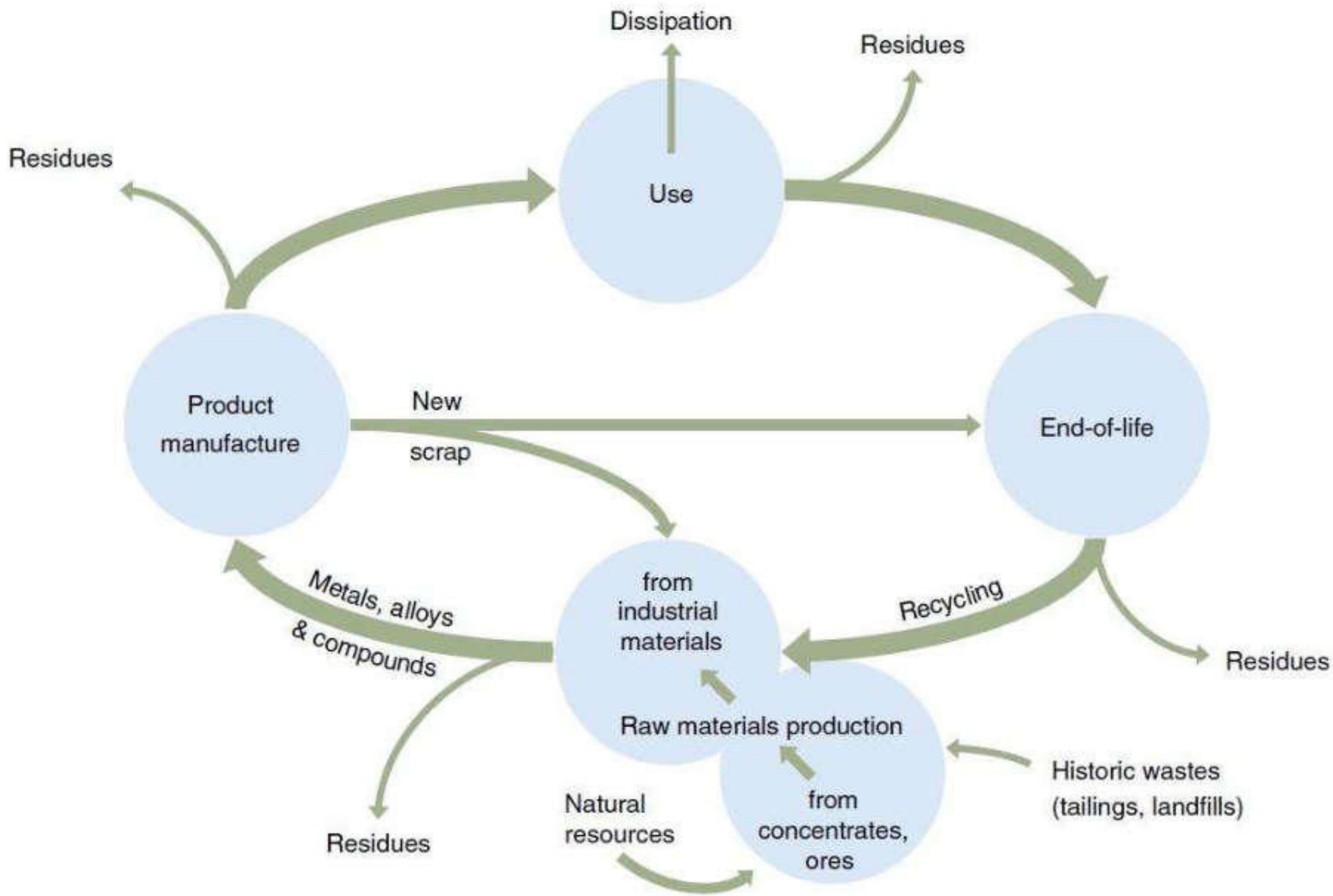
Critical metals - computers & mobile phones

Table 3.1 Average content of precious metals, copper and cobalt in mobile phones and computers, and resulting metals demand from global sales in 2010, compared with world mine production.

	a) Mobile phones		b) PCs and laptop computers			
	1600 million units/year, each with a lithium-ion battery		350 million units/year, of which ca 180 million have a lithium-ion battery		a + b = Urban mine	
Metal	Unit metal content	Total metal content	Unit metal content	Total metal content	Global mine production (2010)	Share a + b of global mine production
Silver	250 mg	400 t	1000 mg	350 t	22,900 t	3%
Gold	24 mg	38 t	220 mg	77 t	2650 t	4%
Palladium	9 mg	14 t	80 mg	28 t	225 t	19%
Copper	9 g	14,000 t	500 g	175,000 t	18 Mt	<1%
Cobalt	3.8 g	6100 t	65 g	11,700 t	88,000 t	20%

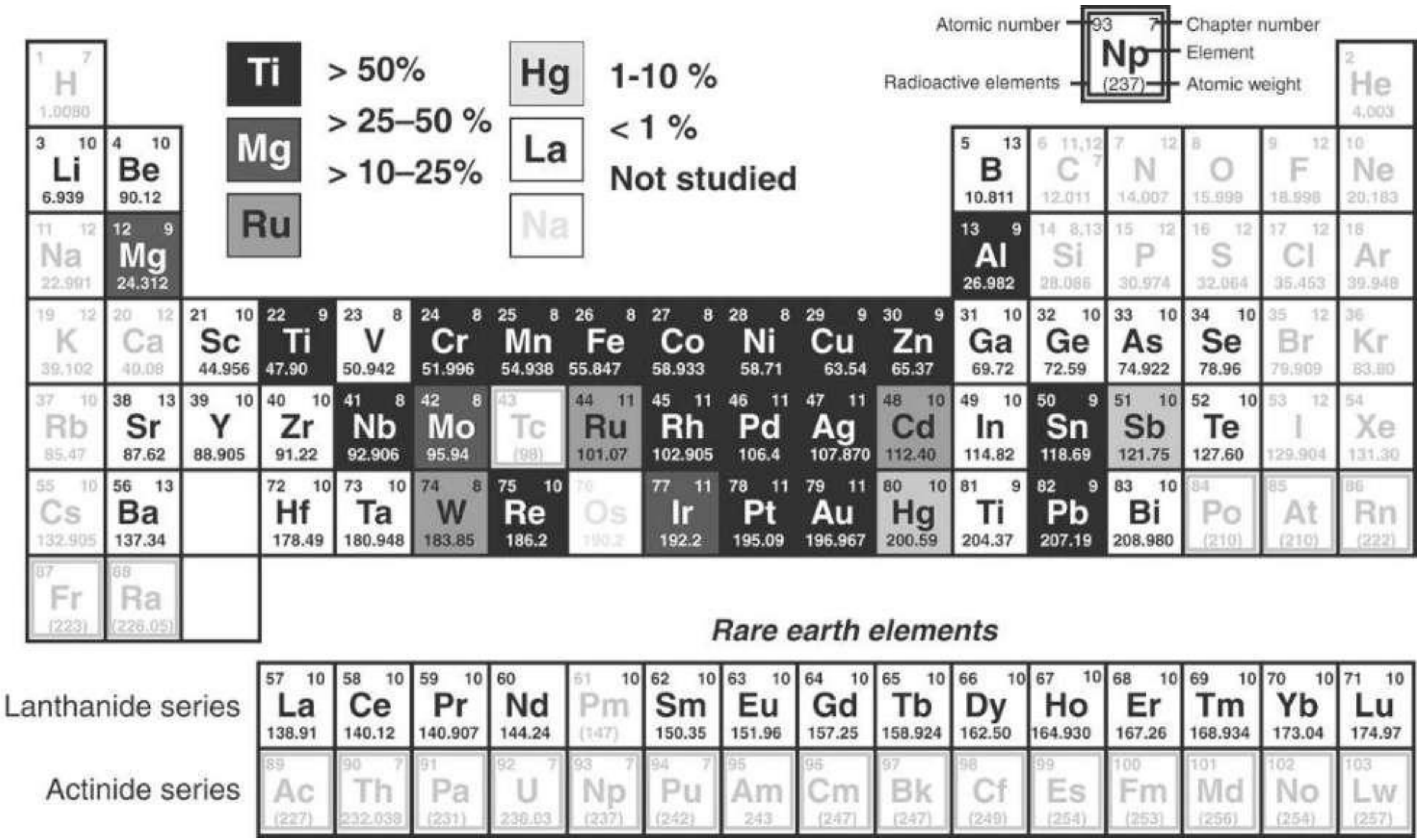
t, tonnes; Mt, million tonnes; g, grams; mg, milligrams

Recycling: how it works



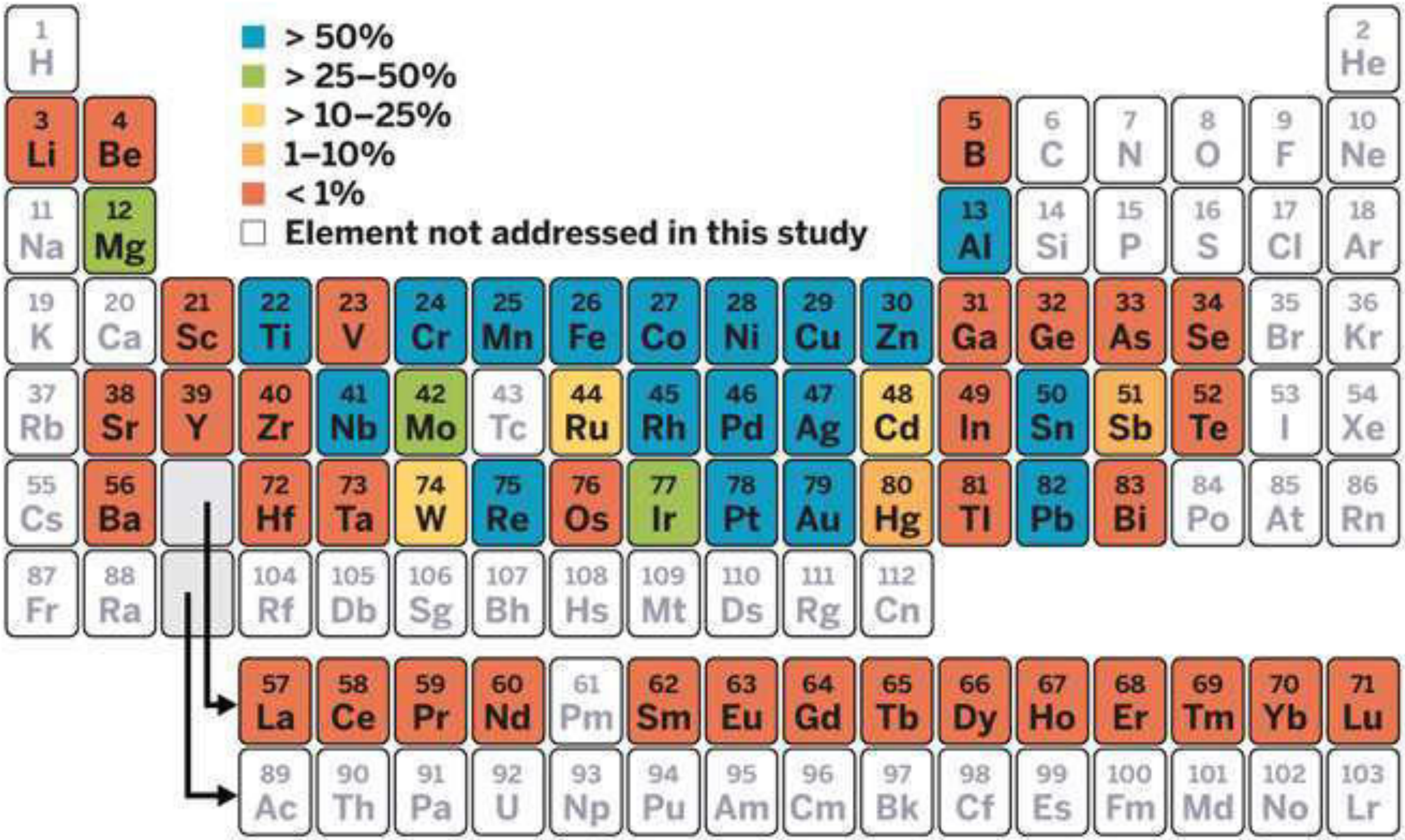
Sustainable use of metals along product life cycles – efficient recycling of residues generated at all stages can minimise use of primary raw materials. (Adapted from Meskers, 2008.)

Recycling rates for metals in metallic applications



Recycling rates

REUSE STATS Global postconsumer recycling rates for many metals show lots of room for improvement.



SOURCE: UN Environment Program

Recycling rates for metals in metallic applications

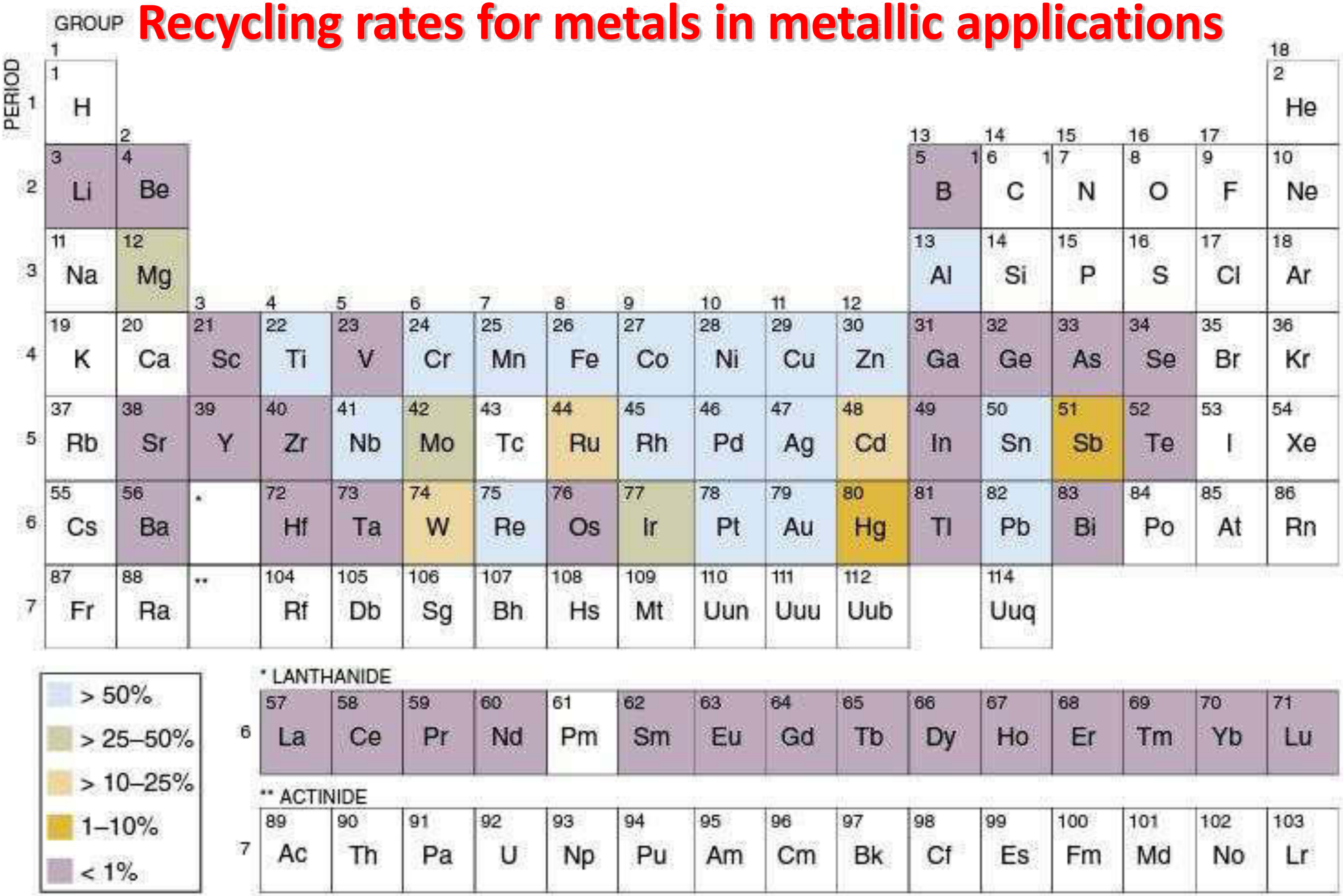


Figure 3.4 Global end-of-life recycling rates for metals in metallic applications. (Modified after UNEP, 2011.)

Recycling rates for precious metals

Importance of end use sector for each metal listed (% of total gross metal demand)*

- > 50%
- > 25–50%
- > 10–25%
- < 10%
- nil

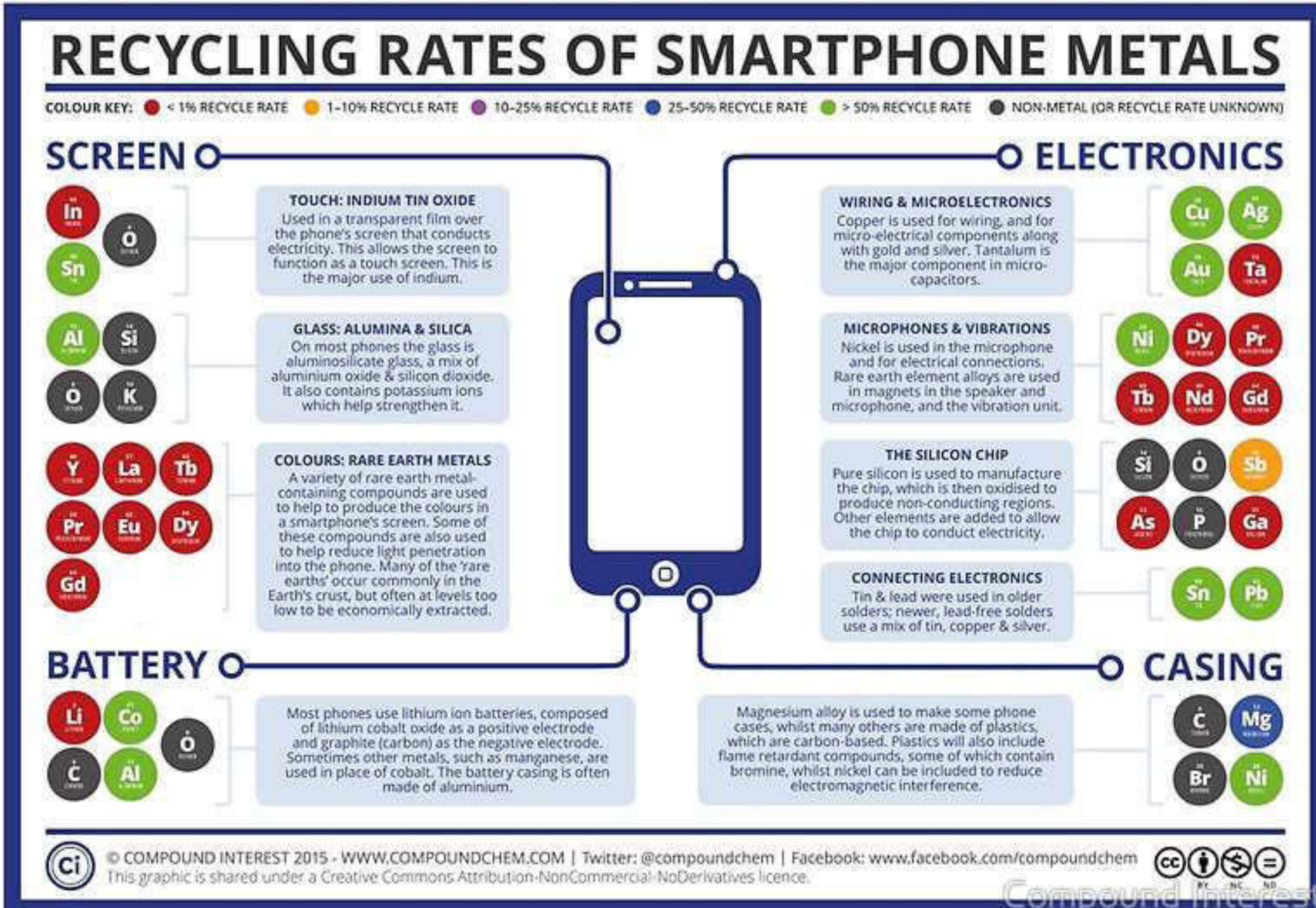
* Including metal demand for closed systems (e.g. process catalysts, glass and other industrial applications)

	EOL recycling rates 1)	Sector-specific EOL recycling rates					Jewellery, coins 5)
		Vehicles 2)	Electronics	Industrial applications 3)	Dental	Others 4)	
Ru	5–15		0–5	40–50		0–5	
Rh	50–60	45–50	5–10	80–90		30–50	40–50
Pd	60–70	50–55	5–10	80–90	15–20	15–20	90–100
Ag	30–50	0–5	10–15	40–60		40–60	90–100
Os	no relevant end use						
Ir	20–30	0	0	40–50		5–10	
Pt	60–70	50–55	0–5	80–90	120	10–20	90–100
Au	15–20	0–5	10–15	70–90	15–20	0–5	90–100

1) Total without jewellery, coins (no typical end-of-life managements for these products).
2) Autocatalysts, spark plugs, conductive Ag-pastes, excluding car electronics.
3) Including process catalysts/ electrochemical, glass, mirror (Ag), batteries (Ag). In some cases, the available EOL metal is reduced due to prior in-use dissipation (e.g. homogeneous Pt-catalysts).
4) Including decorative, medical, sensors, crucibles, photographic (Ag) photovoltaics (Ag).
5) Including medals and silverware.

Figure 3.5 Global end-of-life recycling rates for precious metals by important application fields (after UNEP, 2011). The shading in the boxes indicates the importance of that sector as a proportion of total gross demand e.g. for ruthenium (Ru), >50% is used in electronics and between 25–50% in industrial applications. The actual recycling rates achieved are indicated by the numbers in the boxes. (Ag, silver; Au, gold; Ir, iridium; Os, osmium; Pd, palladium; Pt, platinum; Rh, rhodium; Ru, ruthenium.)

Recycling rates for smartphone metals



Recycling: dismantling and pre-processing

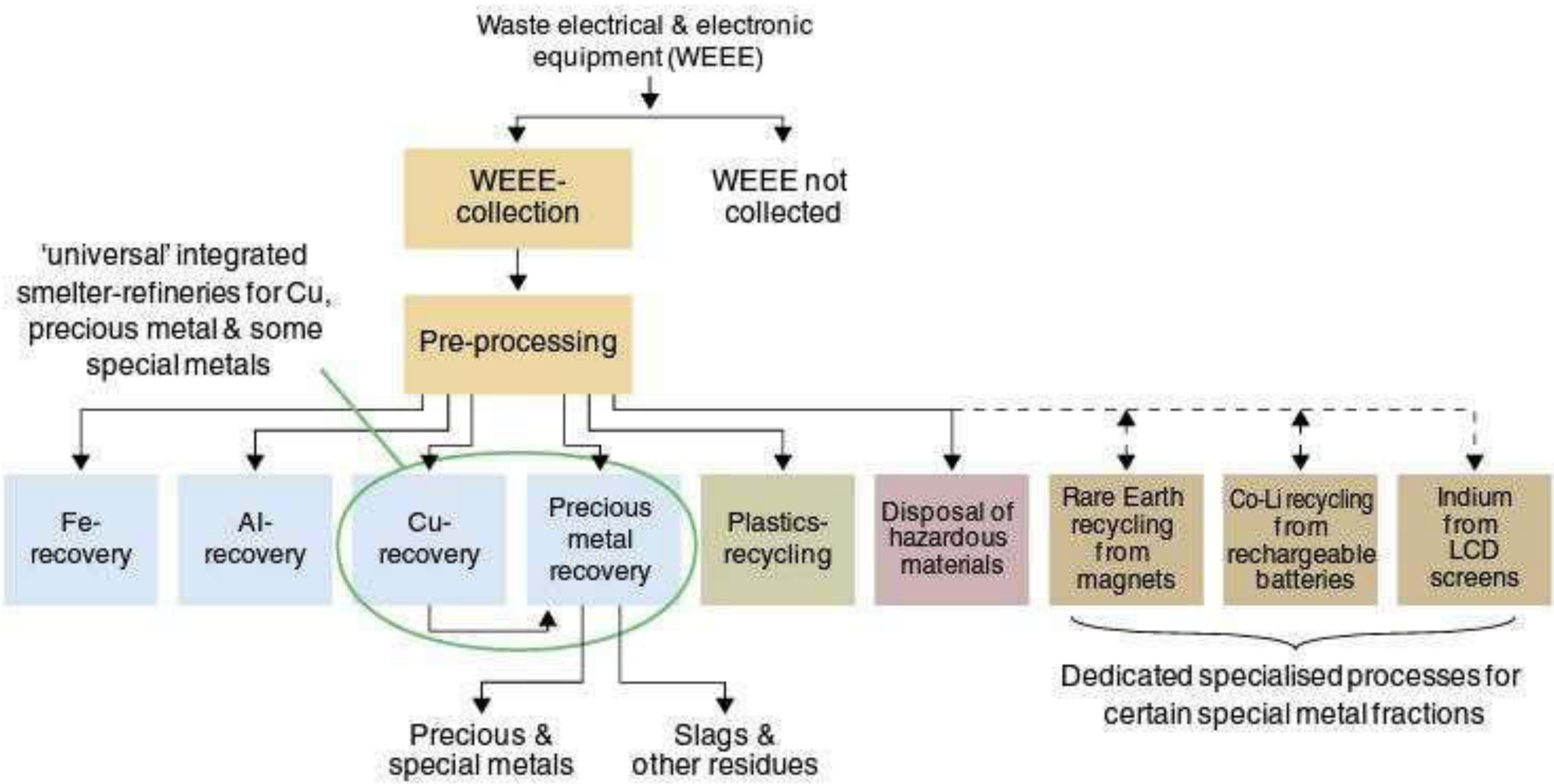


Figure 3.6 Dismantling and pre-processing are crucial to channel substances into the most appropriate metallurgical recovery facilities for final processing. This is illustrated here for waste electrical and electronic equipment. (Al, aluminium; Co, cobalt; Fe, iron; Li, lithium.)

Critical metals – metal recovery

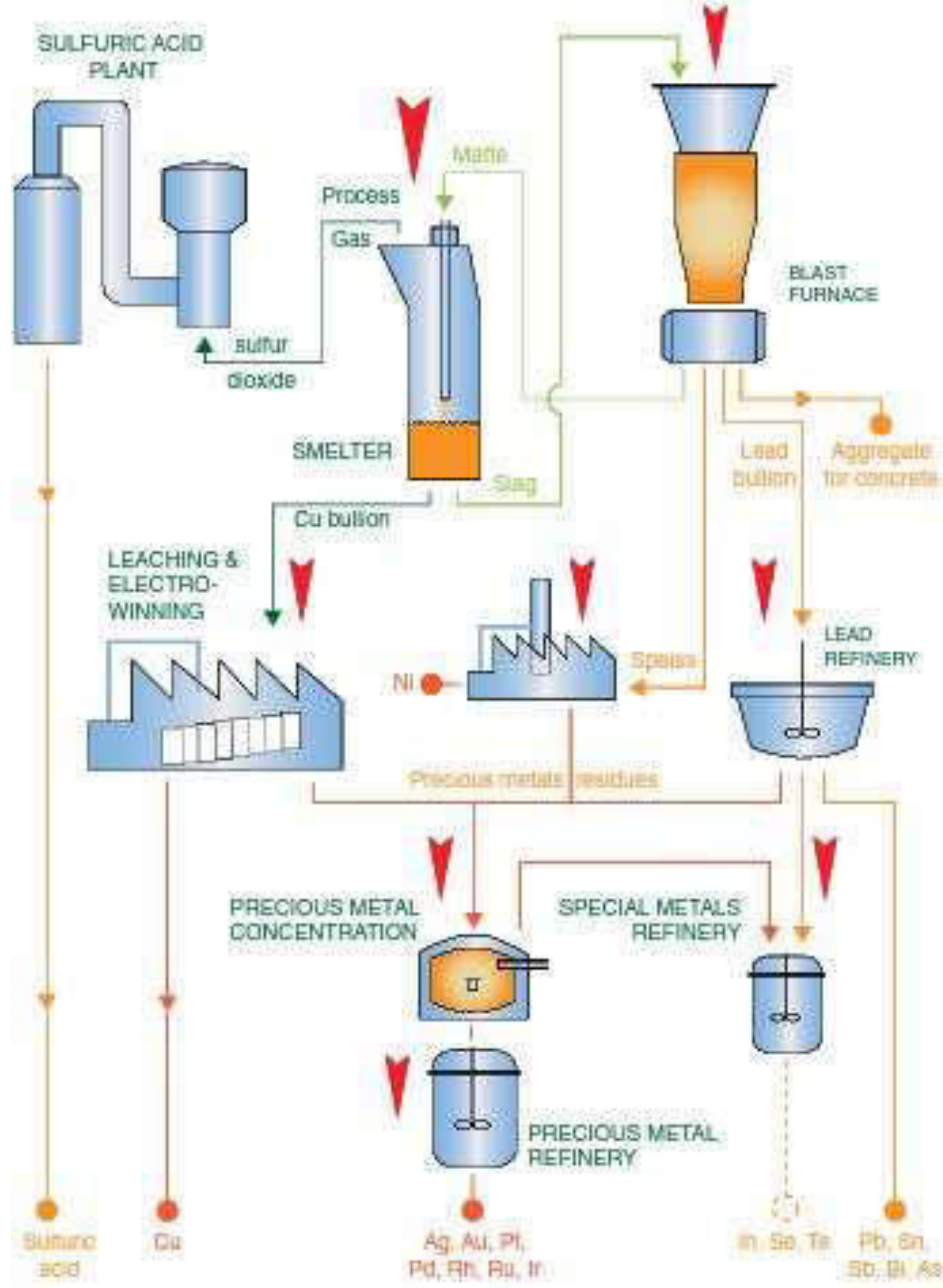


Figure 3.7 Metal combinations that fit thermodynamically can be recovered in a sophisticated integrated smelter-refinery process where copper, lead and nickel act as collectors for precious and some speciality metals. The example shown here is the Hoboken universal process of Umicore. The large red arrows indicate where recycling materials can be fed into the process (depending on concentration and properties). The main feed stream goes into the smelter (upper left arrow). (Ag, silver; As, arsenic; Au, gold; Bi, bismuth; In, indium; Ir, iridium; Ni, nickel; Pd, palladium; Pt, platinum; Rh, rhodium; Ru, ruthenium; Sb, antimony; Se, selenium; Sn, tin; Te, tellurium.)

Critical metals – exhausted batteries recovery

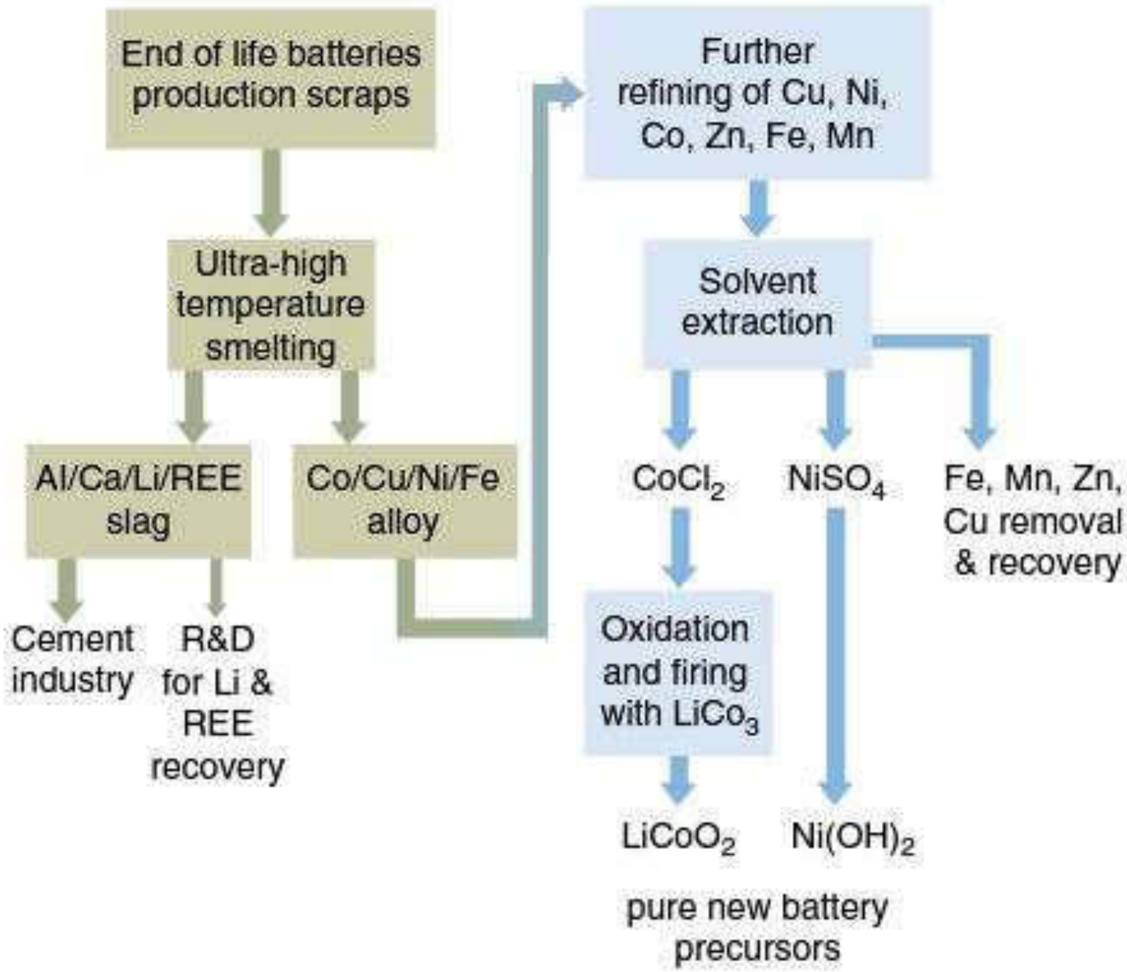
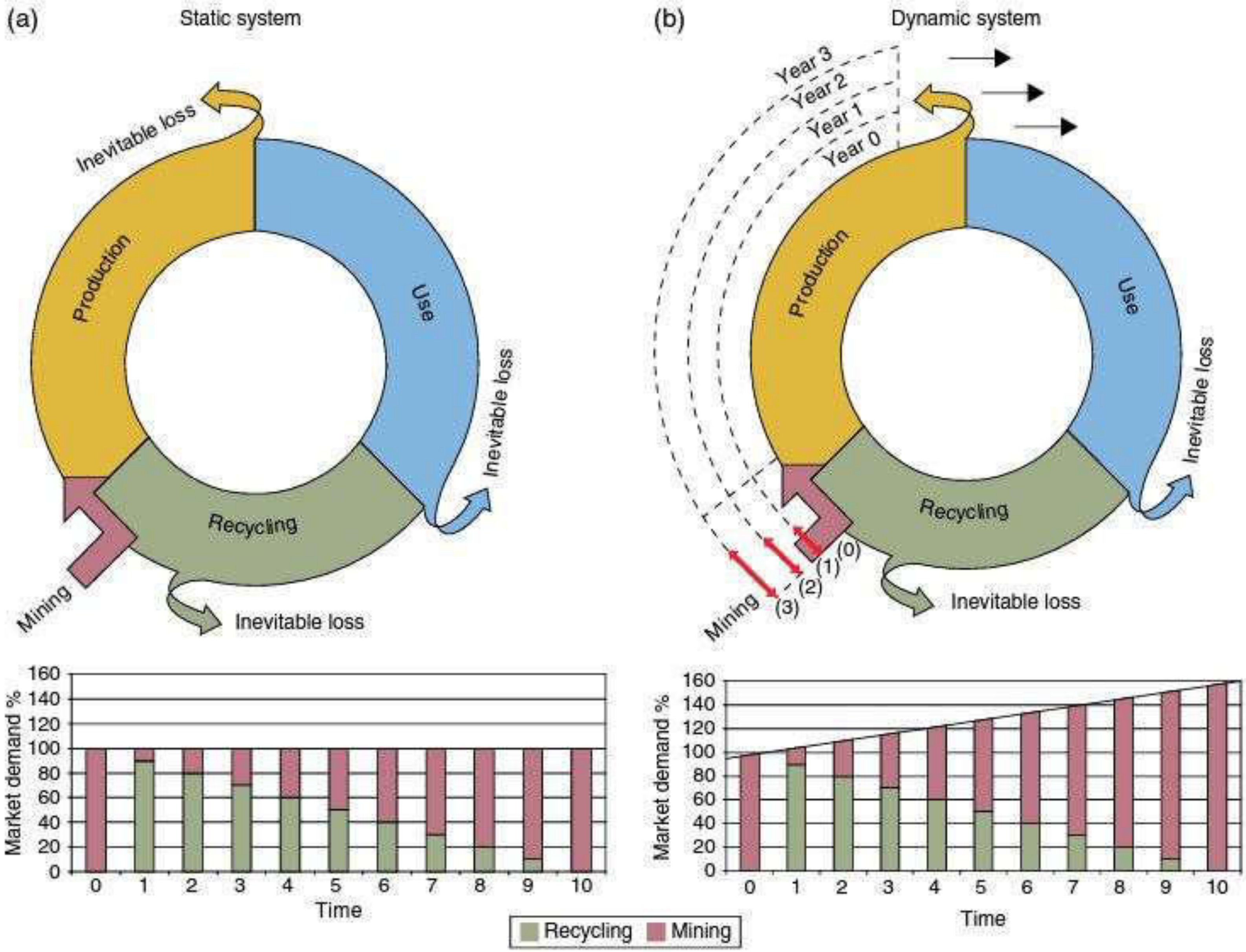


Figure 3.8 Certain metal combinations need dedicated processes. The Umicore process for lithium-ion and nickel-metal hydride batteries is shown here. (Al, aluminium; Ca, calcium; Co, cobalt; Cu, copper; Fe, iron; Li, lithium; Mn, manganese; Ni, nickel; REE, rare earth elements; Zn, zinc. $CoCl_2$, cobalt chloride; $LiCoO_2$, lithium cobalt oxide; $Ni(OH)_2$, nickel hydroxide; $NiSO_4$, nickel sulfate.)

Mining and recycling are complementary systems



Mining waste recycling?

sustainability

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Article

Towards Sustainable Mining: Exploiting Raw Materials from Extractive Waste Facilities

Giovanna Antonella Dino [1], Alessandro Cavallo [2,*], Piergiorgio Rossetti [1], Ernő Garamvölgyi [3], Renáta Sándor [3] and Frederic Coulon [4]

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Mining waste recycling: secondary raw materials (SRM)

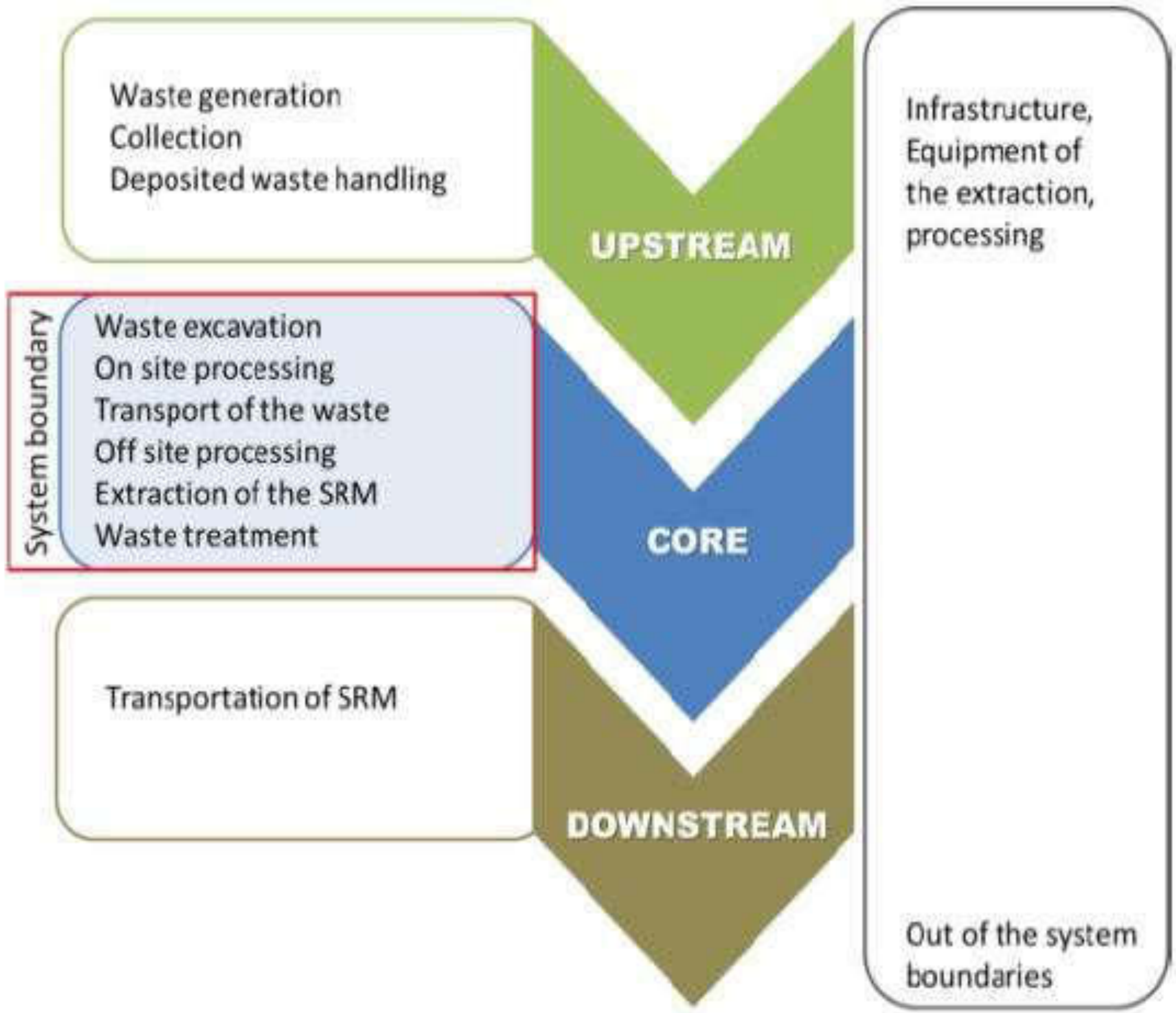


Figure 4. System boundaries for environmental impact assessment.

Mining waste recycling: flow sheet

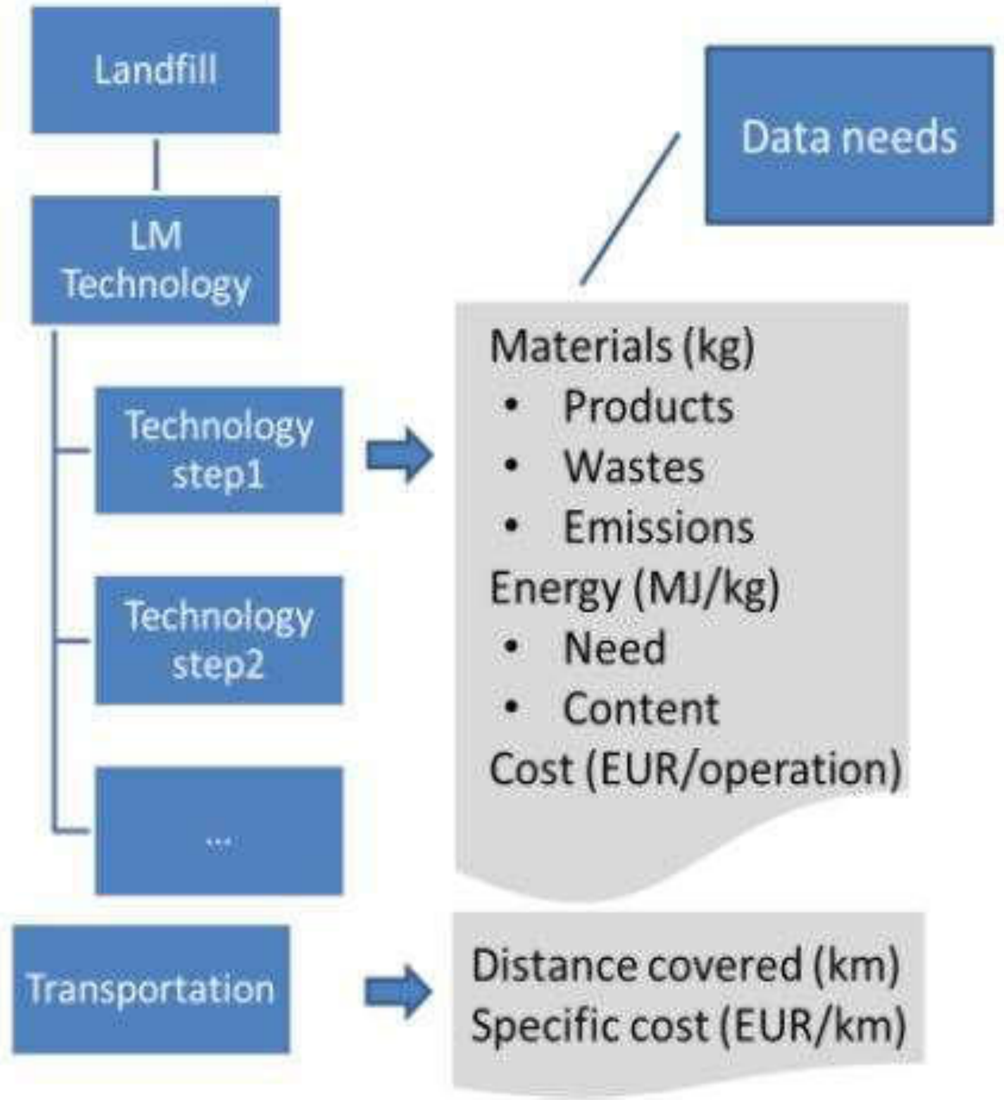


Figure 5. Technology lines are represented as graphs.

Mining waste recycling: an example from granite quarries

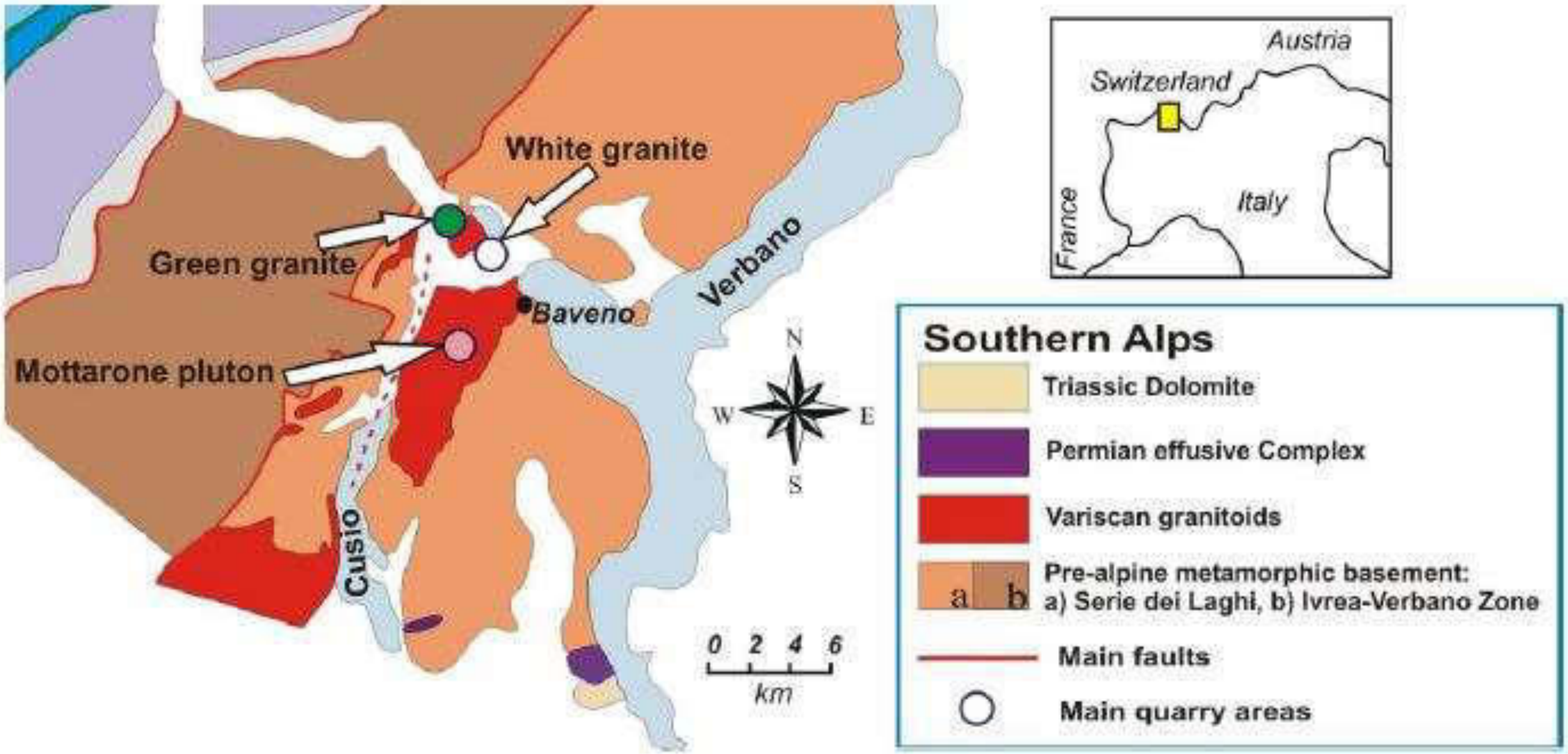


Figure 2. Geographic and geological context of the studied area. In the northern part (Montorfano area), it is possible to individuate the white and green granites. The pink dot indicates the Baveno-Mottarone pluton.

Mining waste recycling: an example from granite quarries

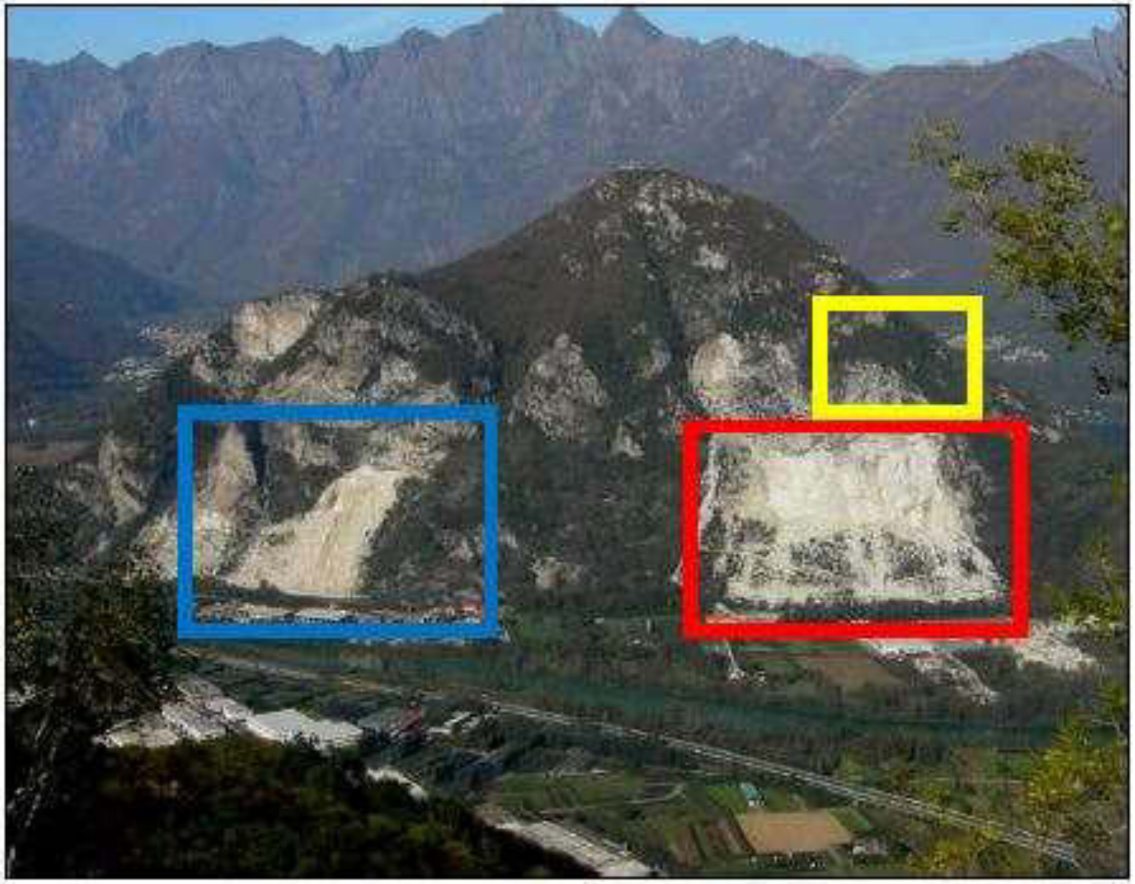
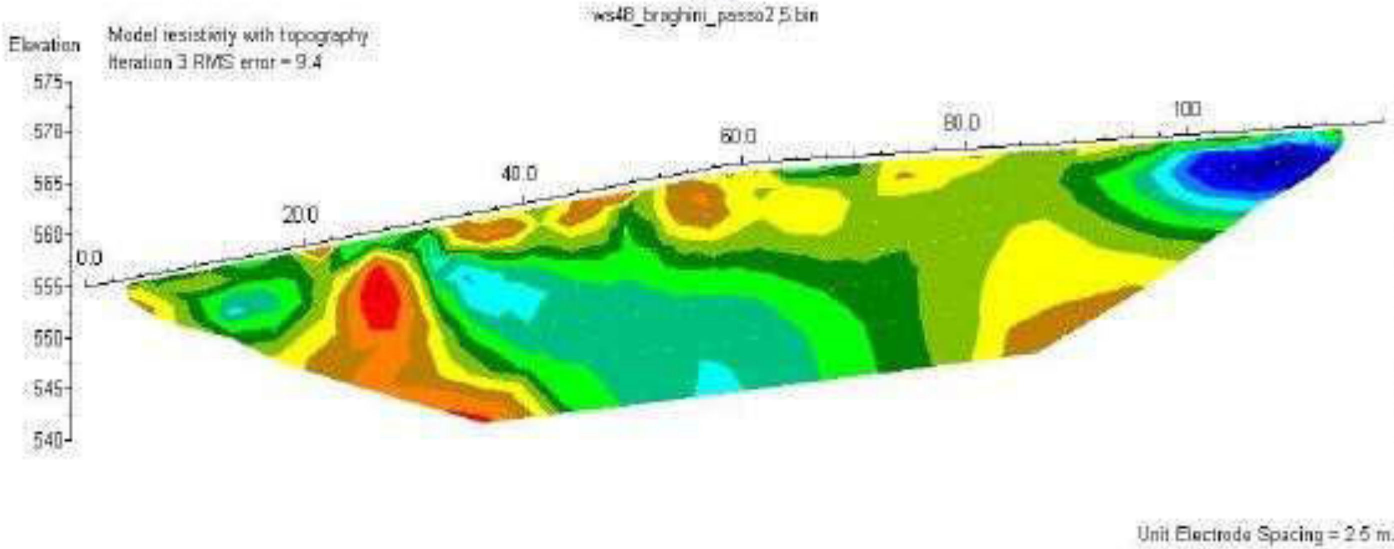


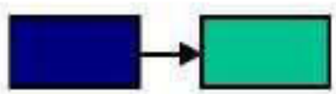
Figure 3. The Montorfano granite Massif lies very close to the Toce River and Maggiore Lake. The yellow square represents the Montorfano area. The figure shows also Sengio (blue square) and Ciana-Tane Pilastretto (red square) EW facilities. The Braghini EW facility is not reported in the picture (it is on the opposite side of the Toce river and pertains to the Monte Camoscio area).

Mining waste recycling: quarry dumps characterization

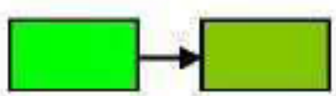
(b)



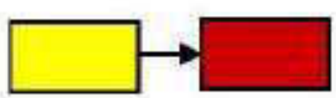
(c)



Low Resistivity values; they represent the finest quarry dump material with presence of water (aquifer).



Medium resistivity values: they represent the most part of the granite quarry waste



High resistivity values: they materialize the granite bedrock and the granite boulder.

Raw materials for the ceramic industry

Table 7. Geochemical analysis on the samples from Montorfano area and from the active dressing plant. waste rock (WR); magnetic fraction (MBP); nonmagnetic fraction (NMBP); feeding material (FM); the analytical error is ± 0.01 wt %.

	SiO_2 %	Al_2O_3 %	Fe_2O_3 %	MnO %	MgO %	CaO %	Na_2O %	K_2O %	TiO_2 %	P_2O_5 %
MO_01_01_WR	71.41	13.38	2.39	0.04	0.45	1.62	3.32	4.8	0.205	0.05
MO_01_02_WR	71.55	13.74	2.28	0.039	0.29	1.43	3.35	4.96	0.208	0.06
MO_01_03_WR	71.74	13.81	2.33	0.04	0.31	1.51	3.42	4.49	0.225	0.08
MO_01_04_WR	71.72	13.86	2.36	0.039	0.32	1.41	3.4	4.71	0.234	0.08
MO_01_05_WR	71.92	14.02	2.41	0.04	0.31	1.49	3.4	4.87	0.233	0.07
MO_01_06_WR	70.84	14.26	2.4	0.041	0.32	1.43	3.39	5.08	0.229	0.07
MO_01_07_WR	70.56	13.57	2.09	0.037	0.3	2.01	3.26	5.18	0.205	0.07
MO_01_08_WR	70.56	14.65	2.3	0.039	0.34	1.33	3.51	5.03	0.225	0.07
MO_02_01_MBP	63.81	14.37	7.93	0.143	1.2	1.4	2.8	4.8	0.73	0.15
MO_02_02_MBP	58.12	14.97	13.34	0.228	1.86	1.47	2.27	5.27	1.226	0.22
MO_02_03_MBP	56.45	15.89	13.2	0.225	1.82	1.74	2.52	5.26	1.285	0.32
MO_02_04 _FM	69.15	16.24	1.98	0.038	0.29	1.57	3.76	6.02	0.205	0.06
MO_02_05_NMBP	77.09	13.02	0.13	0.005	0.02	1.21	3.42	4.42	0.012	<0.01
MO_02_06_NMBP	74.19	14.36	0.3	0.008	0.05	1.5	3.73	5.27	0.027	0.01
MO_02_07_NMBP	76.93	12.99	0.15	0.005	0.04	1.25	3.42	4.51	0.014	<0.01
MO_02_08_NMBP	75.72	13.98	0.36	0.009	0.06	1.36	3.64	4.45	0.036	0.05

Also critical raw materials (REE)!

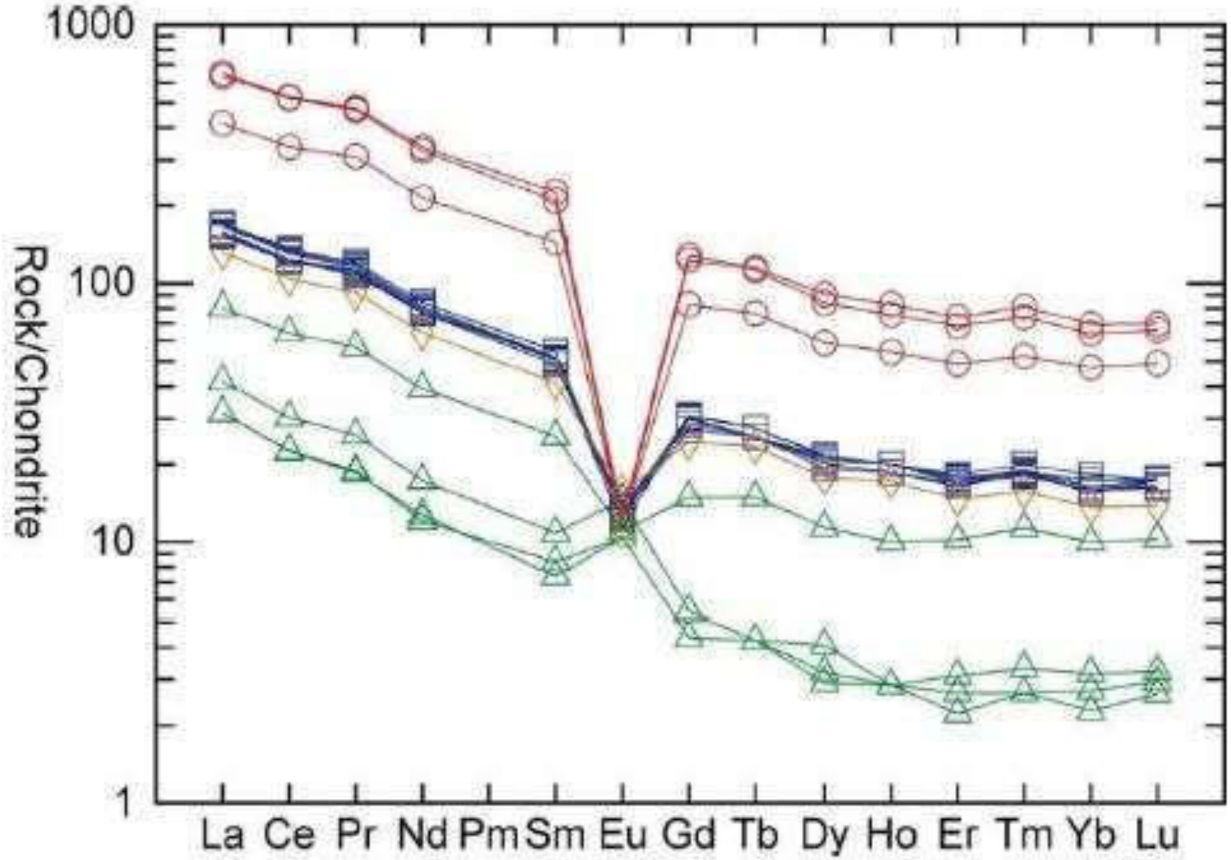


Figure 11. REE pattern for all samples, normalized to chondrite [41], logarithmic scale. Blue: WR; Red: treatment plant, magnetic fraction; Green: treatment plant, nonmagnetic fraction, Orange: treatment plant, feeding material.

Also critical raw materials (REE)!

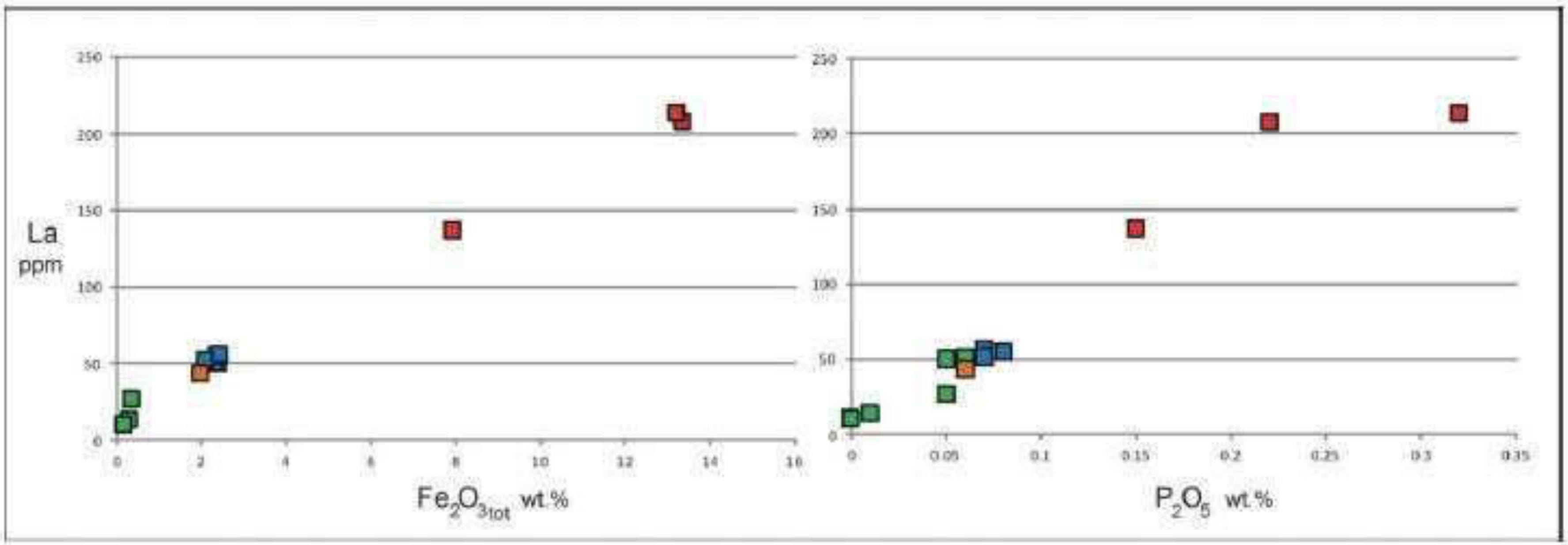


Figure 12. La–Fe_2O_3 and La–P_2O_5 correlations. La as ppm, Fe_2O_3 and P_2O_5 as wt %. Blue: WR; Red: treatment plant, magnetic fraction; Green: treatment plant, nonmagnetic fraction; Orange: feeding material.

LCA – Life Cycle Assessment

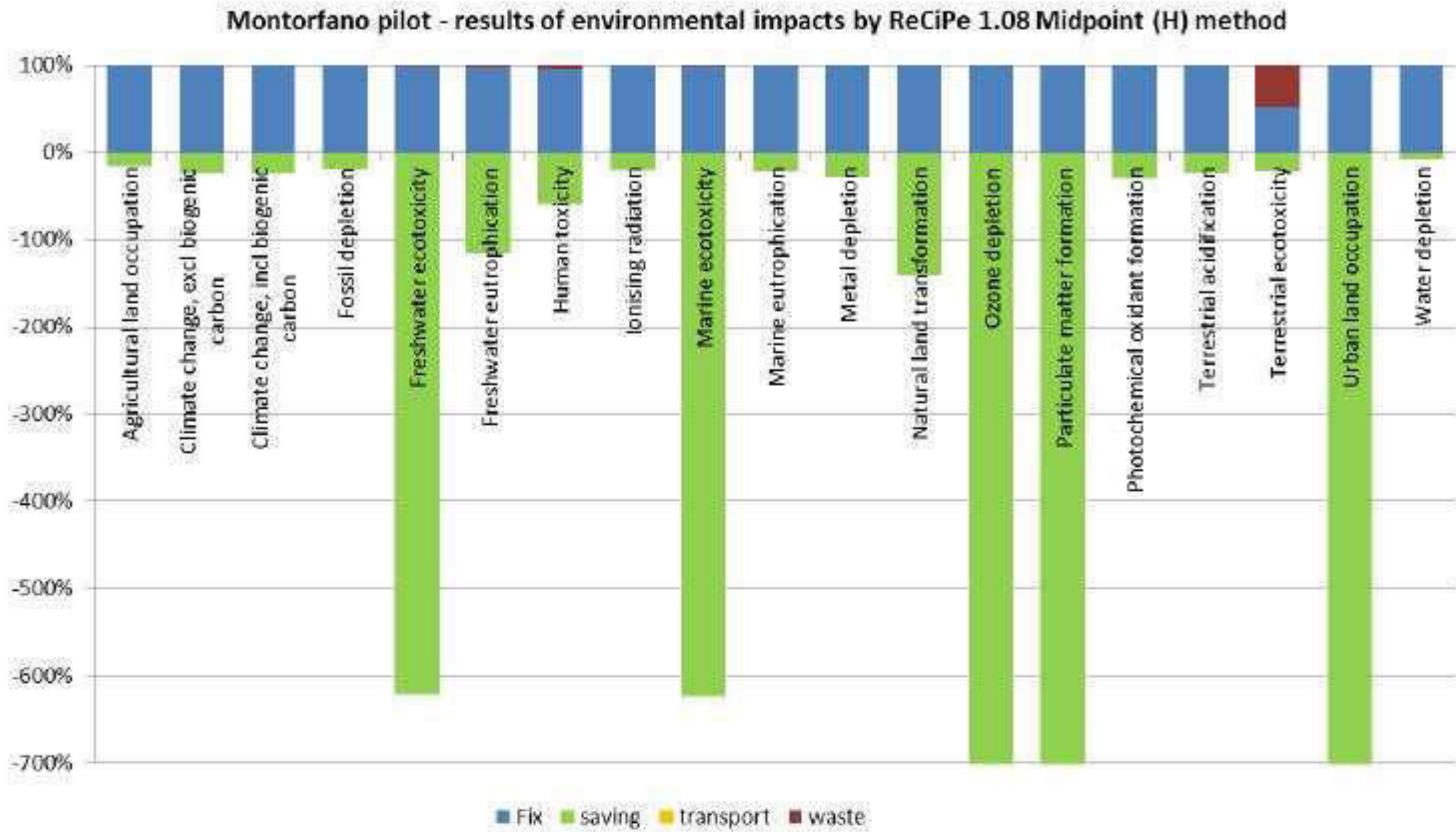
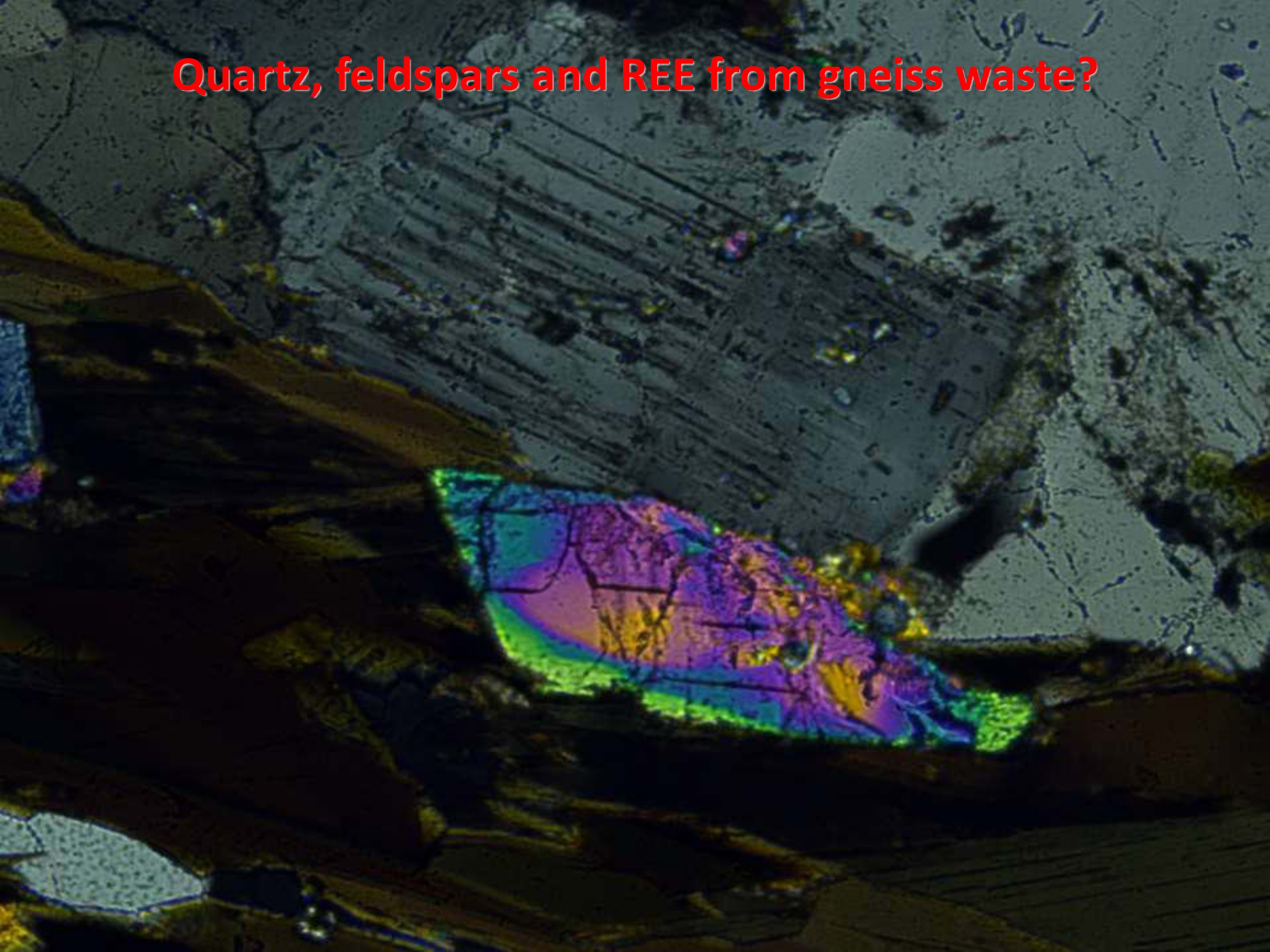


Figure 16. Environmental loads versus savings (Note: Due to the high saving values in several indicators, the chart has been cut to show other indicators).


Quartz, feldspars and REE from gneiss waste?

sustainability

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Article

Extractive Waste as a Resource: Quartz, Feldspars, and Rare Earth Elements from Gneiss Quarries of the Verbano-Cusio-Ossola Province (Piedmont, Northern Italy)

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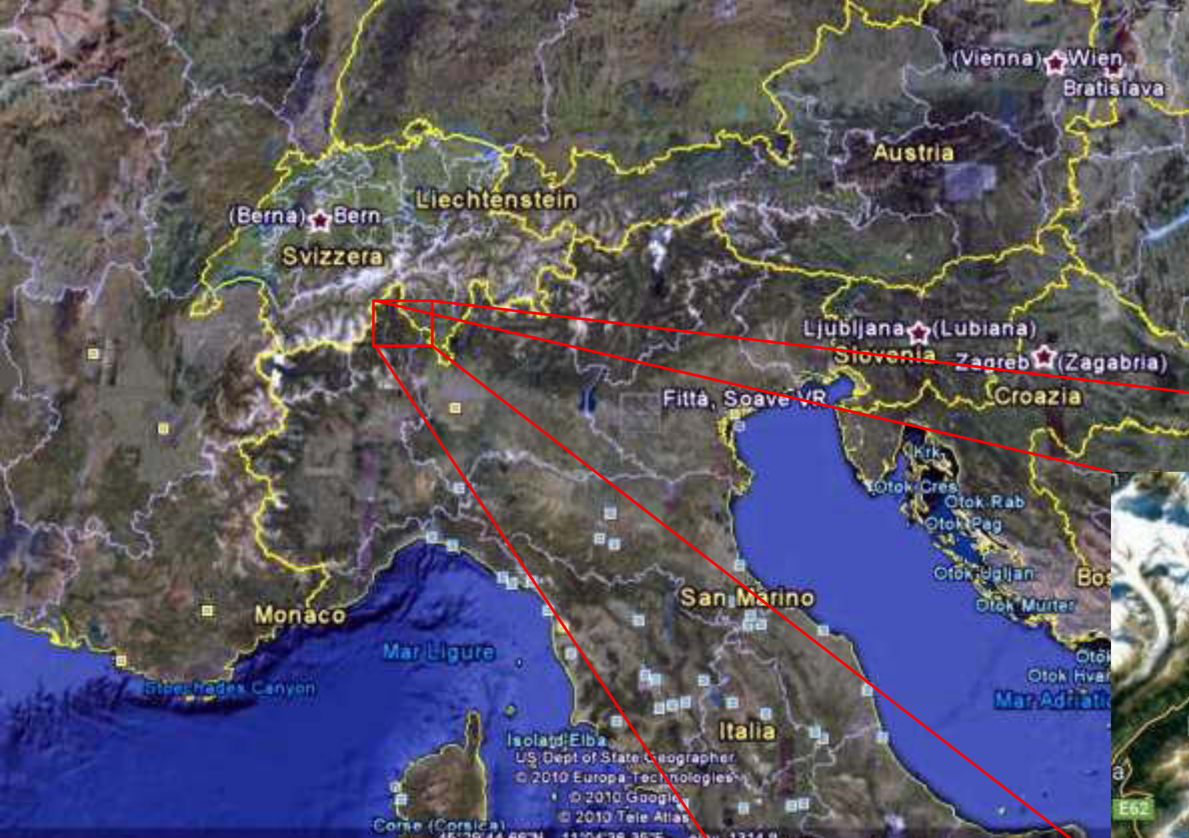
* Correspondence: alessandro.cavallo@unimib.it; Tel.: +39-0264482027

The VCO area


(Vienna) Wien
Bratislava
Austria
Liechtenstein
(Berna) Bern
Svizzera
Ljubljana (Lubiana)
Slovenia
Zagreb (Zagabria)
Croazia
Fittà, Soave VR
Krk
Otok Cres
Otok Rab
Otok Pag
Otok Ugljan
Otok Murter
Otok Hvar
Mar Adriatic
San Marino
Monaco
Mar Ligure
Stoechades Canyon
Italia
Isola d'Elba
US Dept of State Geographer
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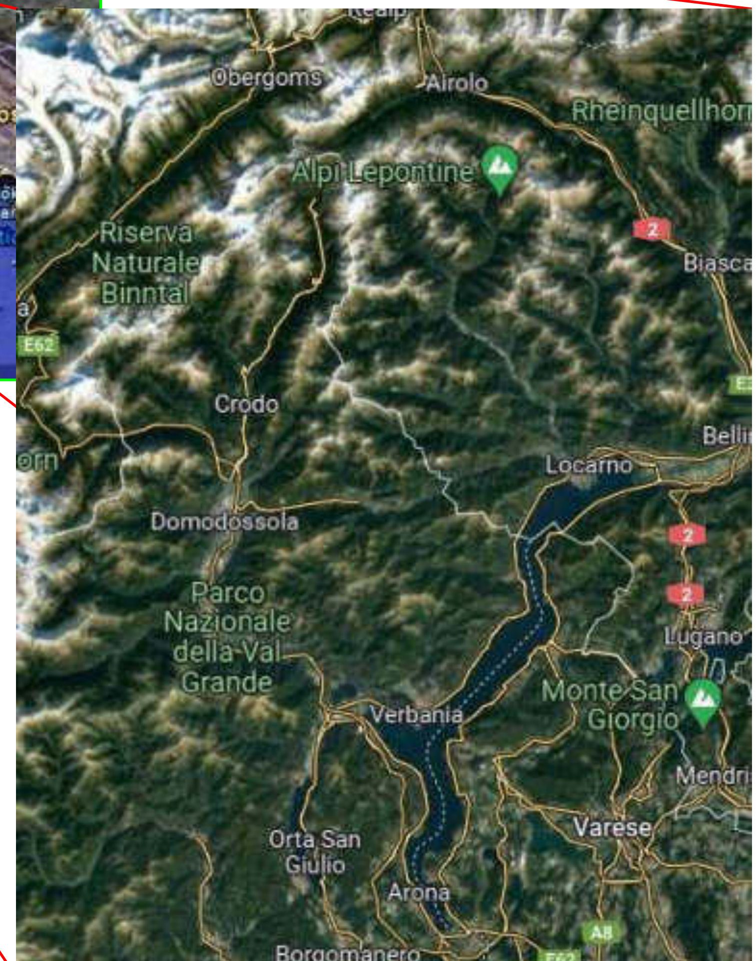
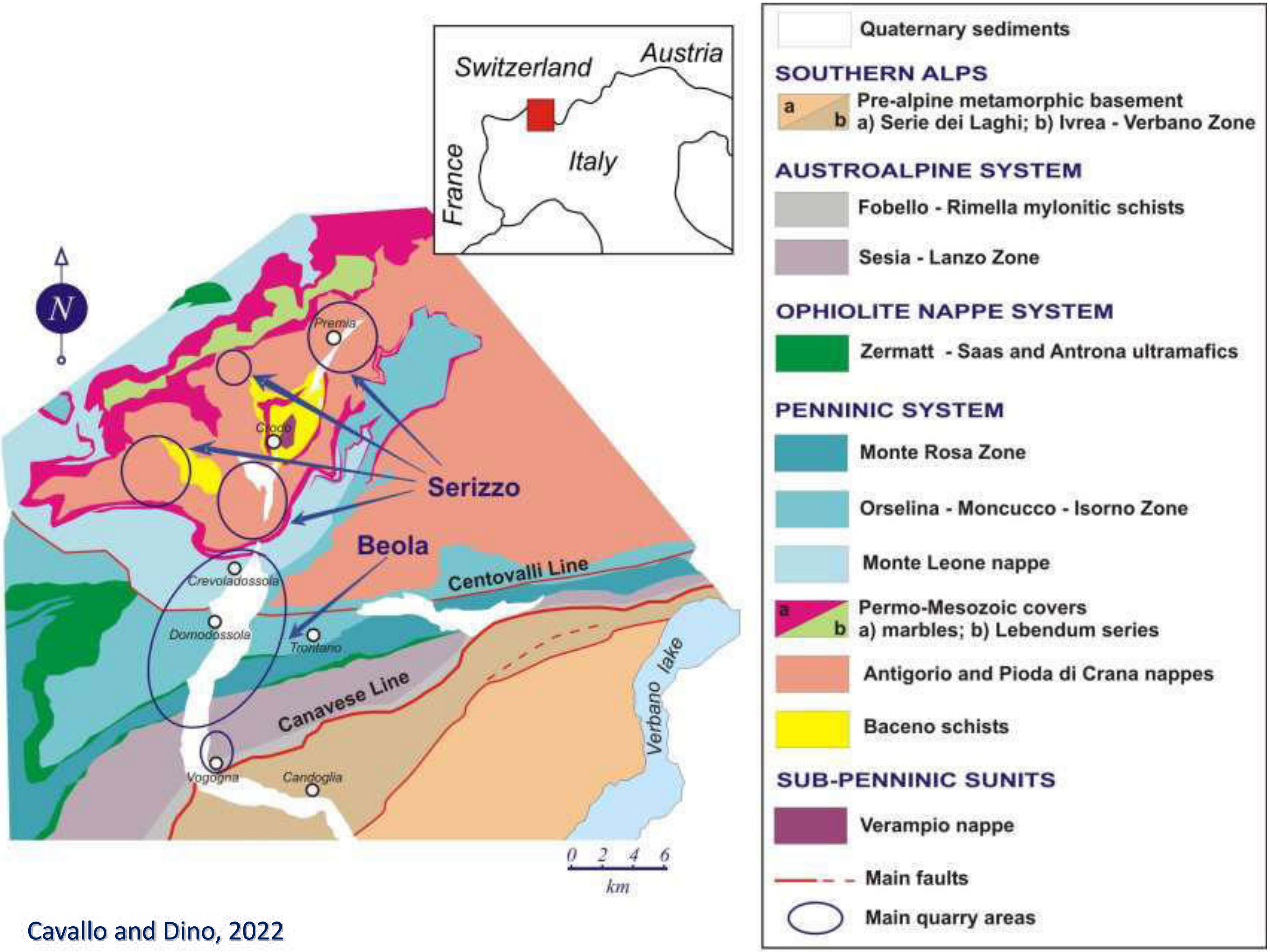
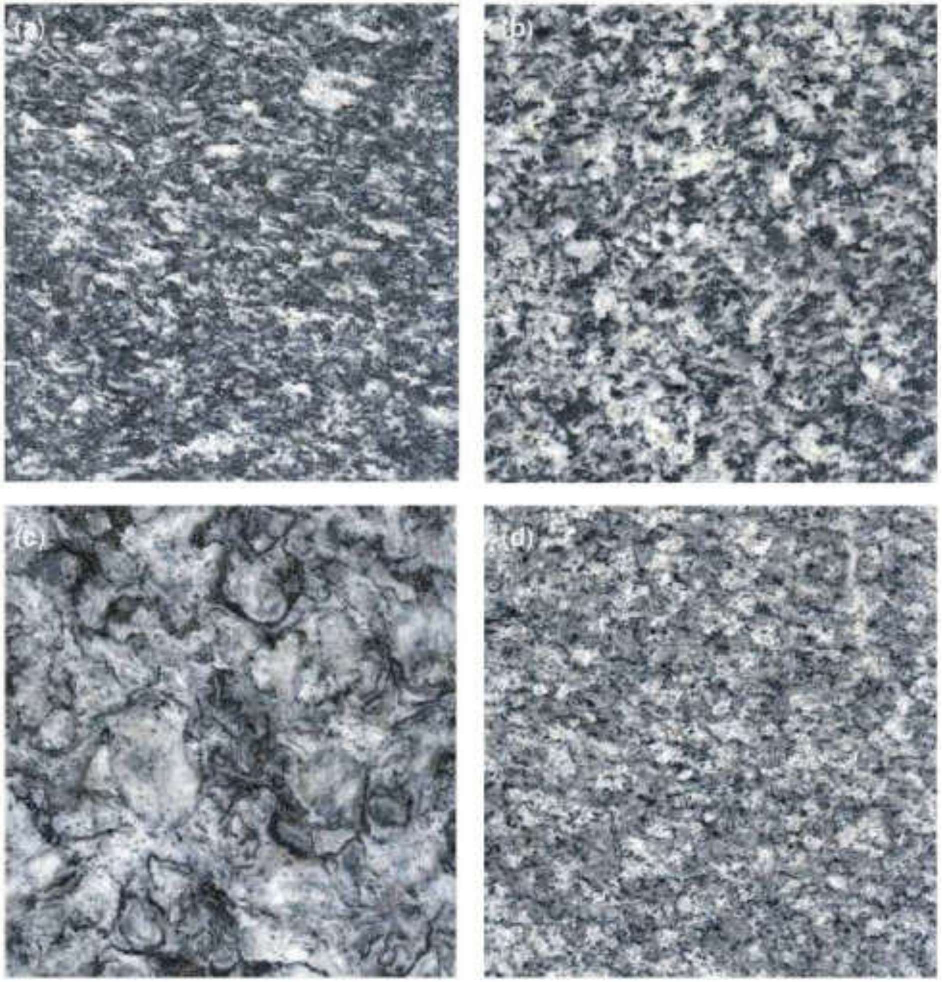

Obergoms
Airolo
Rheinquellhor
Alpi Lepontine
Riserva Naturale Binntal
Biasca
E62
Crodo
Locarno
Domodossola
Parco Nazionale della Val Grande
Lugano
Verbania
Monte San Giorgio
Orta San Giulio
Varese
Arona
Borgomanero
A8

Geological setting and dimension stones

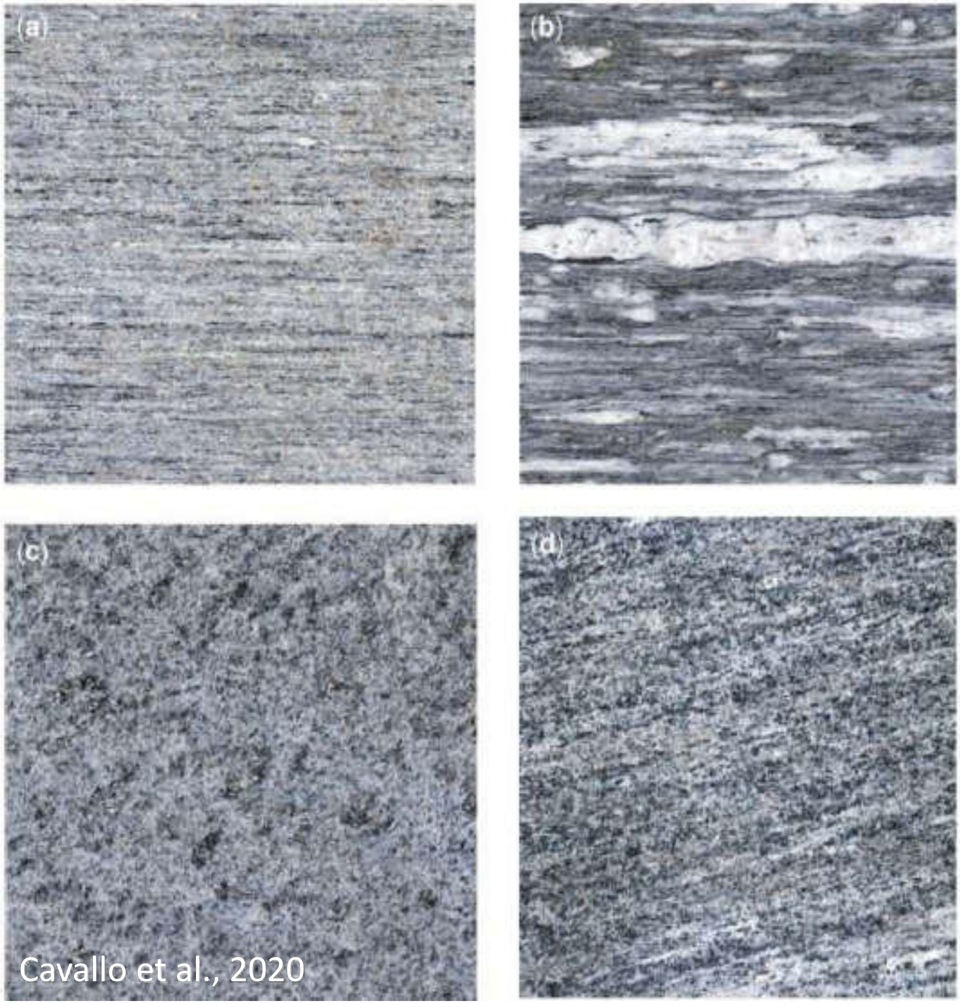


Cavallo and Dino, 2022

Serizzo and Beola: quarry production and waste materials

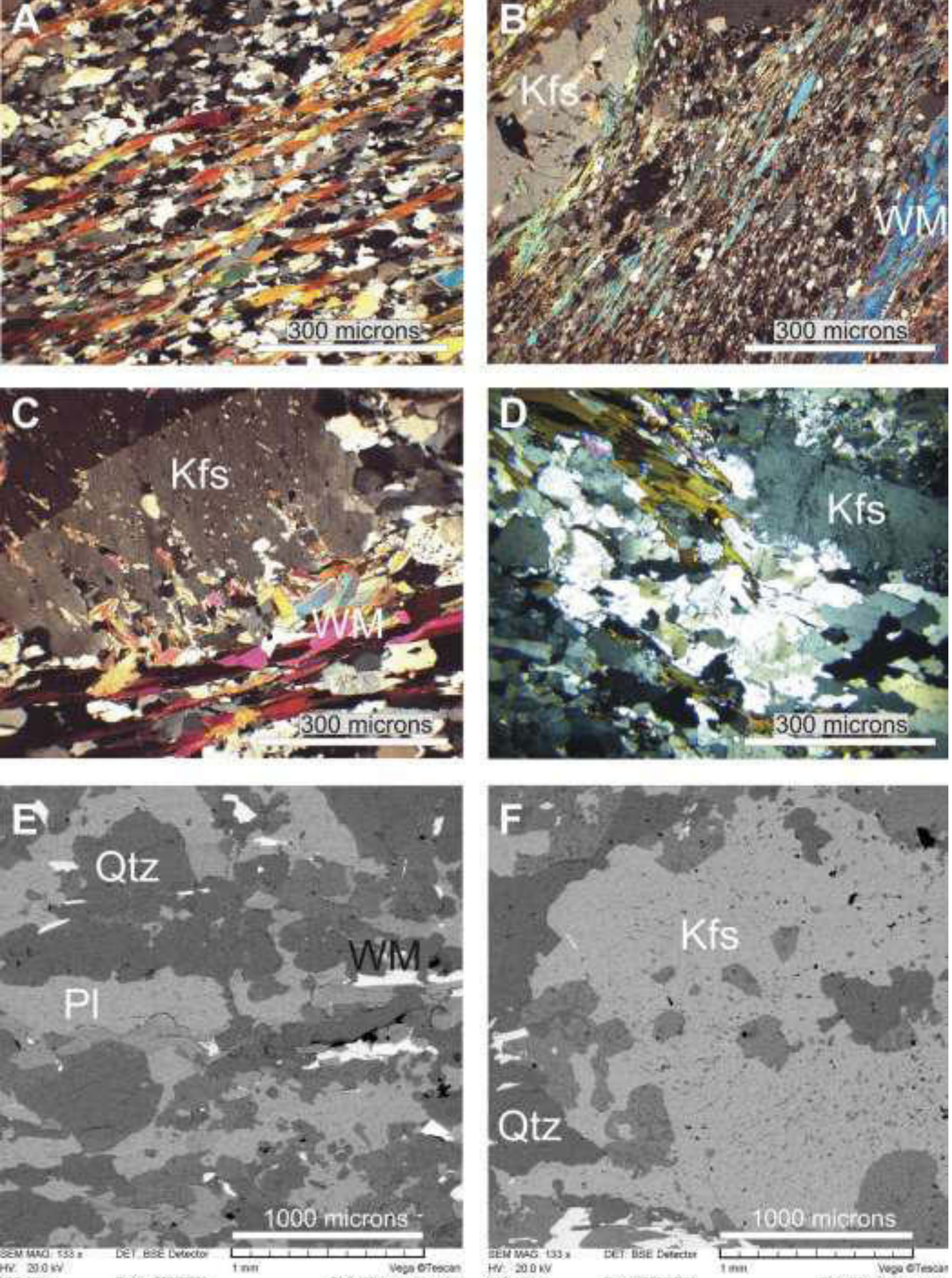


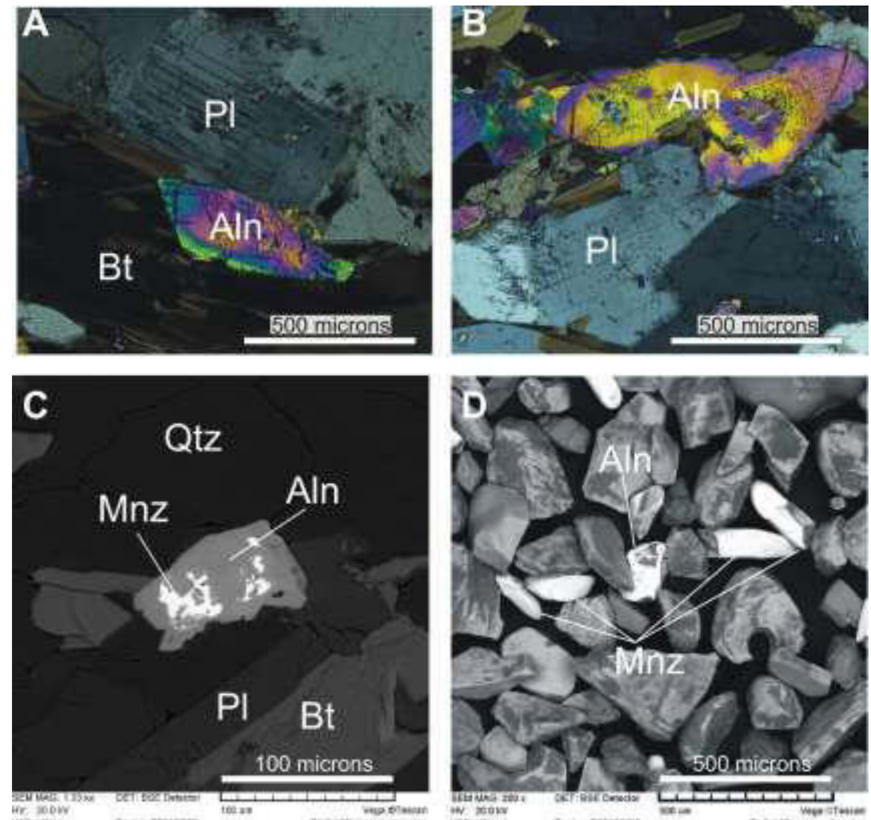
- 184,801.47 t/y in 2017
- 110,880 t/y of shapeless blocks and rock chips
- 17,700 t/y sludge (after filter-pressing)



Quarries and waste materials

Petrography and mineralogy





Cavallo and Dino, 2022

Table 1. Whole-rock geochemistry by ICP-OES and ICP-MS (C and S by LECO®) of *Serizzo* and *Beola* (115 *Beola* and 75 *Serizzo* waste rock chips, median values and range, wt.%).

	Serizzo (Median)	*Serizzo* (Range)	*Beola* (Median)	*Beola* (Range)
SiO_2	67.82	65.32–71.21	72.68	57.35–75.49
TiO_2	0.29	0.19–0.41	0.24	0.02–1.09
Al_2O_3	17.21	15.85–18.33	14.43	12.81–15.38
Fe_2O_3	1.35	0.85–1.74	1.90	0.39–6.88
MnO	0.18	0.09–0.25	0.17	0.01–0.11
MgO	0.74	0.41–1.05	0.47	0.21–5.16
CaO	3.25	2.86–3.86	1.22	0.72–7.06
Na_2O	3.39	2.85–4.06	3.58	2.89–7.09
K_2O	3.12	2.67–4.11	4.28	0.39–5.93
P_2O_5	0.19	0.14–0.36	0.17	0.11–0.26
LOI	1.2	0.5–1.9	0.7	0.4–2.7
C	0.02	0.01–0.07	0.03	0.01–0.13
S	0.06	0.01–0.18	0.05	<0.01–0.13
ΣREE * (ppm)	379	125–520	174	101–320

* Includes Y.

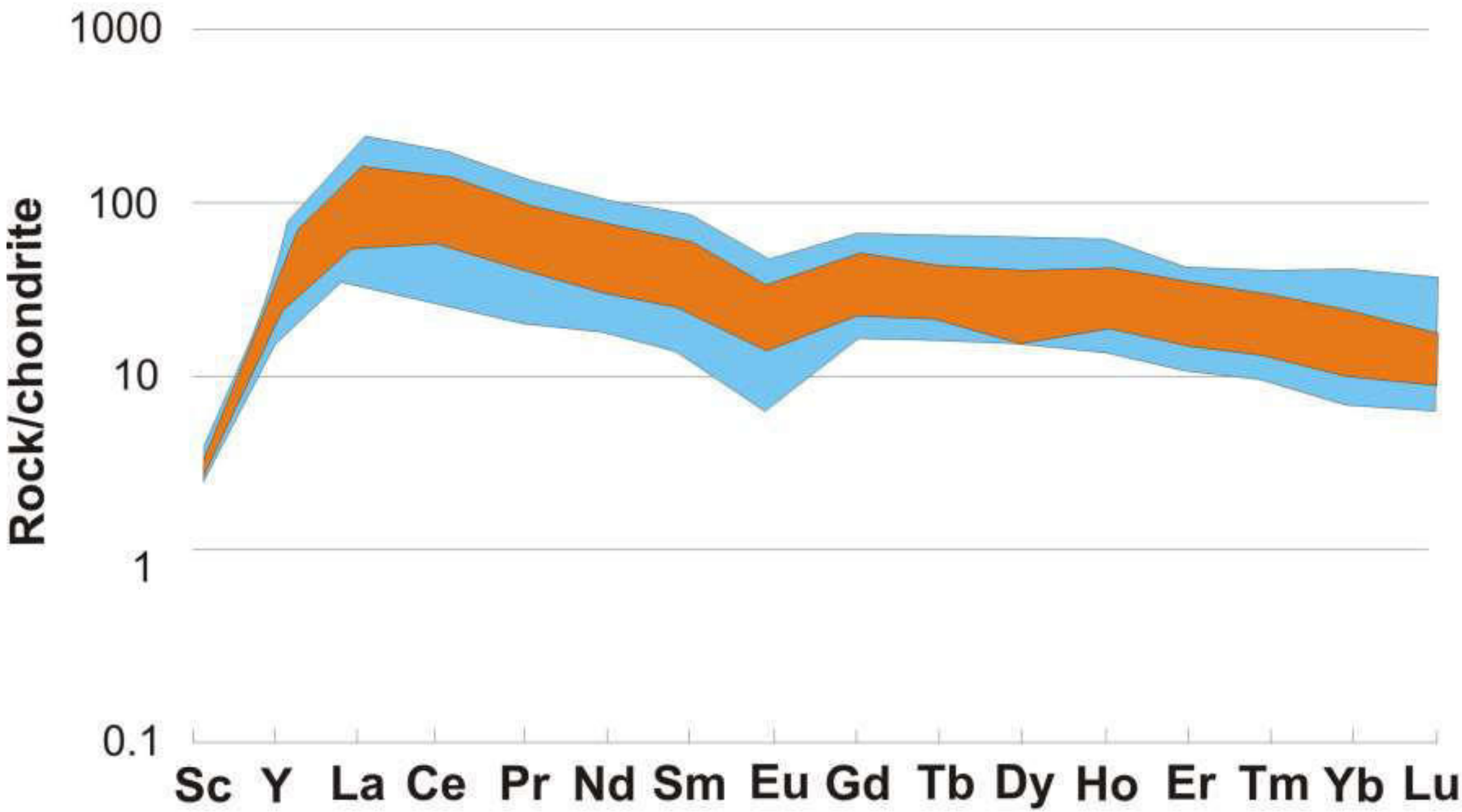
Table 2. Mineralogical composition of *Serizzo* and *Beola* (mean values and range of 190 samples, wt.%), determined by quantitative XRPD and OM (point counting).

	Serizzo (Mean)	*Serizzo* (Range)	*Beola* (Mean)	*Beola* (Range)
Qtz	35.1	28.2–35.6	40.6	14.3–52.2
Pl	30.2	28.2–36.4	27.1	21.1–32.5
Kfs	19.2	15.1–23.7	16.3	5.6–26.1
Bt	9.5	4.3–16.1	8.1	2.2–12.3
WM	4.2	1.9–8.6	5.3	3.5–15.4
Chl	1.8	0.8–3.2	2.6	2.5–9.6

Qtz = quartz; Pl = plagioclase; Kfs = K-feldspar; Bt = biotite; WM = white mica (muscovite); Chl = chlorite.

Cavallo and Dino, 2022

REE pattern of Serizzo and Beola



Cavallo and Dino, 2022

REE and allanite

Table 5. Mineral chemistry of allanite (median values and range, core, wt.%).

	Aln	Range
Sio_2	35.21	33.76–35.86
TiO_2	0.08	0.05–0.13
ThO_2	0.86	0.55–1.38
Al_2O_3	19.54	17.35–20.65
FeO	7.85	6.65–12.14
MnO	0.05	0.02–0.12
MgO	0.16	0.08–0.31
CaO	14.04	12.21–16.18
Y_2O_3	0.32	0.21–0.50
La_2O_3	3.67	2.86–5.12
Ce_2O_3	9.32	6.89–12.24
Pr_2O_3	1.21	0.82–1.95
Nd_2O_3	4.36	3.54–5.68
Sm_2O_3	0.67	0.34–1.11
Na_2O	0.04	0.02–0.10
K_2O	0.05	0.03–0.12
Total	97.43	

Cavallo and Dino, 2022

Quartz, feldspars and REE from gneiss waste? Why not!

- ***Quartz and feldspars could be reused in the industrial minerals sector, especially in the ceramics industry;***

- the most critical issues relate to the small grain size and the relative abundance of micas in some ***commercial varieties;***

- ***the presence of allanite opens new possibilities for the recovery of rare earth elements (REE, critical raw materials).***

Mining and quarrying waste recycling, again

Resources Policy 74 (2021) 102413

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Raw materials supply: Kaolin and quartz from ore deposits and recycling activities. The example of the Monte Bracco area (Piedmont, Northern Italy)

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[b] *University of Milano-Bicocca, Department of Earth and Environmental Sciences - DISAT, Milano, Italy*
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A R T I C L E I N F O

Keywords:
Kaolinitic clays
Quartz
Sustainable mining

A B S T R A C T

Demand and availability of raw materials, especially "critical" raw materials (e.g., rare earths), are becoming increasingly topical issues. In this article we show the potential of an Italian mining and quarrying site (Monte Bracco area, quartzites and kaolin): the combined study of geological, environmental, technical, and economic factors can lead to a sustainable exploitation of the waste from past mining activities, as well as to a resumption

Resources Policy, 2021

Sustainable supply or raw materials

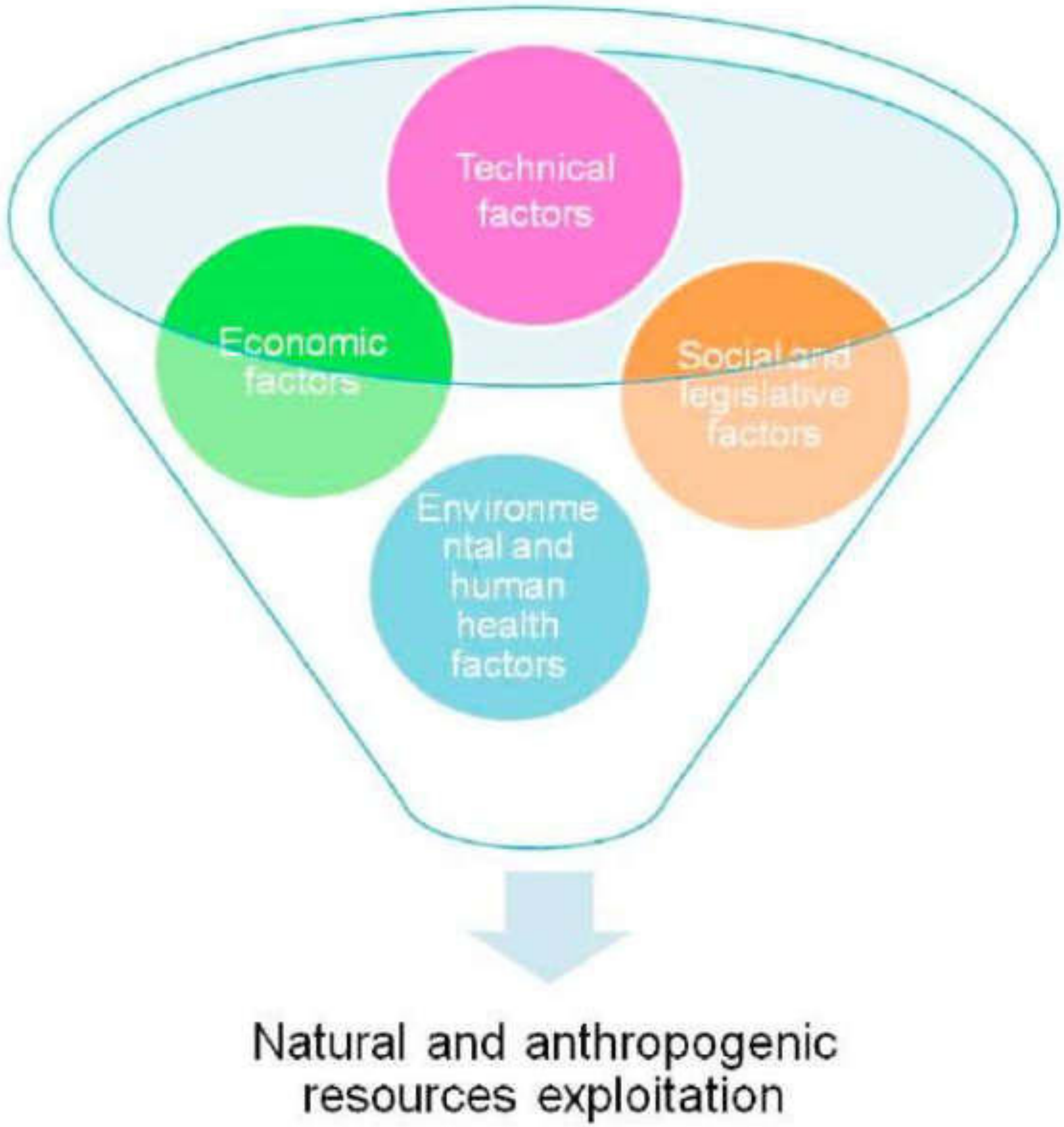


Fig. 2. scheme of the issues to considering when approaching RM (CRMs/SRM) supply in a sustainable way.

Dino *et al.*, 2021

Raw materials from extractive waste

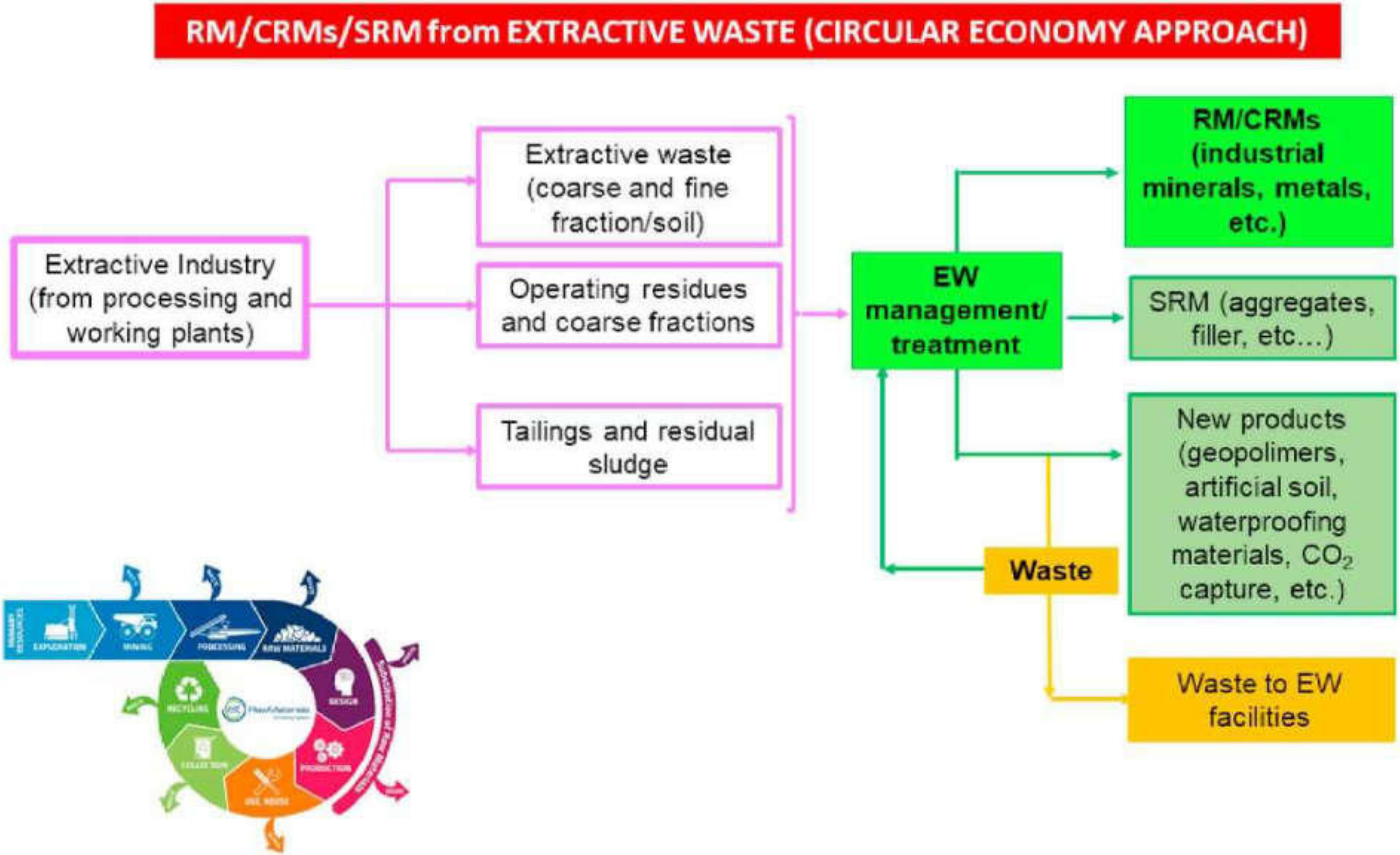


Fig. 3. RM/CRMs/SRM from EW (ongoing activities), in a circular economy approach.

Dino *et al.*, 2021

Raw materials from "landfill mining"

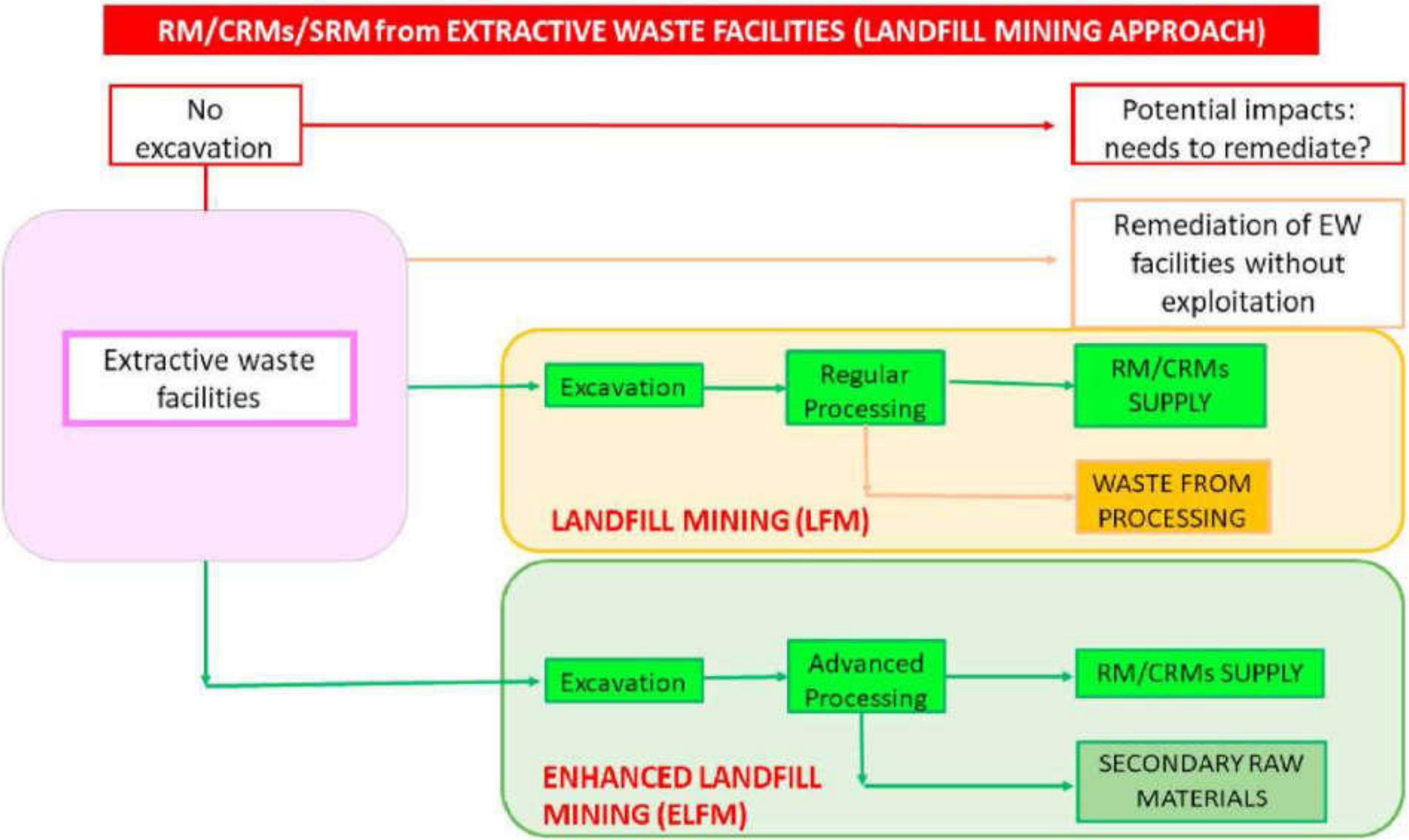


Fig. 4. RM/CRMs/SRM from EW facilities, in a landfill mining approach.

Dino *et al.*, 2021

Environmental and human health risk analysis

SOURCE (MATRIX)	TRANSPORT MECHANISM	EXPOSURE MODE	RECEPTOR
Superficial soil layer	DIRECT	DERMAL CONTACT - INGESTION	**ADULTS** (industrial, commercial, residential), **KIDS** (residential)
	EROSION DUE TO THE WIND (DUST) - VOLATILIZATION	INHALATION – RESPIRATION INDOOR OR OUTDOOR	
	PERCOLATION IN GW		GROUNDWATER
Deep soil layer	VOLATILIZATION	INHALATION – RESPIRATION INDOOR OR OUTDOOR	**ADULTS** (industrial, commercial, residential), **KIDS** (residential)
	PERCOLATION IN GW		GROUNDWATER
Groundwater (GW)	TRANSPORTATION AND DISPERSION IN GW		GROUNDWATER

Fig. 5. General conceptual model of specific site environmental and human health risk analysis.

Dino *et al.*, 2021

Silica sand and kaolinitic clays

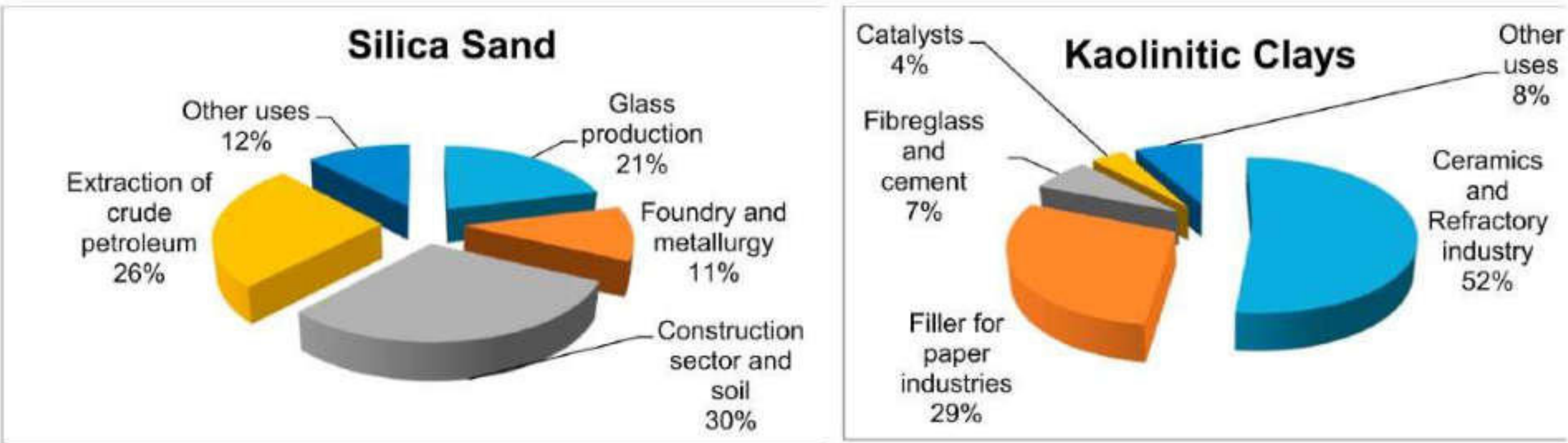
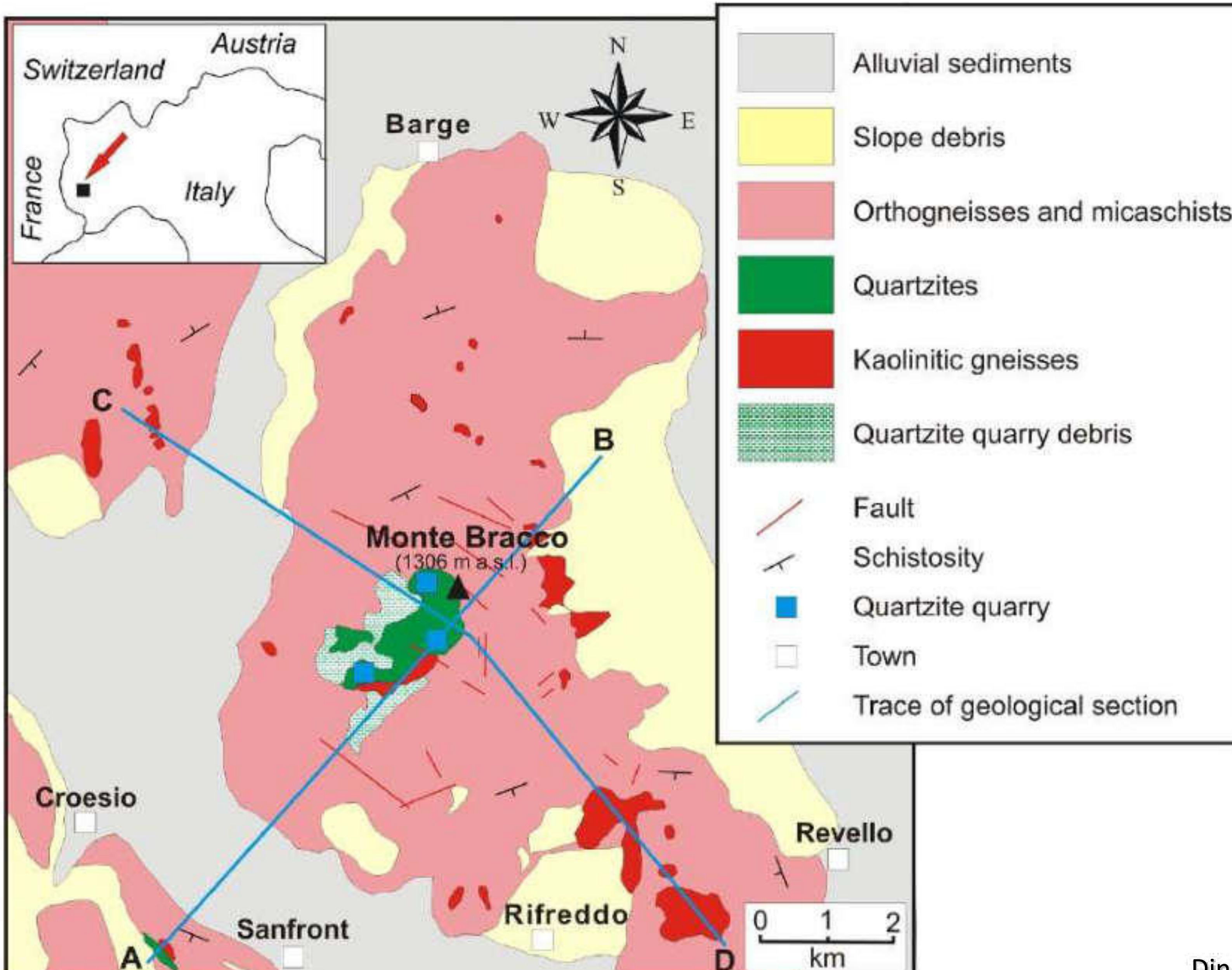


Fig. 1. Main applications of silica (on the left) and kaolinitic clays (on the right). Statistical data for global use, on average 2012–2016.

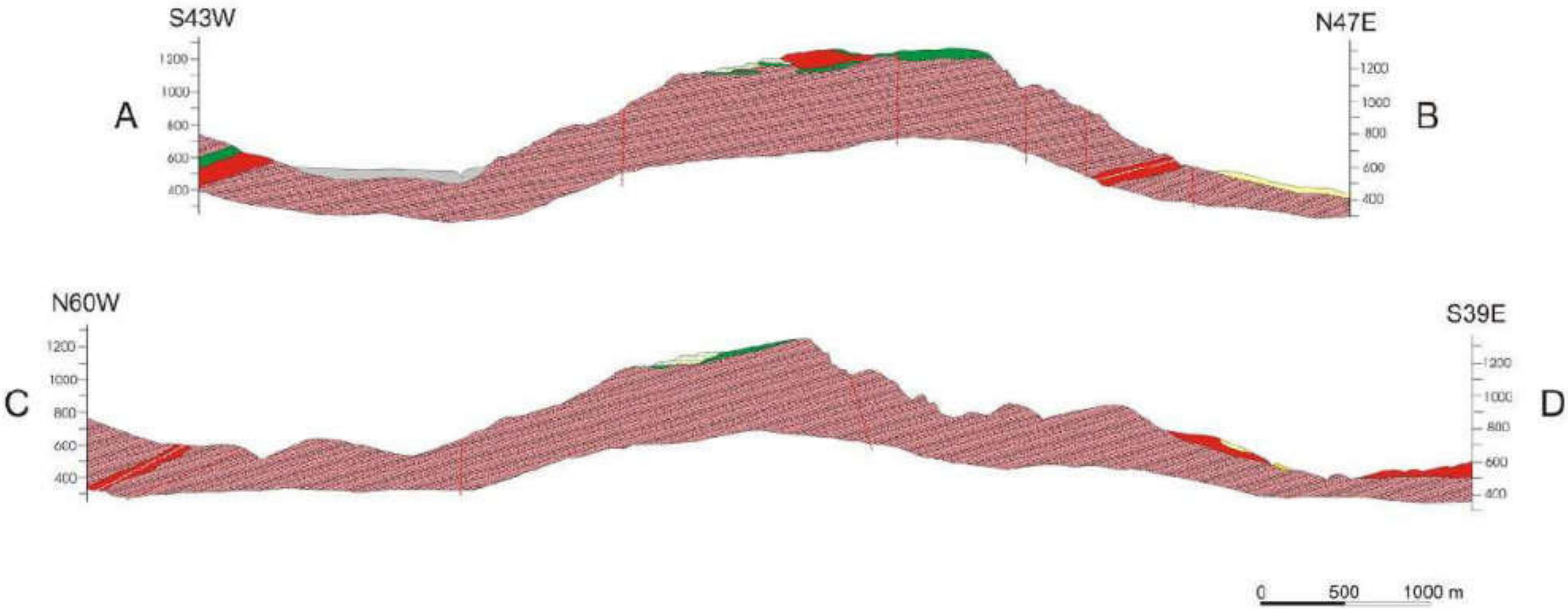
Dino *et al*., 2021

Geology of the Monte Bracco area



Dino *et al.*, 2021

Geology of the Monte Bracco area



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REE within kaolinitic clays!

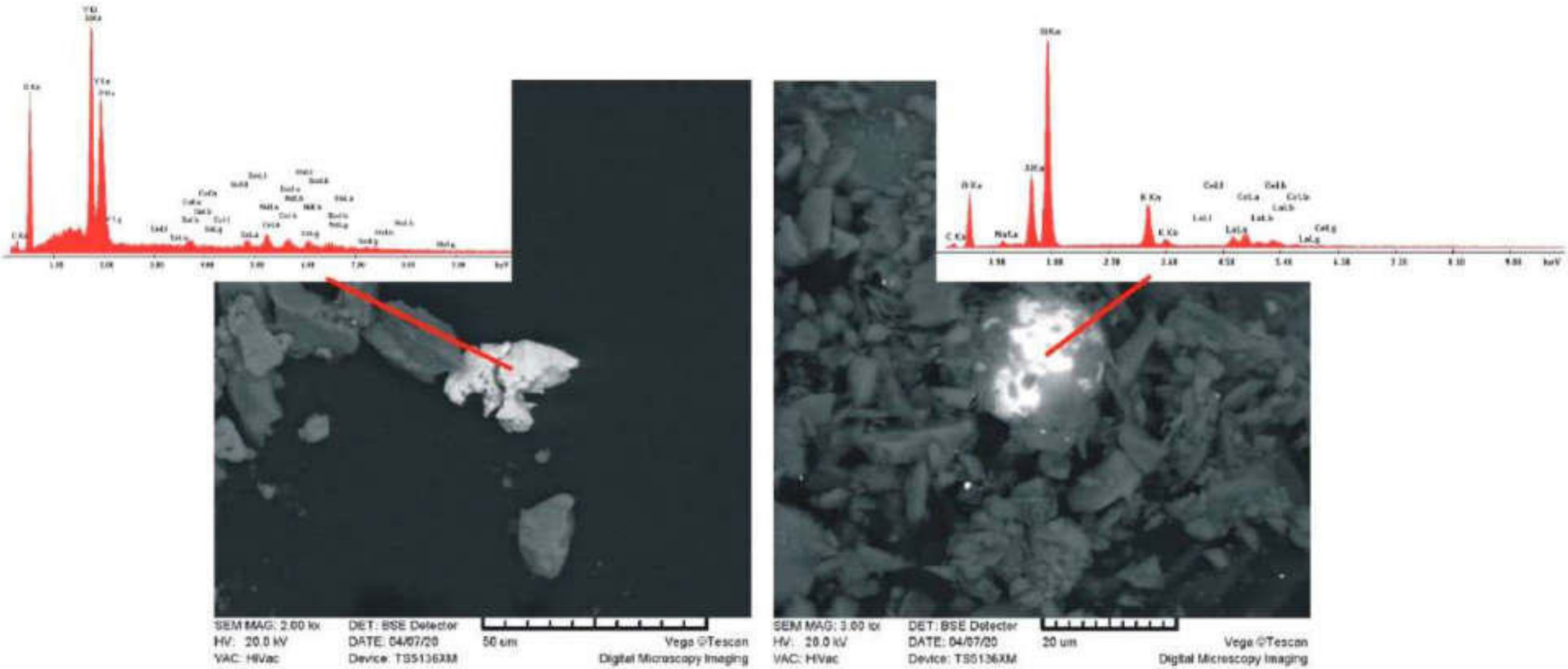

Fig. 8. SEM back-scattered electron micrographs of kaolinitic gneiss samples. A xenotime grain is shown on the left, whereas a LREE-enriched illite grain is evidenced on the right.

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REE within kaolinitic clays!

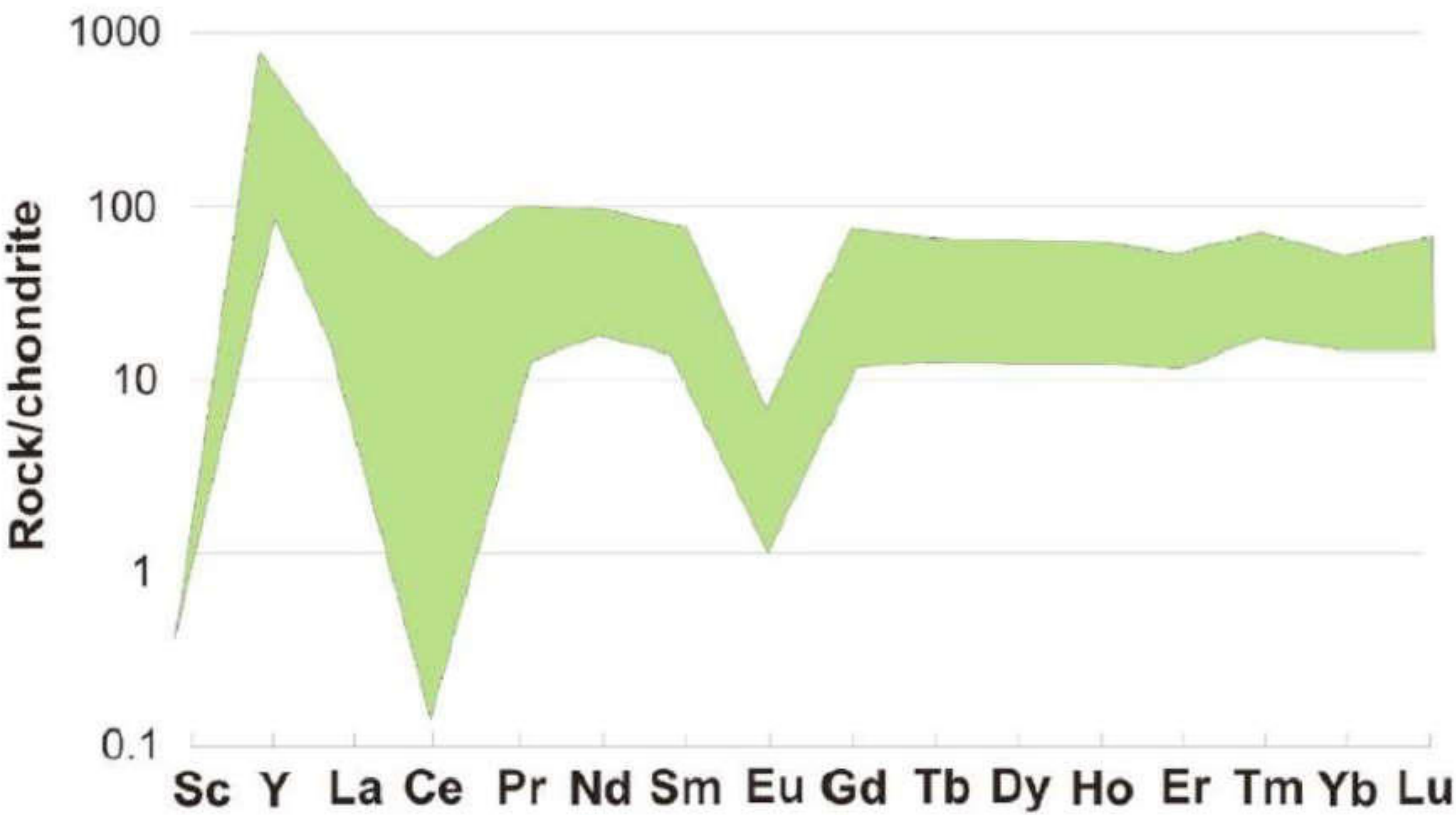

Fig. 9. Rock/chondrite normalized spidergram of the kaolinitic gneiss (mean of 32 samples). Chondritic values after Nakamura (1974) and Wood et al. (1979) (Sc and Y).

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The processing plant

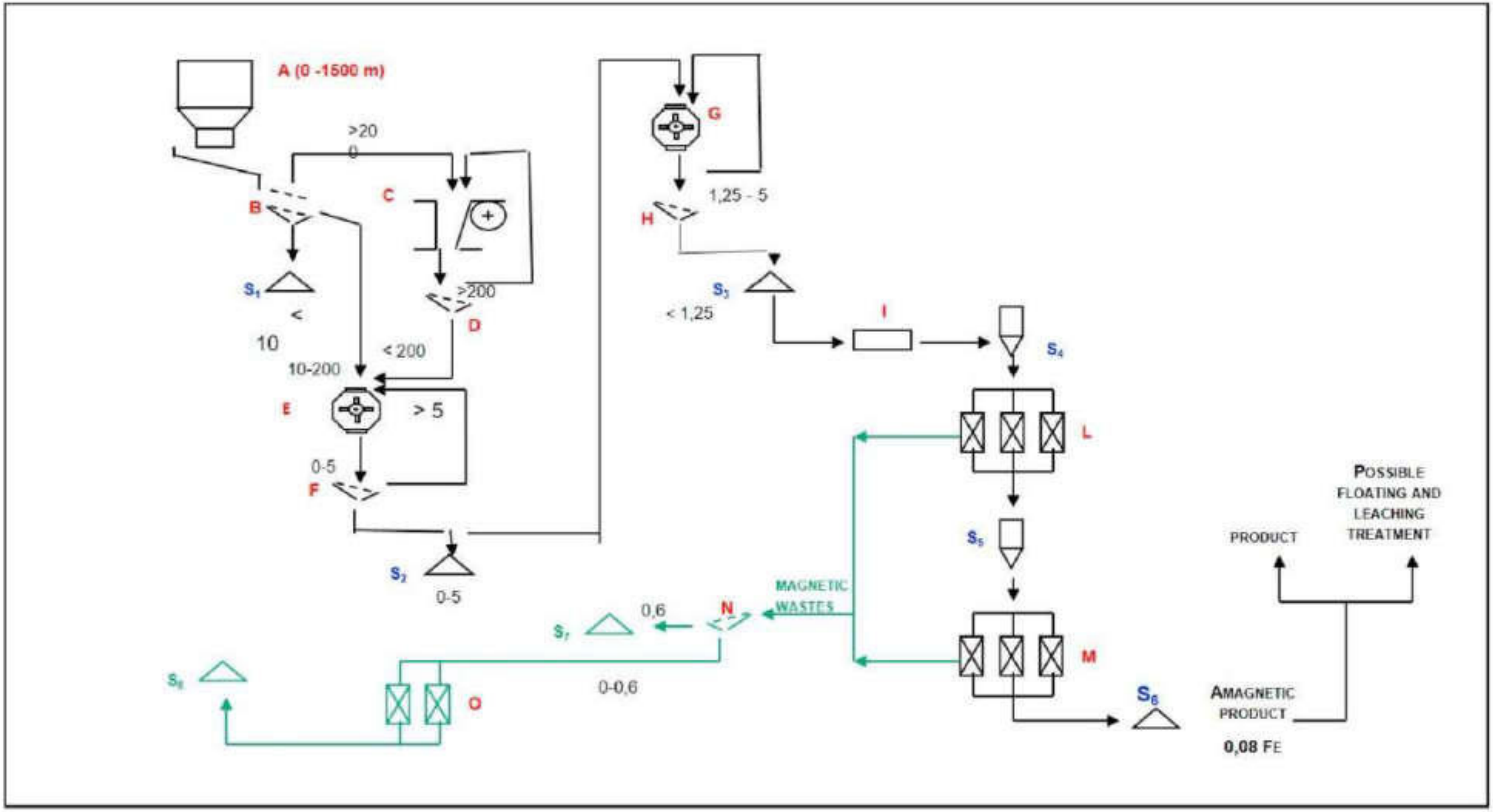

Fig. 10. "Dry process" plant flowsheet for quartzite quarry wastes (in black). It is also shown a possible treatment concentrating phase (in green). Where: A: vibrating feeder; B: vibrating screen classifier (200-10 mm); C: jaw crusher; D: vibrating screen classifier (200 mm); E: gyratory crusher; F: vibrating screen classifier (5 mm); G: gyratory crusher; H: vibrating screen classifier (1.25 mm); I: continuous dryer; L: magnetic separators; M: magnetic separators; N: vibrating screen classifier (0.6 mm); O: magnetic separators. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

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Particular waste materials…

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Serpentinitic waste materials from the dimension stone industry: Characterization, possible reuses and critical issues

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ABSTRACT

Serpentinites, ultramafic rocks with a peculiar chemical and mineralogical composition, can be used as dimension stones, but there are no significant re-uses of waste materials deriving from quarrying and processing. This paper presents the example from Valmalenco (central Alps, northern Italy), with a detailed mineralogical, chemical, physical and microstructural characterization of waste materials, ranging from shapeless blocks to residual sludge. The mineralogical composition is characterized by abundant antigorite and olivine, with minor chlorite, clinopyroxene and magnetite, and the chemical composition by high MgO grades. The preliminary results suggest interesting applications in the ceramic industry, especially in high-MgO ceramics and forsterite refractories materials, as well as alternative uses as filler for plastic and rubber materials, up to carbon dioxide sequestration. Special care must be taken to avoid chrysotile asbestos contamination.

Cavallo, 2018

Serpentinite quarries and quarry debris

Fig. 1. Open-cast hillside serpentinite quarries with huge debris fans.

Cavallo, 2018

Serpentinite processing

Fig. 2. Serpentinite processing activities, diamond wire squaring off of blocks (on the left) and diamond disk cutting (on the right).

Cavallo, 2018

Quarry production and waste

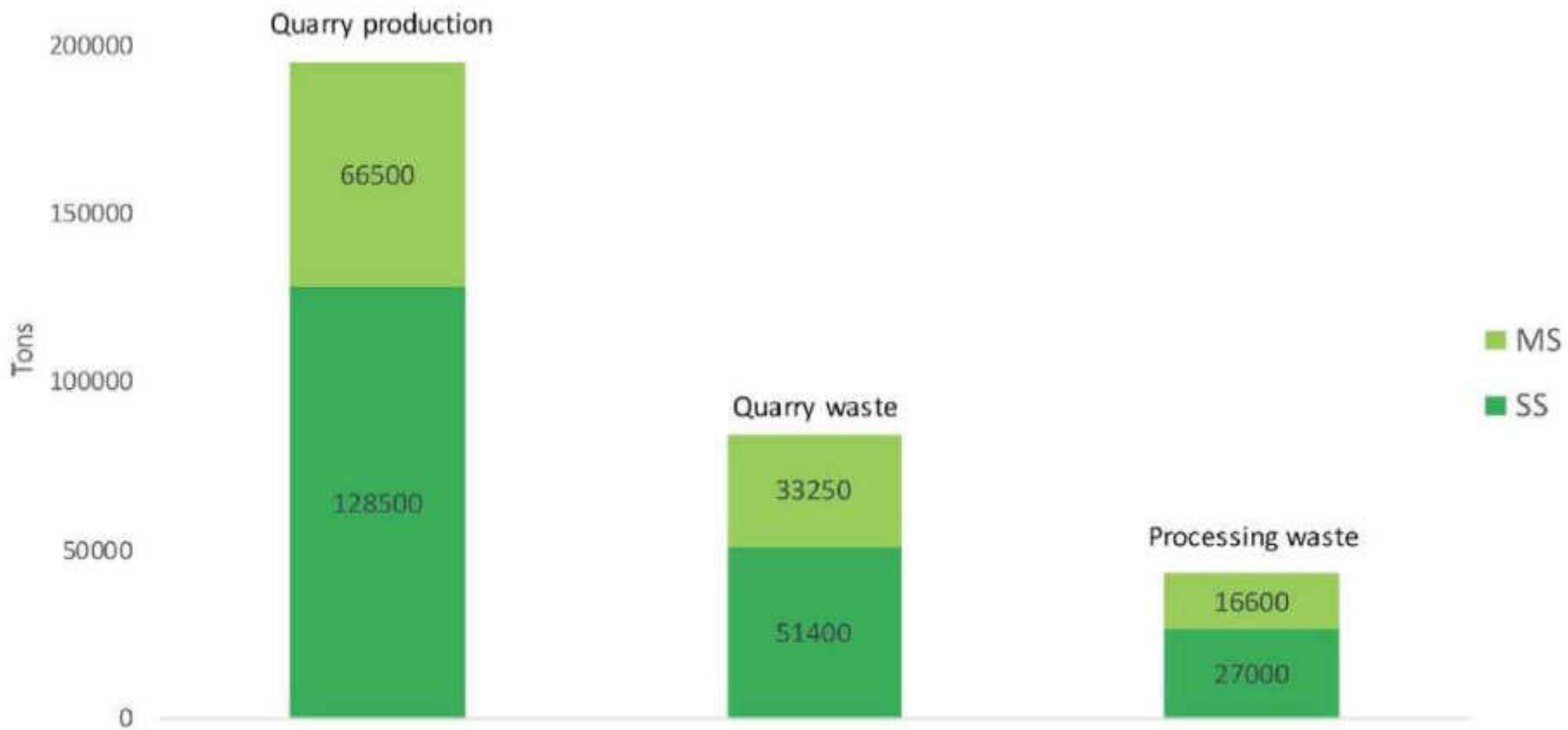


Fig. 3. Quarry production, quarry and processing waste for [SS] and [MS] in t/yr.

Cavallo, 2018

Serpentinitic waste mineralogy

Table 1
Mineralogical composition (wt%) of debris rock samples ([SS] and [MS] varieties) and residual processing sludge, determined by quantitative XRPD (Chipera and Bish, 2002).

	Antigorite mean (range)	Olivine mean (range)	Clinopyroxene mean (range)	Chlorite mean (range)	Magnetite mean (range)	Brucite mean (range)
SS schistose serpentinite debris	63.5 (59.4–73.7)	19.6 (9.6–31.1)	6.1 (3.0–8.9)	6.6 (1.5–17.4)	3.6 (0.5–6.8)	0.5 (< 0.5–1.5)
MS massive serpentinite debris	75.5 (71.4–89.3)	14.3 (3.0–28.4)	3.6 (0.5–9.8)	3.3 (1.8–12.2)	2.6 (1.1–5.7)	0.7 (0.5–2.0)
residual processing sludge	69.1 (57.1–79.5)	18.5 (7.2–31.4)	5.3 (1.1–6.1)	3.5 (1.5–11.7)	3.1 (1.2–6.0)	0.5 (< 0.5–1.1)

Cavallo, 2018

Table 2
Chemical composition of debris rock samples ([SS] and [MS] varieties) and residual processing sludge, determined by ICP-AES, ICP-MS and LECO®.

	[SS] debris mean (range)	[MS] debris mean (range)	Residual processing sludge mean (range)
wt%			
SiO_2	40.75 (39.18 – 41.93)	39.33 (38.73 – 40.67)	42.21 (38.12 – 45.41)
TiO_2	0.02 (0.02 – 0.06)	0.03 (0.01 – 0.11)	0.11 (0.01 – 0.18)
Al_2O_3	2.23 (0.78 – 2.54)	1.74 (1.36 – 2.65)	2.48 (0.95 – 5.54)
Fe_2O_3	8.11 (7.15 – 8.95)	8.35 (7.72 – 9.57)	7.75 (7.54 – 7.93)
MnO	0.10 (0.09 – 0.13)	0.09 (0.09 – 0.12)	0.11 (0.11 – 0.15)
MgO	39.42 (37.46 – 43.84)	40.31 (35.07 – 42.78)	36.24 (29.83 – 41.22)
CaO	1.88 (0.81 – 2.89)	1.42 (0.12 – 3.16)	1.71 (0.67 – 3.62)
Na_2O	0.01 (< 0.01 – 0.04)	0.01 (< 0.01 – 0.03)	0.38 (0.02 – 0.98)
K_2O	0.02 (< 0.02 – 0.03)	0.03 (< 0.02 – 0.05)	0.26 (< 0.02 – 0.67)
P_2O_5	0.05 (< 0.01 – 0.08)	0.04 (< 0.01 – 0.07)	0.05 (0.02 – 0.08)
Cr_2O_3	0.31 (0.23 – 0.39)	0.33 (0.28 – 0.41)	0.29 (0.25 – 0.37)
C	0.01 (0.01 – 0.04)	0.01 (0.01 – 0.04)	0.19 (0.09 – 0.43)
S	0.01 (< 0.01 – 0.05)	0.01 (0.01 – 0.05)	0.02 (0.01 – 0.04)
LOI	7.1 (5.4 – 10.4)	8.3 (6.3 – 9.9)	8.2 (6.7 – 9.2)
ppm			
Sc	(9–14)	(9 – 13)	(8 – 10)
V	(33 – 66)	(44 – 70)	(30 – 47)
Co	(97 – 124)	(87 – 118)	(88 – 134)
Ni	(1317 – 1965)	(1279 – 2357)	(1621 – 2118)
Cu	(1.9 – 24.5)	(5.3 – 17.1)	(32 – 72)
Zn	(19 – 41)	(21 – 36)	(32 – 45)
Ga	(1.1 – 2.8)	(1.1 – 2.9)	(1.3 – 6.2)
Rb	(< 0.5 – 1)	(< 0.5 – 0.8)	(< 0.5 – 21.1)
Sr	(0.7 – 12.5)	(< 0.5 – 3.8)	(1.4 – 101.2)
Y	(0.3 – 2.3)	(0.1 – 3.5)	(0.4 – 4.8)
Zr	(< 0.5 – 2.6)	(< 0.5 – 3.1)	(0.5 – 4.8)

Serpentinitic waste geochemistry

Cavallo, 2018

Serpentinites: petrography

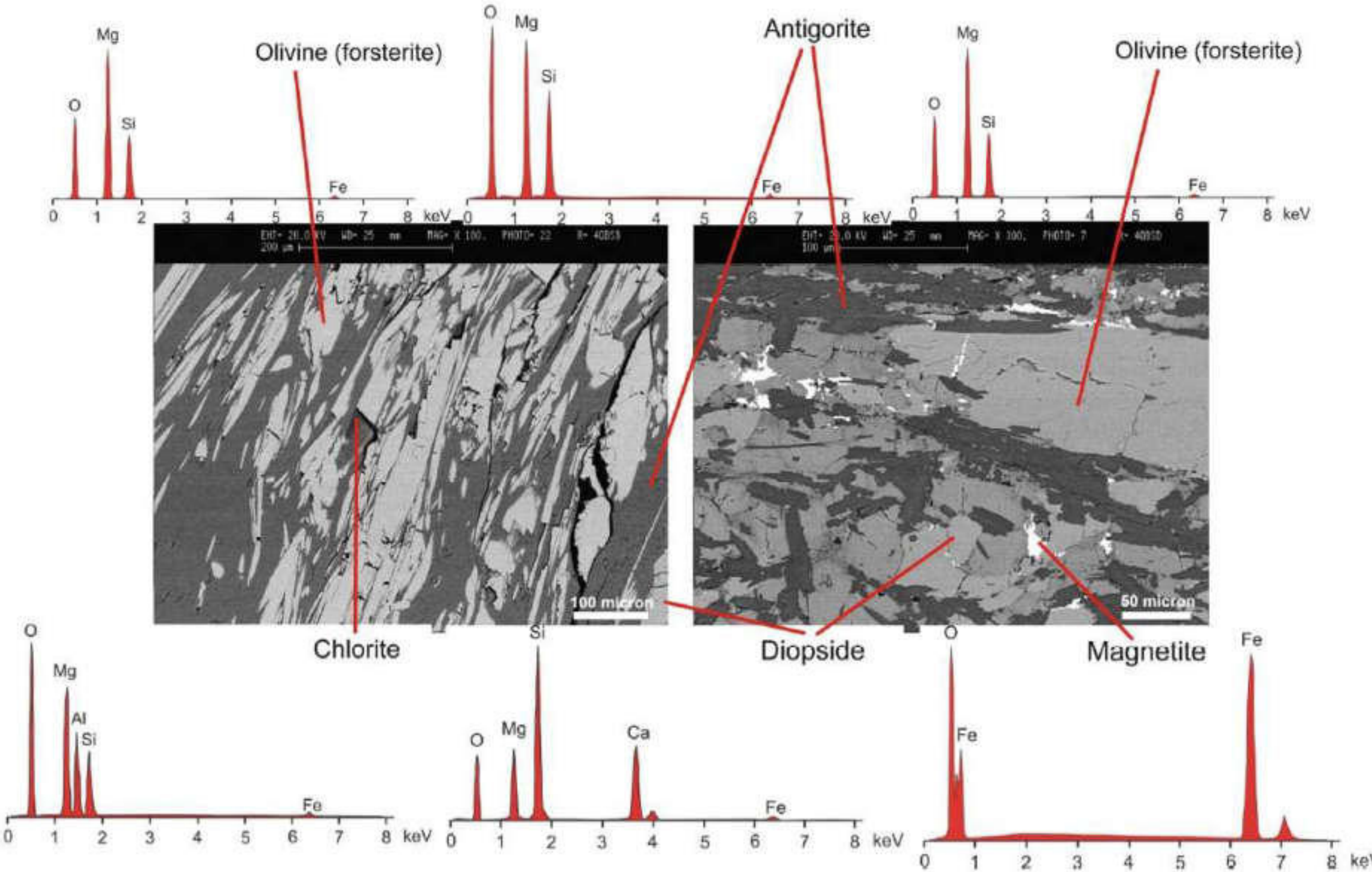


Fig. 4. SEM back-scattered electrons micrographs of the main serpentinite varieties, [SS] on the left and [MS] on the right). Dark grey areas are antigorite blades, whereas light grey grains are mainly olivine and clinopyroxene (diopside).

Cavallo, 2018

Serpentinitic processing sludge

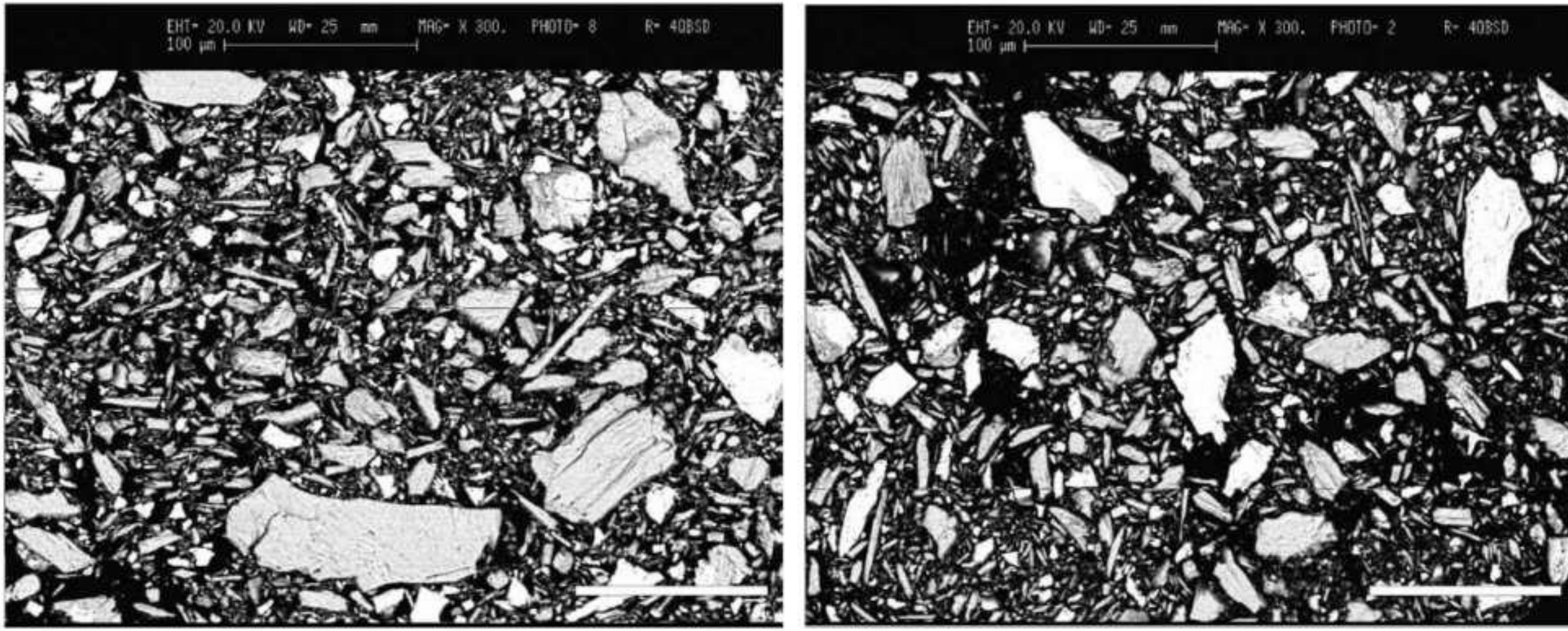


Fig. 5. SEM back-scattered electrons micrographs of residual sludge deriving from serpentinite processing; scale bar is 100 µm.

Cavallo, 2018

Serpentinites and chrysotile asbestos

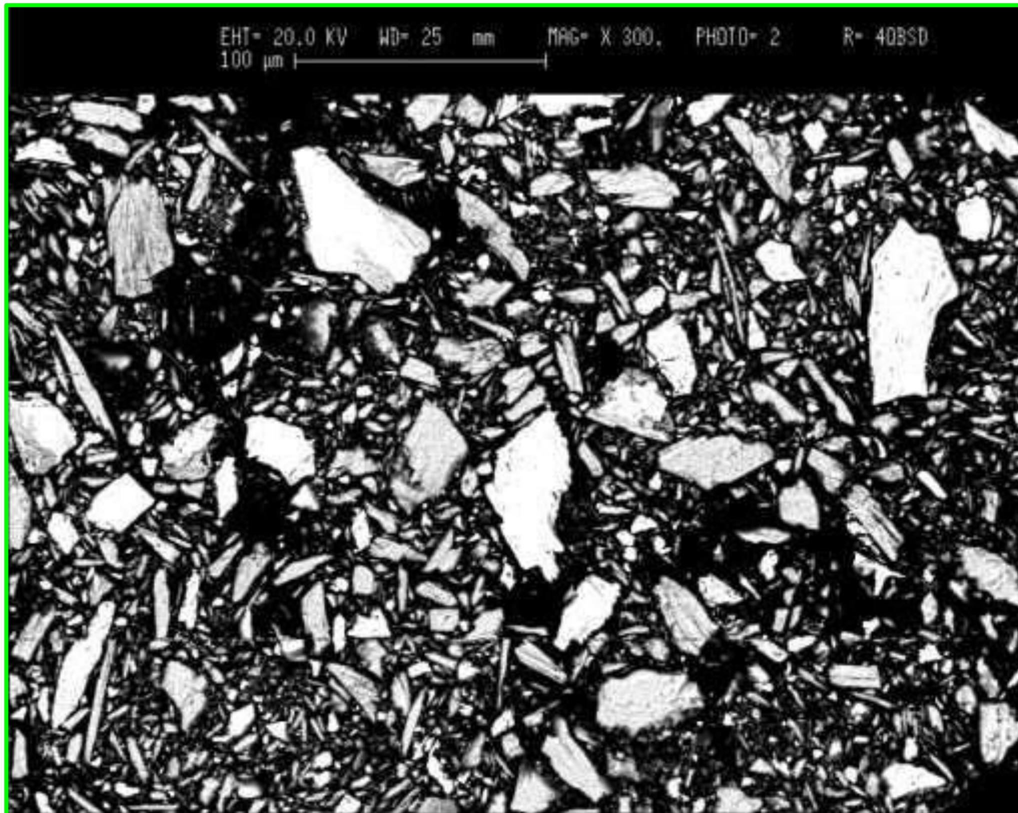
Chrysotile asbestos concentrations (mean values and range + 1σ, experimental error related to counting statistics) of debris rock samples ([SS] and [MS] varieties) and residual processing sludge.

	Chrysotile mean	Chrysotile range + 1σ
[SS] debris	< 100	< 100–350
[MS] debris	390	< 100–1600
residual processing sludge	250	< 100–670

Cavallo, 2018

Possible reuses:
1) artificial “green” marbles

Possible reuses:
2) Filler for plastic and rubber materials instead of talc!

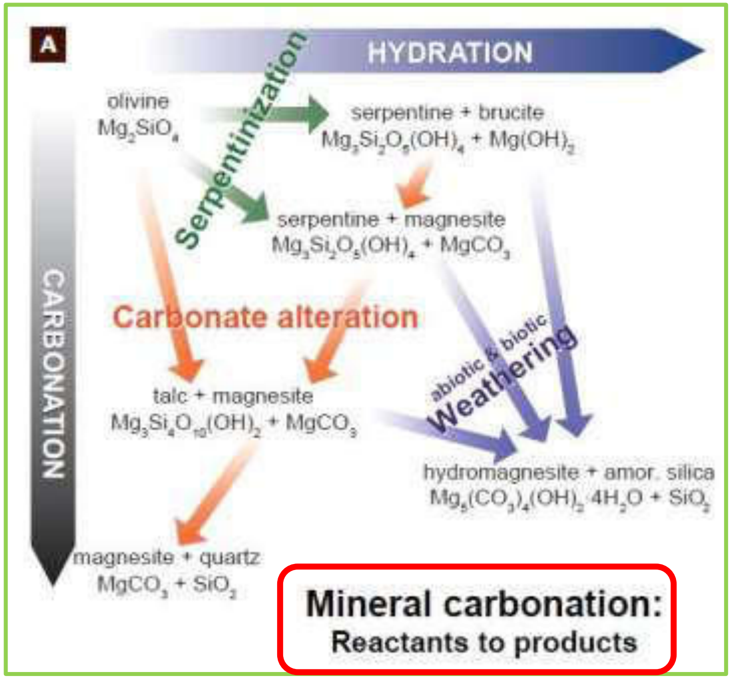


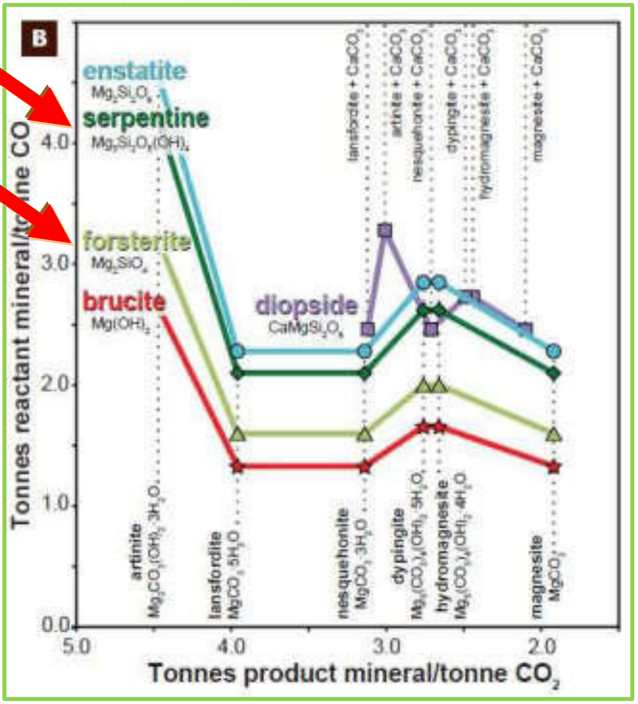
First results are encouraging!

Possible reuses:
3) Ceramics

- forsterite and/or high-MgO ceramics;
- forsterite refractories (with periclase addition);
- cordierite ceramics (adding kaolin);
- high-hardness vitroceramics.

Possible reuses: 4) CO_2 sequestration



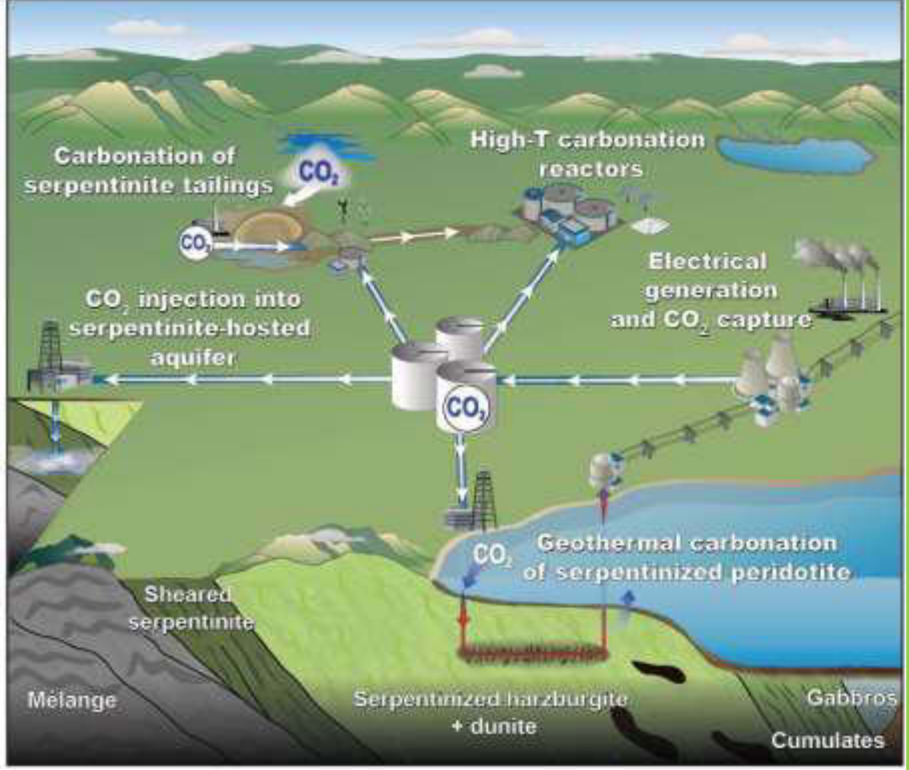


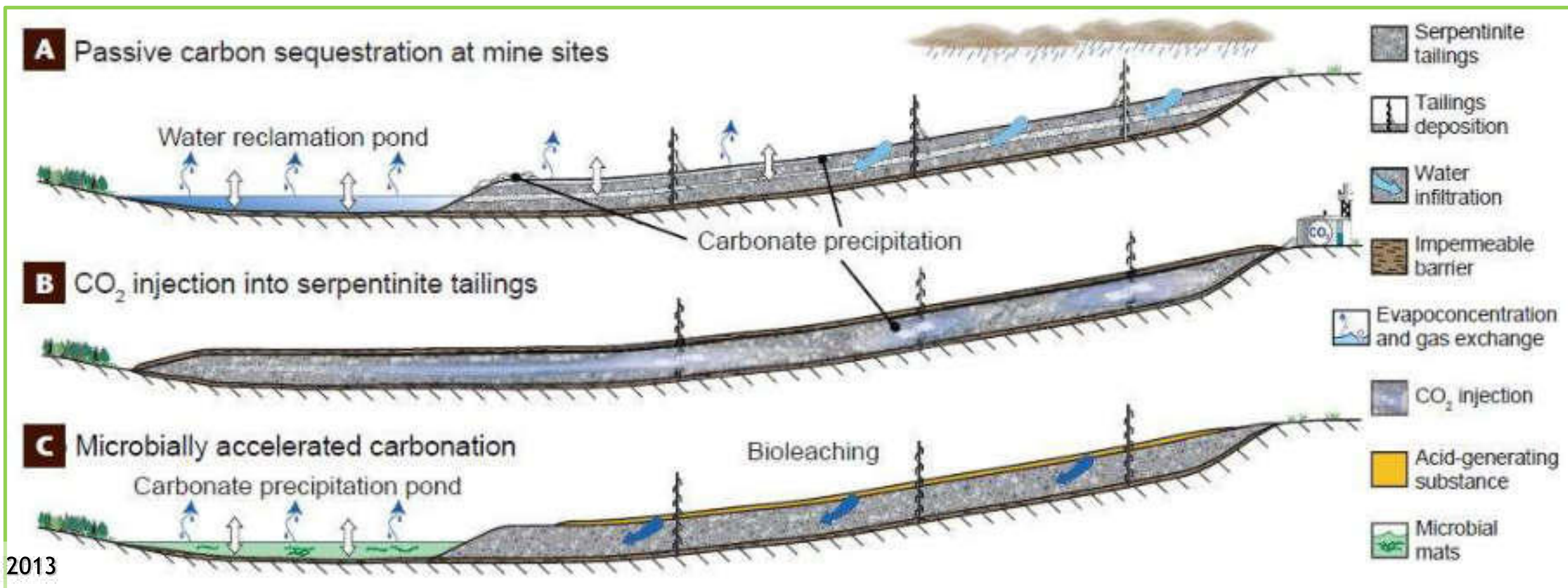
SOLID	CHEMICAL FORMULA	Tons required to sequester 1 ton of carbon
Wollastonite	$CaSiO_3$	9.68[a]
Forsterite	Mg_2SiO_4	5.86[b]
Serpentine/ chrysotile	$Mg_3Si_2O_5(OH)_4$	7.69[b]
Anorthite	$CaAl_2Si_2O_8$	23.1[a]
Basaltic glass	$Na_{0.08}K_{0.008}Fe(II)_{0.17}Mg_{0.28}Ca_{0.26}Al_{0.36}Fe(III)_{0.02}SiTi_{0.02}O_{3.45}$	8.76[c]

[a] as calcite; [b] as magnesite; [c] assuming all Ca, Mg and Fe are converted into calcite, magnesite and siderite

Power et al., 2013

Possible reuses:
4) CO_2 sequestration





Power et al., 2013

Take-home messages

- **Mining is crucial** to our development and well-being
- **Recycling is not always easy and obvious**, mining is and will be increasingly important
- **Intelligent and "sustainable" exploitation** of mineral resources is possible, including in Europe and Italy
- We should also try to **exploit the waste** from past mining activity
- We need more **modern legislation** and a more **scientific and factual environmentalism**