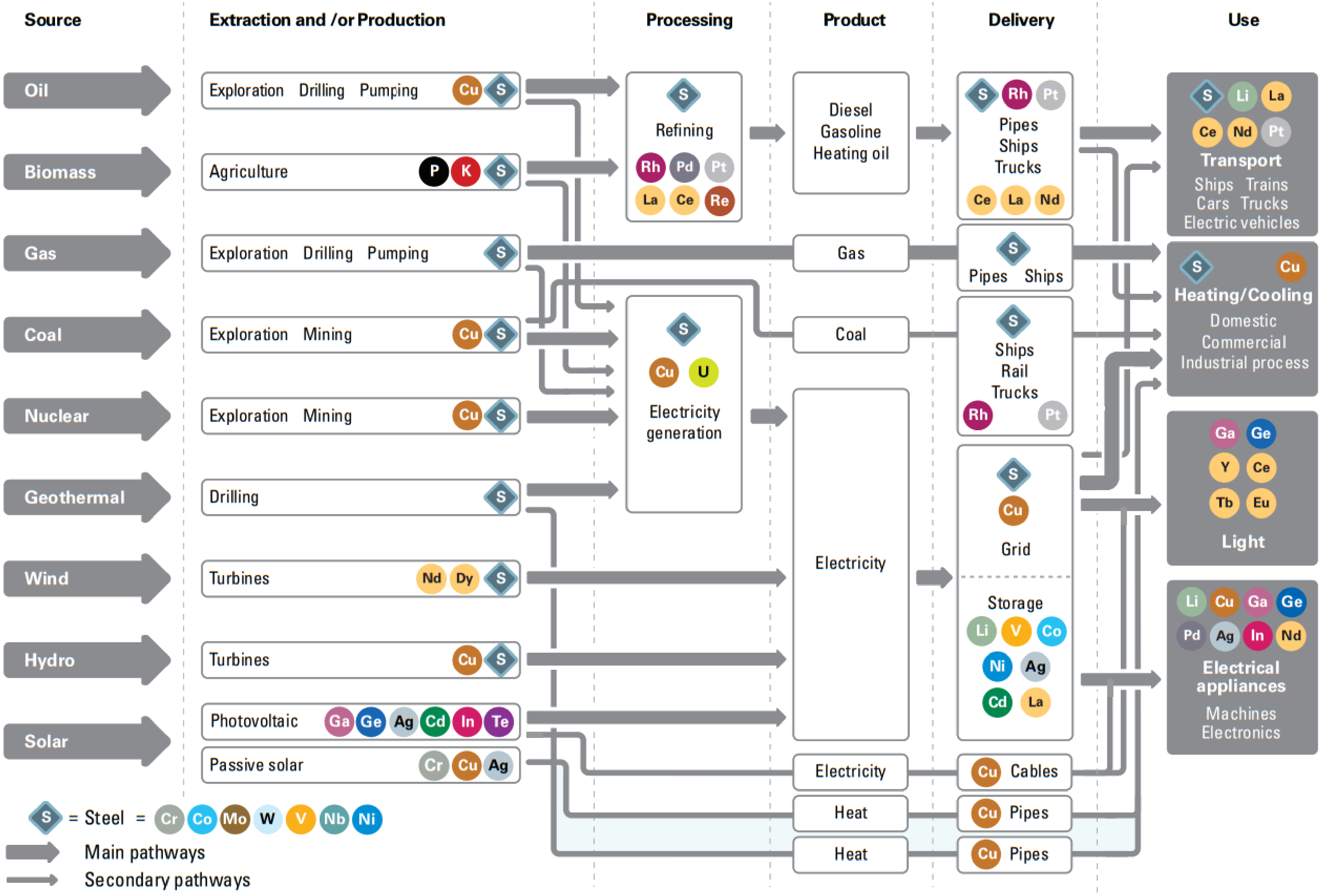
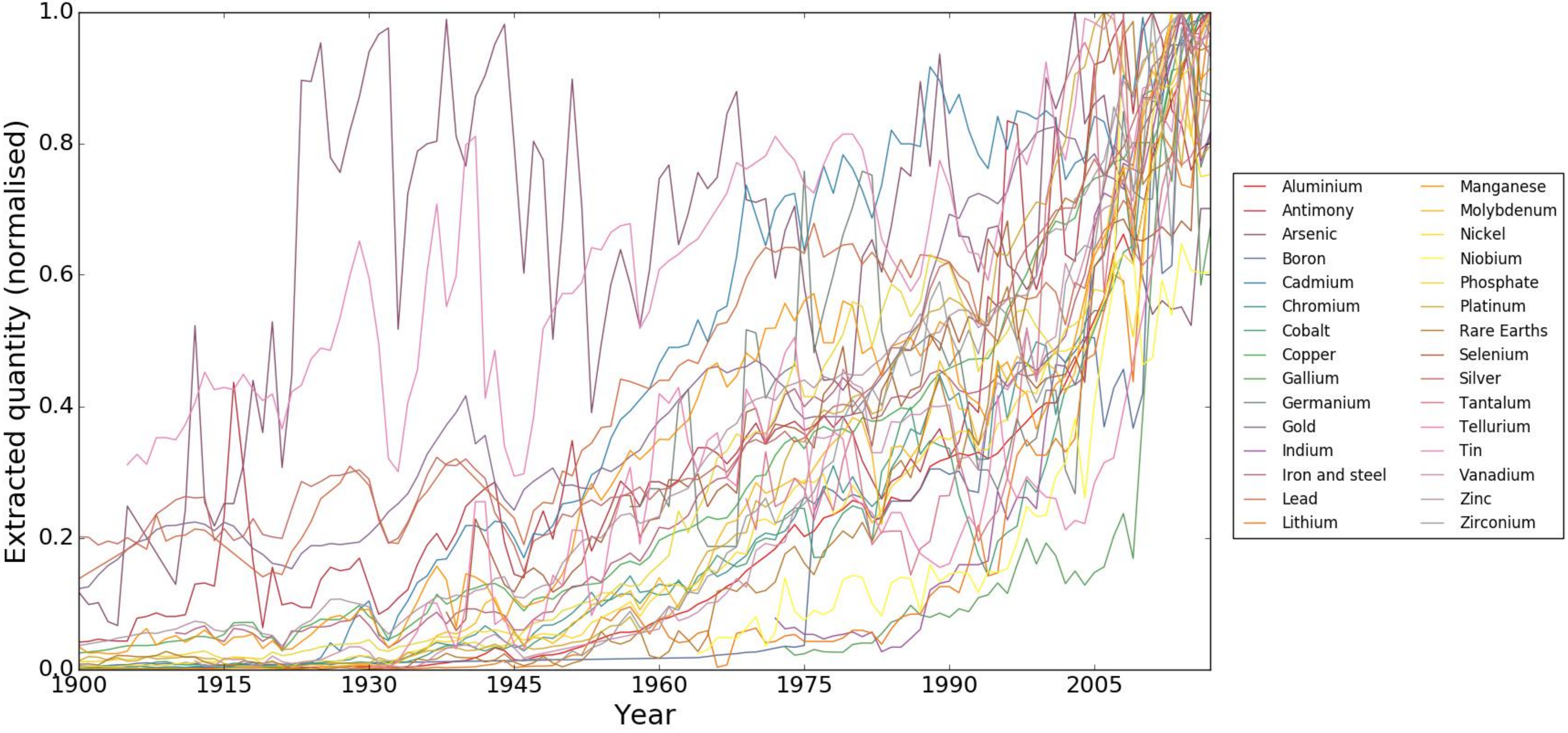
Importance des ressources minérales pour les procédés de production d’énergie

José Halloy
Laboratoire des Énergies de Demain (LIED UMR 8236)
Université Paris Diderot.



Source
Extraction and /or Production
Processing
Product
Delivery
Use
Oil
Biomass
Gas
Coal
Nuclear
Geothermal
Wind
Hydro
Solar
Exploration Drilling Pumping Cu S
Agriculture P K S
Exploration Drilling Pumping S
Exploration Mining Cu S
Exploration Mining Cu S
Drilling S
Turbines Nd Dy S
Turbines Cu S
Photovoltaic Ga Ge Ag Cd In Te
Passive solar Cr Cu Ag
S Refining Rh Pd Pt La Ce Re
S Cu U Electricity generation
Diesel Gasoline Heating oil
Gas
Coal
Electricity
Electricity
Heat
Heat
S Rh Pt Pipes Ships Trucks Ce La Nd
S Pipes Ships
S Ships Rail Trucks Rh Pt
S Cu Grid
Storage Li V Co Ni Ag Cd La
Cu Cables
Cu Pipes
Cu Pipes
S Li La Ce Nd Pt Transport Ships Trains Cars Trucks Electric vehicles
S Cu Heating/Cooling Domestic Commercial Industrial process
Ga Ge Y Ce Tb Eu Light
Li Cu Ga Ge Pd Ag In Nd Electrical appliances Machines Electronics
S = Steel = Cr Co Mo W V Nb Ni
Main pathways
Secondary pathways

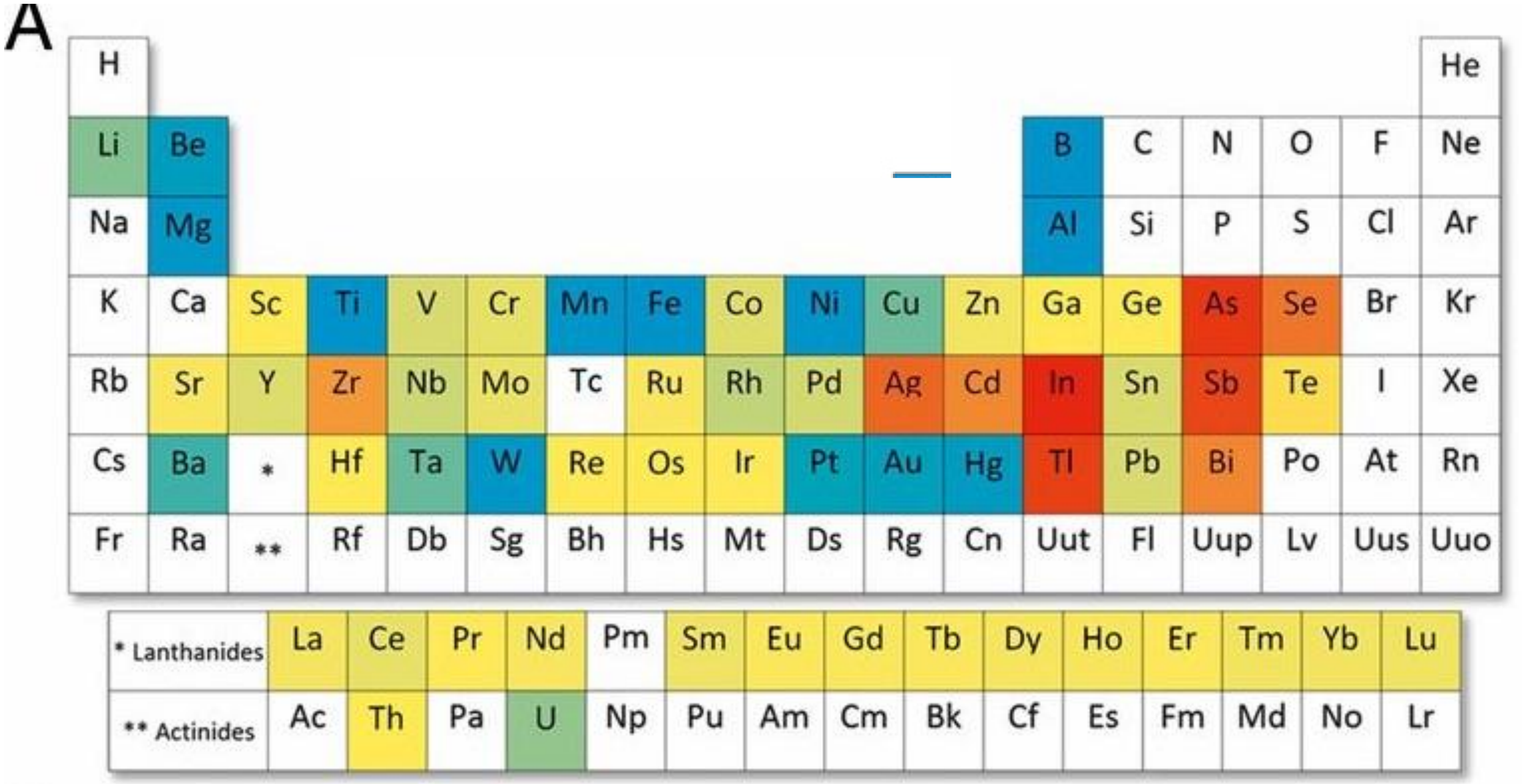


Extracted quantity (normalised)
1.0
0.8
0.6
0.4
0.2
0.0
1900
1915
1930
1945
1960
1975
1990
2005
Year
Aluminium
Antimony
Arsenic
Boron
Cadmium
Chromium
Cobalt
Copper
Gallium
Germanium
Gold
Indium
Iron and steel
Lead
Lithium
Manganese
Molybdenum
Nickel
Niobium
Phosphate
Platinum
Rare Earths
Selenium
Silver
Tantalum
Tellurium
Tin
Vanadium
Zinc
Zirconium

Criticality of metals and metalloids

T. E. Graedel[a,b,1], E. M. Harper[a], N. T. Nassar[a], Philip Nuss[a], and Barbara K. Reck[a]

[a]Center for Industrial Ecology, Yale University, New Haven, CT 06511; and [b]Stellenbosch Institute for Advanced Study, Stellenbosch 7602, South Africa



Challenges in Metal Recycling

10 AUGUST 2012 VOL 337 SCIENCE

Barbara K. Reck* and T. E. Graedel

Metals are infinitely recyclable in principle, but in practice, recycling is often inefficient or essentially nonexistent because of limits imposed by social behavior, product design, recycling technologies, and the thermodynamics of separation. We review these topics, distinguishing among common, specialty, and precious metals. The most beneficial actions that could improve recycling rates are increased collection rates of discarded products, improved design for recycling, and the enhanced deployment of modern recycling methodology. As a global society, we are currently far away from a closed-loop material system. Much improvement is possible, but limitations of many kinds—not all of them technological—will preclude complete closure of the materials cycle.

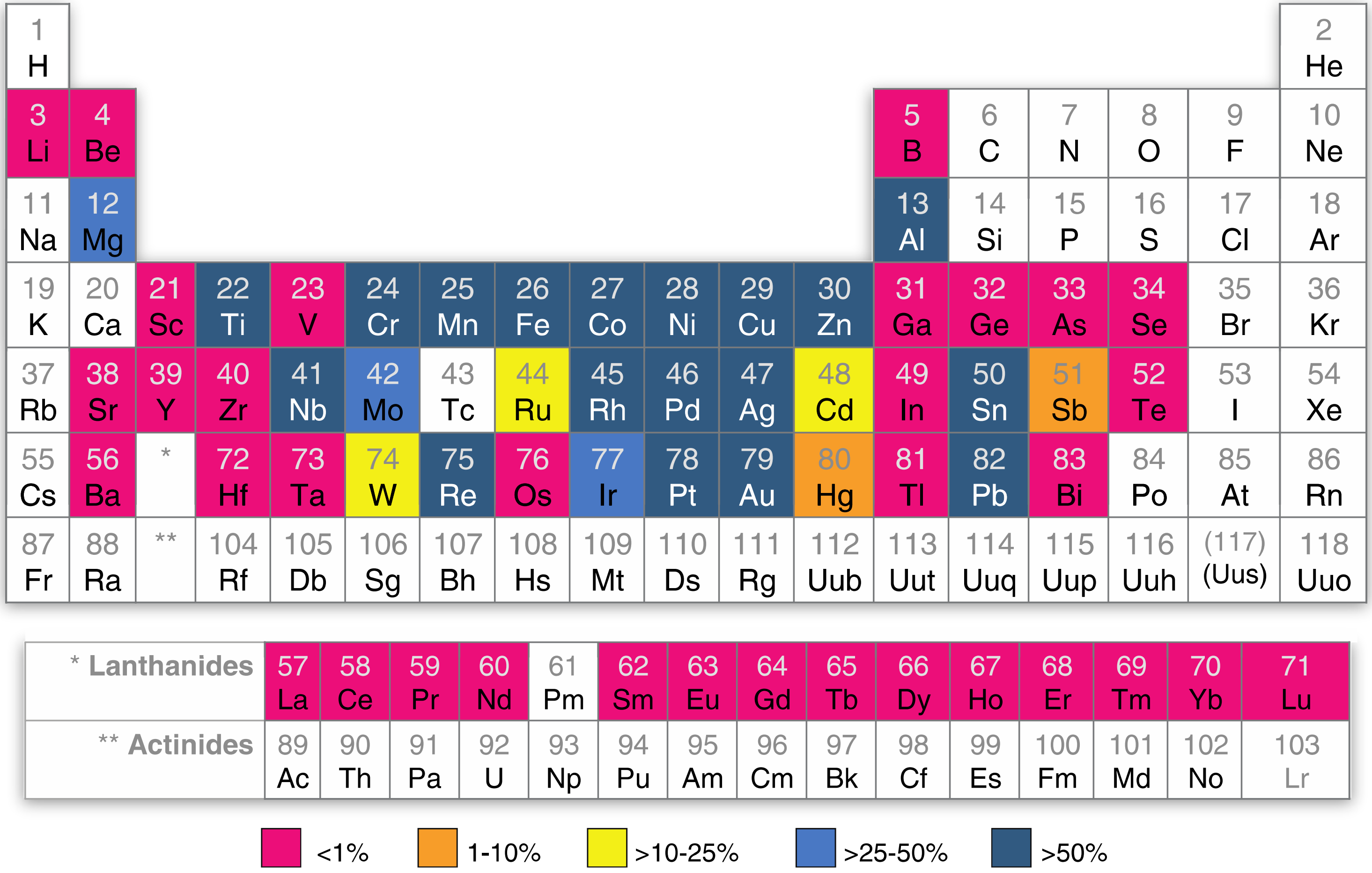
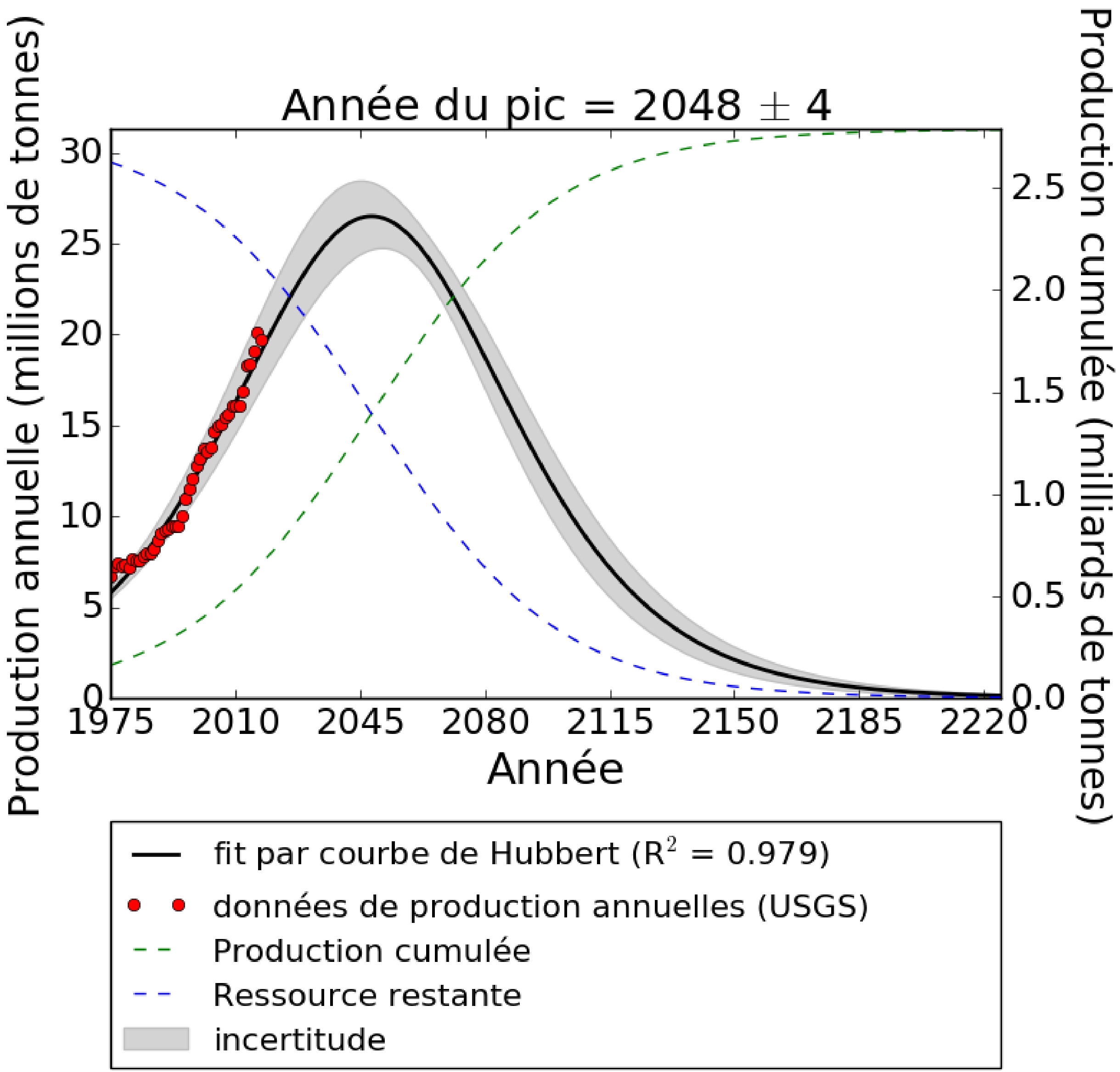


Fig. 1. Global estimates of end-of-life recycling rates for 60 metals and metalloids, circa 2008 [adapted from (*6*)].



$$Q(0) = Q_0$$

$$\frac{dQ}{dt} = rQ\left(1 - \frac{Q}{K}\right) \quad \text{avec } r > 0 \text{ et } K > 0$$

$$Q(t) = \frac{K}{1 + ae^{-rt}}$$

$$P(t) = \frac{dQ}{dt} = \frac{raKe^{-rt}}{(1 + ae^{-rt})^2}$$

M.K. Hubbert
peak oil model (1953)

Modelling future copper ore grade decline based on a detailed assessment of copper resources and mining

S. Northey [a,*], S. Mohr [b], G.M. Mudd [a], Z. Weng [a], D. Giurco [b]

[a] Environmental Engineering, Department of Civil Engineering, Monash University, Clayton, VIC 3168, Australia
[b] Institute for Sustainable Futures, University of Technology, Sydney, Ultimo, NSW 2007, Australia

Resources, Conservation and Recycling 83 (2014) 190–201

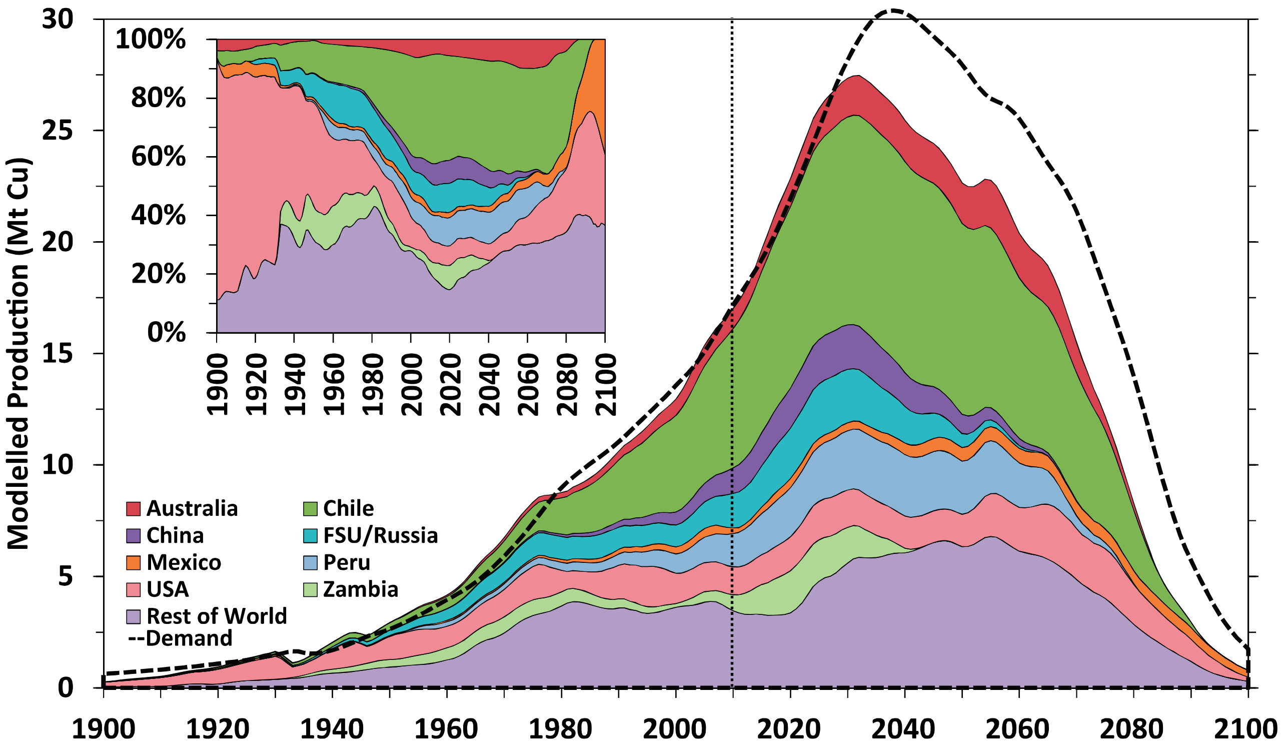
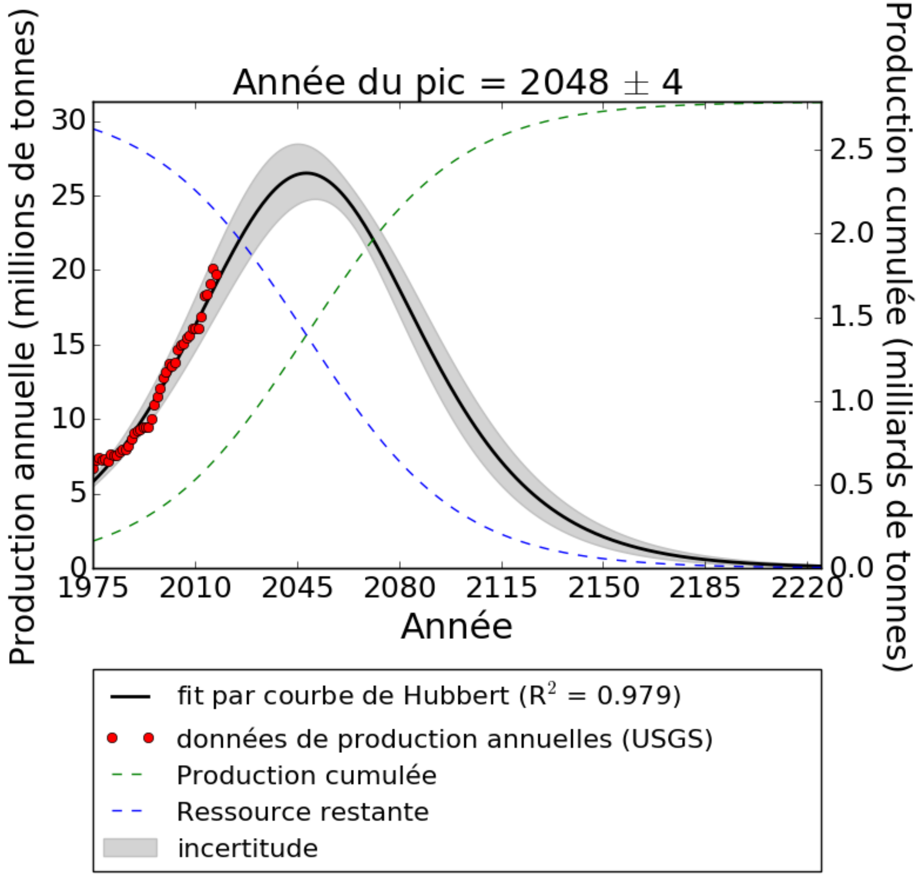
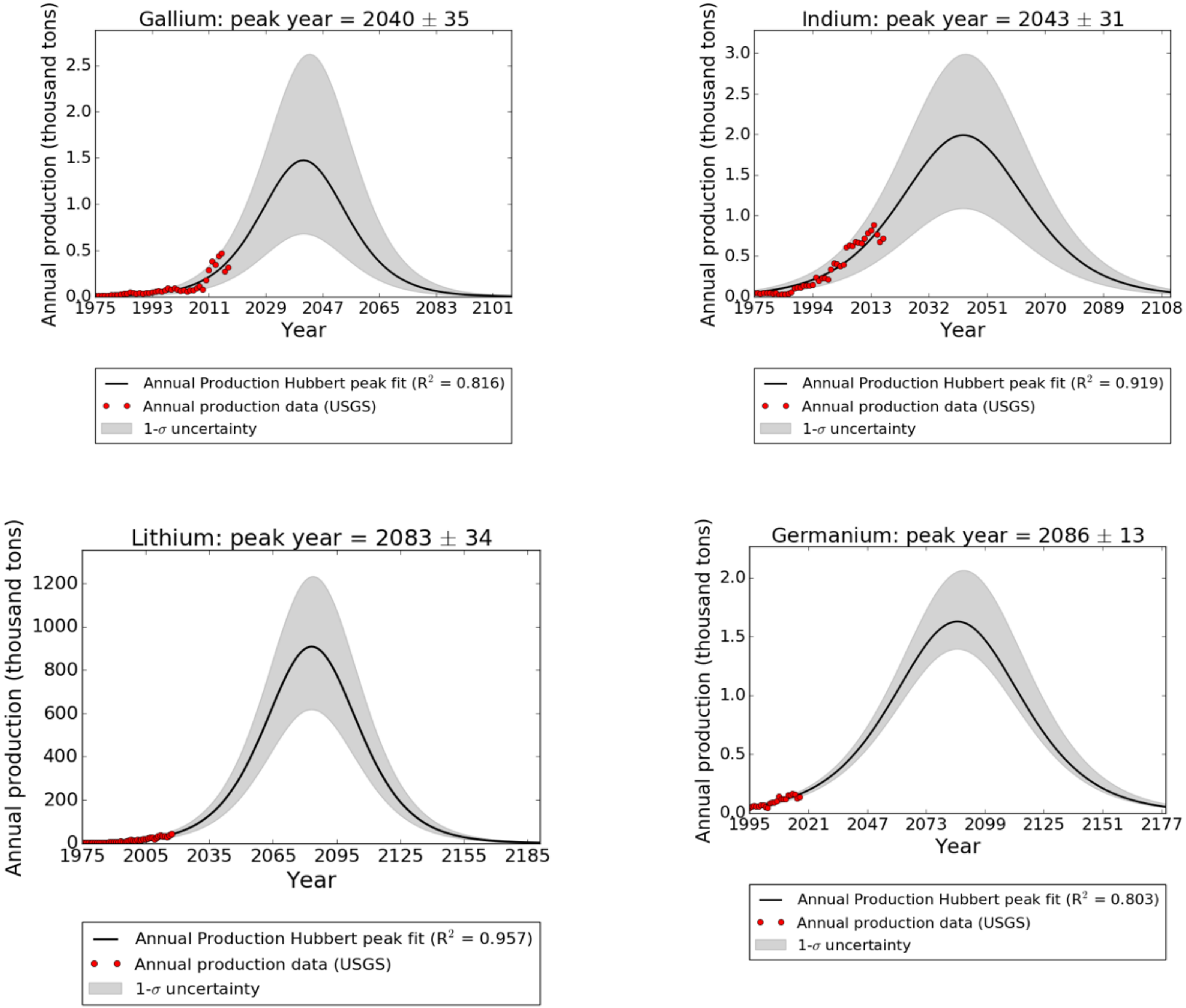


Fig. 7. Global Cu production by countries and regions as modelled by GeRS-DeMo in dynamic demand mode.

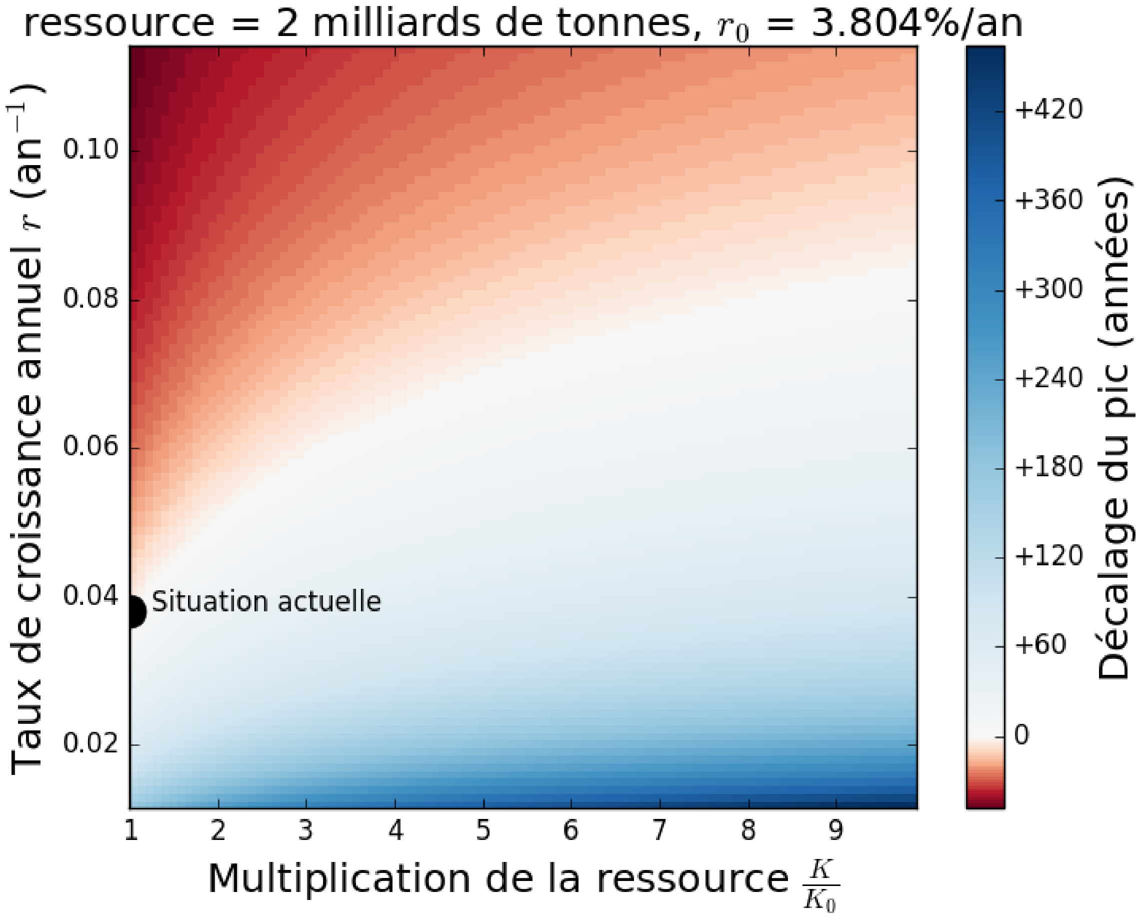




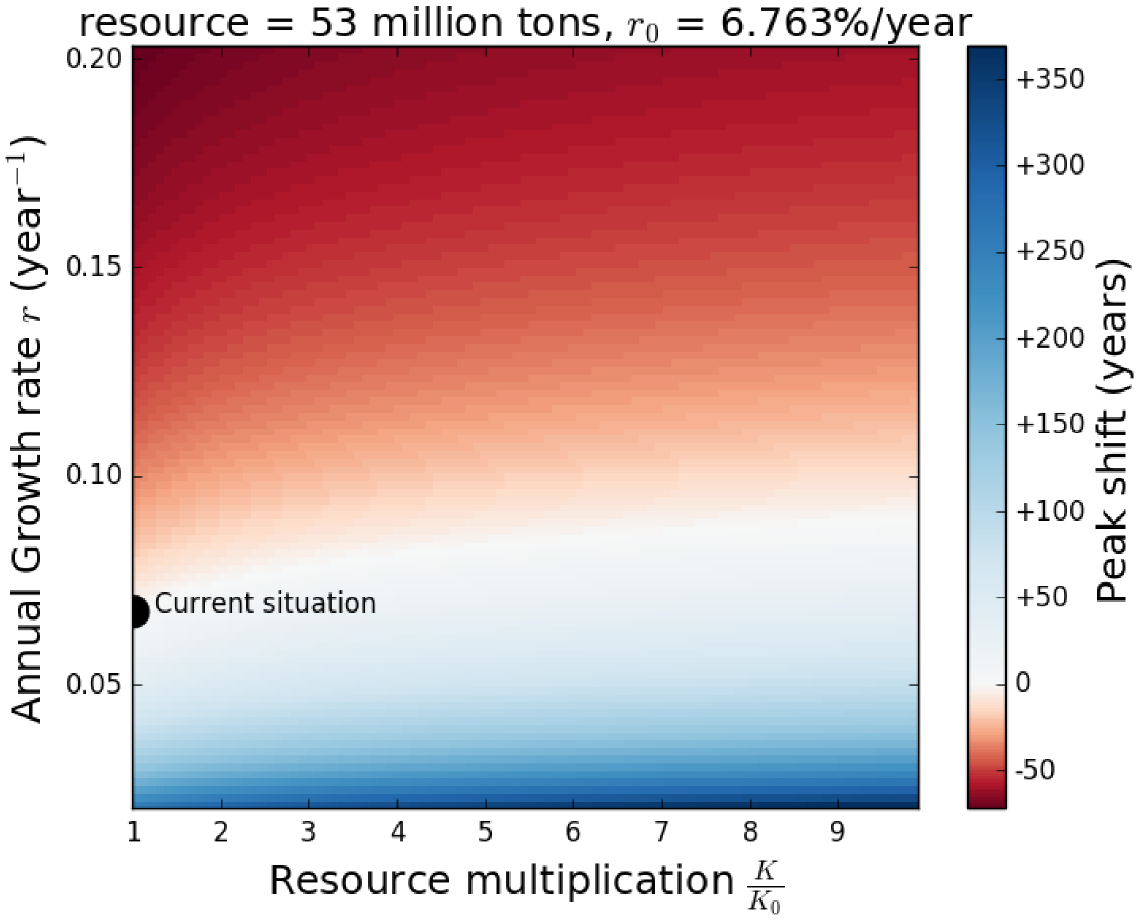
Gallium: peak year = 2040 ± 35
Annual production (thousand tons)
Year
Annual Production Hubbert peak fit (R^2 = 0.816)
Annual production data (USGS)
1-σ uncertainty
Indium: peak year = 2043 ± 31
Annual production (thousand tons)
Year
Annual Production Hubbert peak fit (R^2 = 0.919)
Annual production data (USGS)
1-σ uncertainty
Lithium: peak year = 2083 ± 34
Annual production (thousand tons)
Year
Annual Production Hubbert peak fit (R^2 = 0.957)
Annual production data (USGS)
1-σ uncertainty
Germanium: peak year = 2086 ± 13
Annual production (thousand tons)
Year
Annual Production Hubbert peak fit (R^2 = 0.803)
Annual production data (USGS)
1-σ uncertainty

Métal	Pic (année)	Croûte + Océans (année)	Douce (année)	Réserve (t)	Ressource (t)	Quantité terrestre (t)	Quantité marine (t)
Acier	2070 ± 37	2541	2031	8,30E+10	2,30E+11	1,07E+18	2,74E+09
Aluminium	2070 ± 18	2456	2060	—	1,63E+010	1,56E+18	2,74E+09
Antimoine	2022 ± 10	2239	2021	1,50E+006	5,00E+006	3,80E+12	3,29E+08
Argent	2021 ± 11	2204	2029	5,30E+005	7,80E+005	1,43E+12	5,48E+07
Arsenic	2062 ± 48	3429	—	9,20E+005	1,10E+007	3,42E+13	5,07E+09
Bore	2052 ± 33	2264	—	1,10E+09	—	1,90E+13	6,08E+12
Cadmium	2002 ± 3	2305	—	6,90E+005	5,70E+006	2,85E+12	1,51E+08
Chrome	2117 ± 26	2369	2030	5,10E+08	1,20E+10	1,94E+15	4,11E+08
Cobalt	2061 ± 19	2377	2048	7,10E+006	2,50E+007	4,75E+14	2,74E+07
Cuivre	2048 ± 4	2389	2037	7,90E+008	2,10E+009	1,14E+15	3,43E+08
Étain	2024 ± 5	2434	2029	4,80E+06	1,17E+07	4,37E+13	5,48E+06
Gallium	2040 ± 29	2249	—	—	5,00E+004	3,61E+14	4,11E+07
Germanium	2113 ± 17	2464	—	1,19E+005	4,40E+005	2,85E+13	6,85E+07
Indium	2043 ± 26	2283	—	2,30E+004	9,50E+004	4,75E+12	2,74E+10
Lithium	2083 ± 31	2316	2027	1,60E+007	5,30E+007	3,80E+14	2,47E+11
Manganèse	2083 ± 16	2385	2037	6,80E+008	9,00E+009	1,81E+16	2,74E+08
Molybdène	2044 ± 13	2345	2037	1,70E+07	2,54E+07	2,28E+13	1,37E+10
Nickel	2032 ± 9	2338	2033	7,40E+07	1,30E+08	1,60E+15	7,67E+08
Niobium	2033 ± 22	2288	2050	4,30E+006	—	3,80E+14	1,37E+07
Or	2020 ± 7	2301	2027	5,40E+004	1,00E+005	7,60E+10	5,48E+06
Phosphate	2101 ± 6	2237	—	7,00E+010	3,00E+011	2,00E+16	8,22E+10
Platine	2069 ± 42	2549	2067	6,90E+004	1,00E+005	9,50E+10	0,00E+00
Plomb	2092 ± 8	2438	2027	8,80E+007	2,00E+009	2,66E+14	4,11E+07
Selenium	2017 ± 8	2368	—	1,00E+005	—	9,50E+11	2,74E+08
Tantale	2039 ± 24	2423	—	1,10E+005	—	3,80E+13	2,74E+06
Tellure	2108 ± 40	—	—	3,10E+004	—	1,90E+10	—
Terres Rares	2054 ± 30	2399	—	1,20E+008	—	—	—
Vanadium	2113 ± 30	2629	—	2,00E+07	6,30E+07	2,28E+15	3,43E+09
Zinc	2057 ± 7	2473	2026	2,30E+008	1,90E+009	1,33E+15	6,71E+09
Zirconium	2024 ± 16	2384	—	7,40E+007	—	3,14E+15	4,11E+07

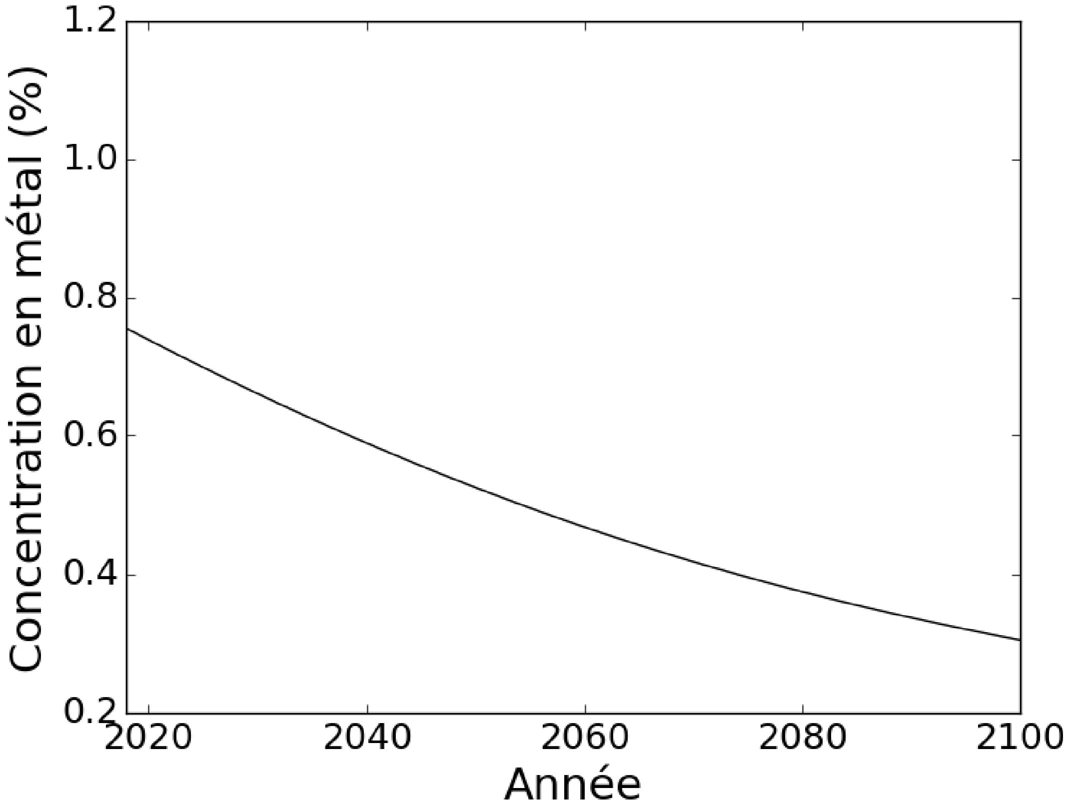
Cuivre



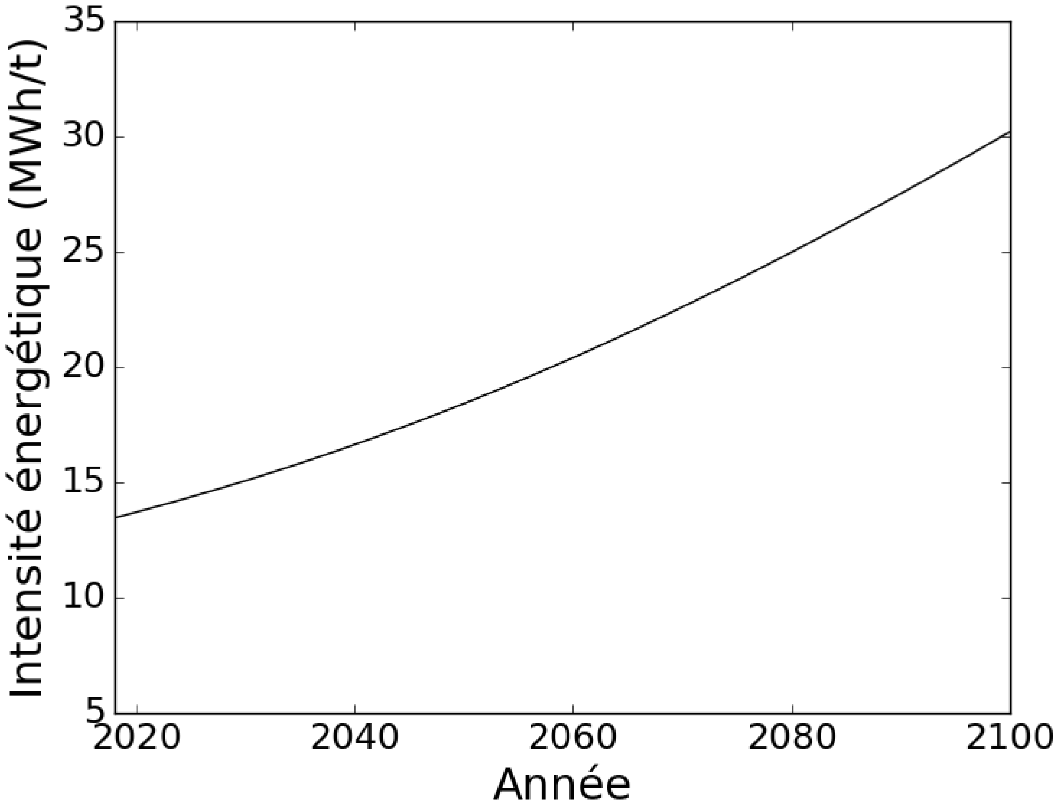
Lithium



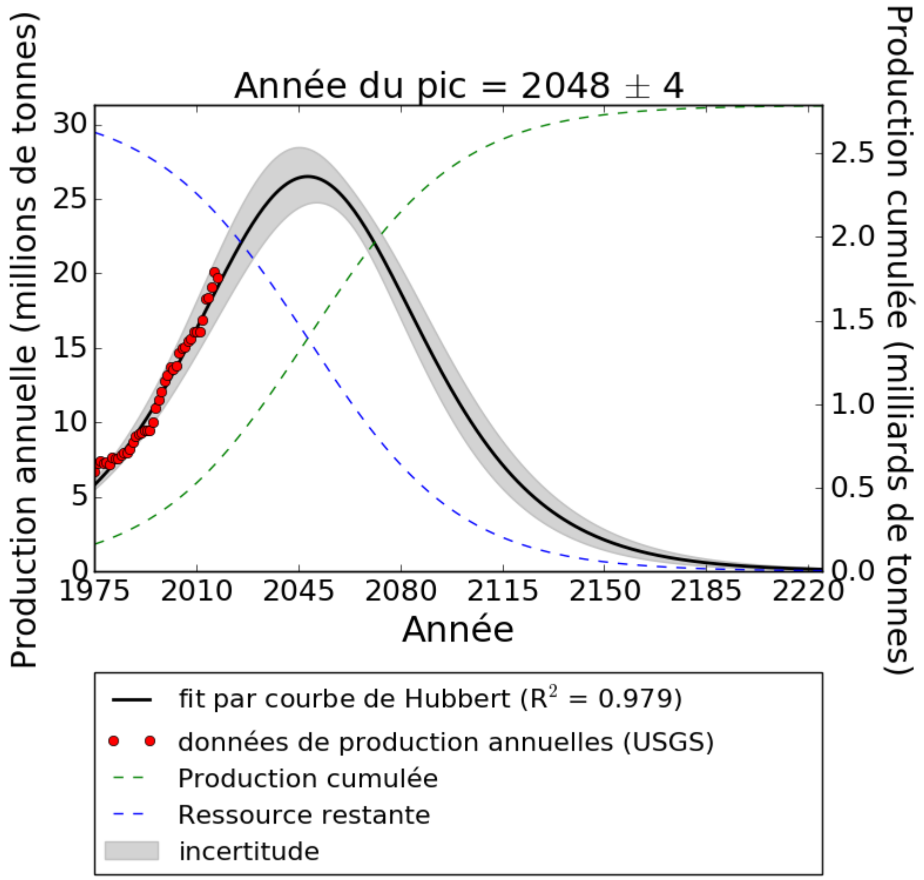
Concentration en Cu dans les minerais diminue

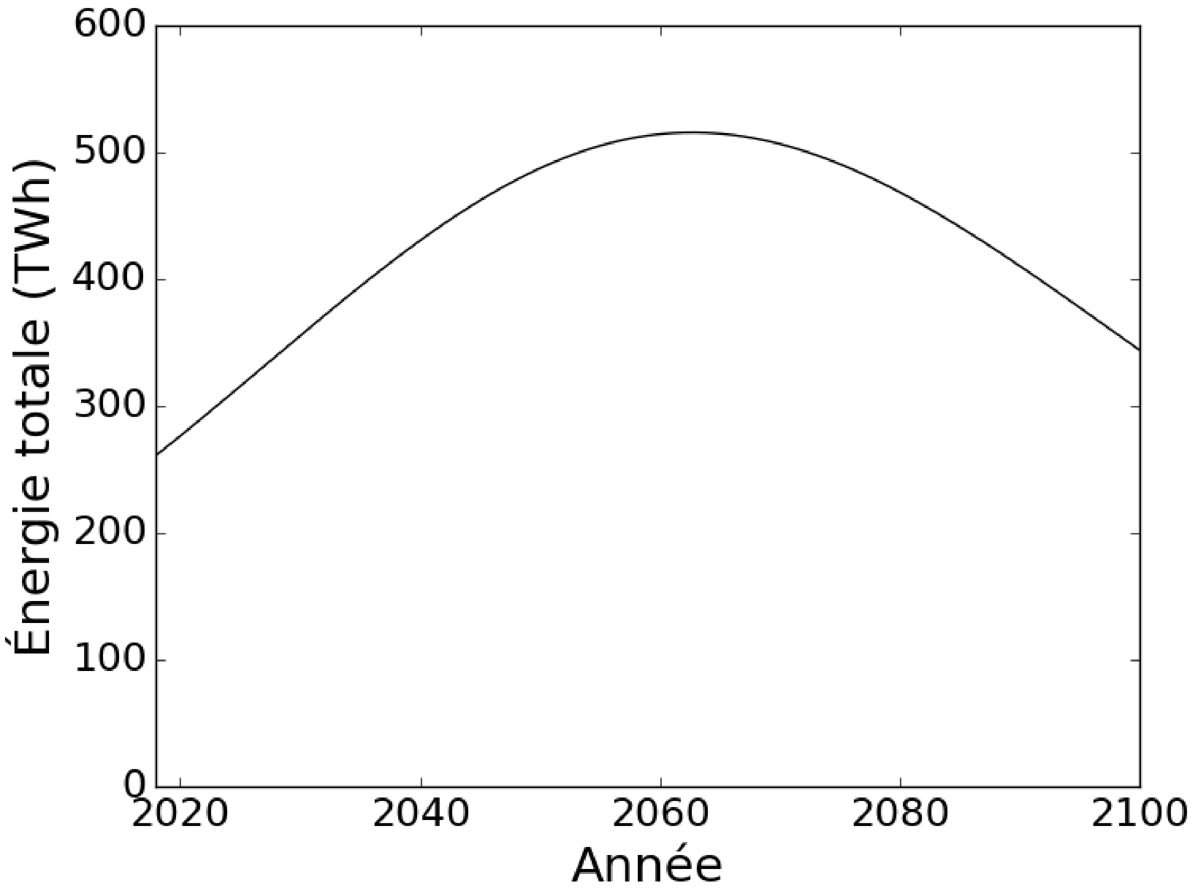


Ce qui augmente la consommation énergétique du minage

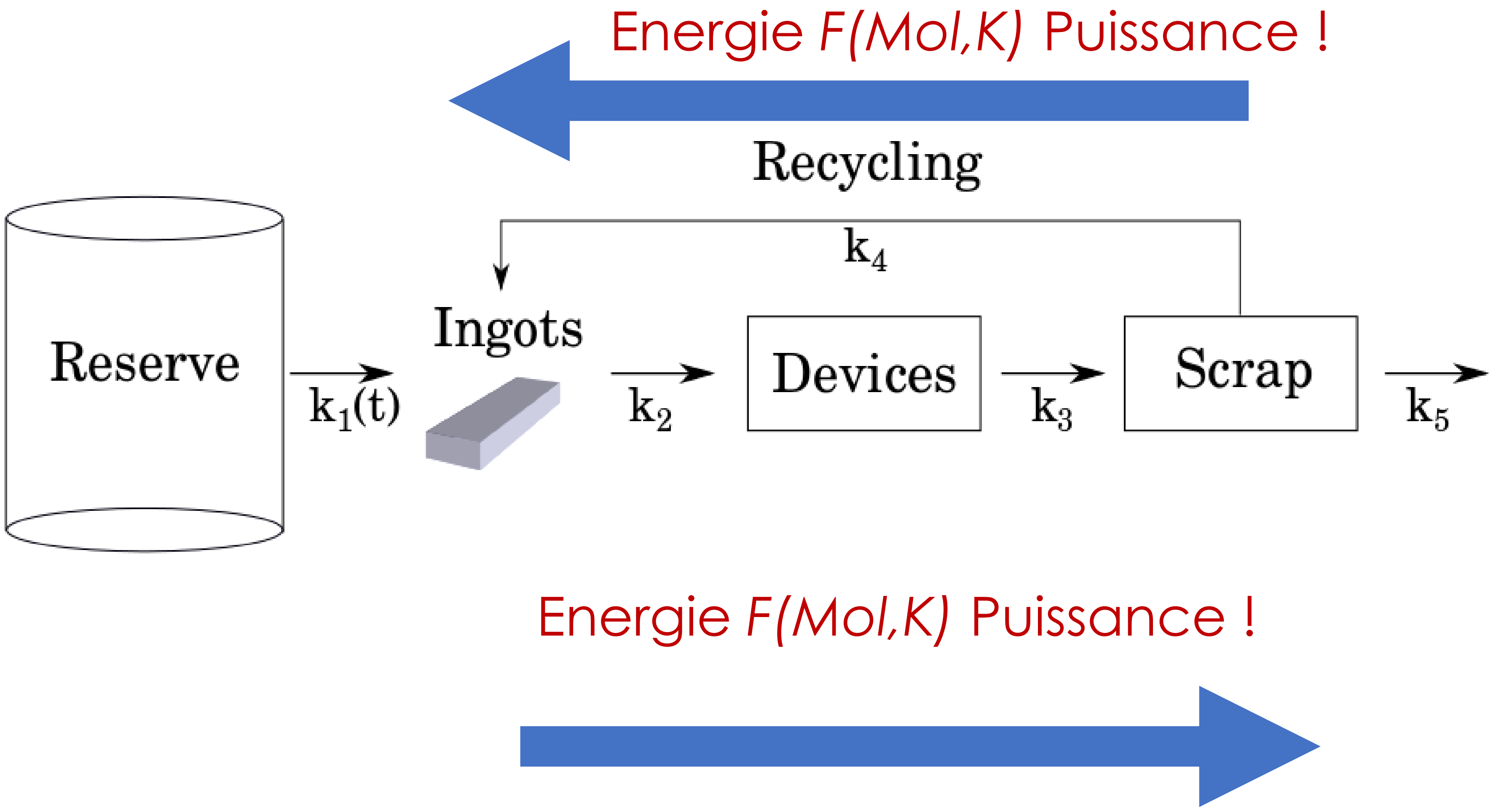


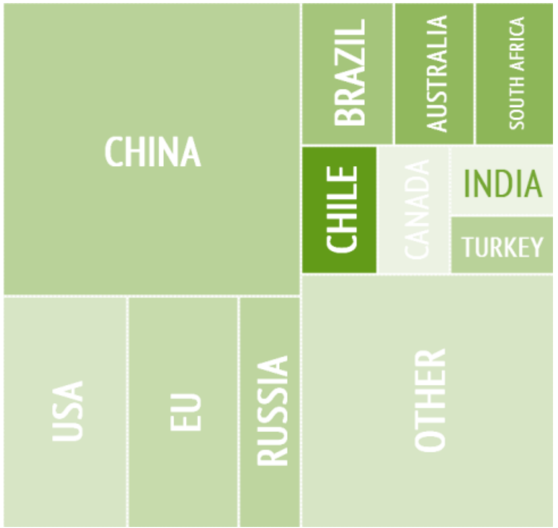
Consommation d'énergie pour extraire le cuivre





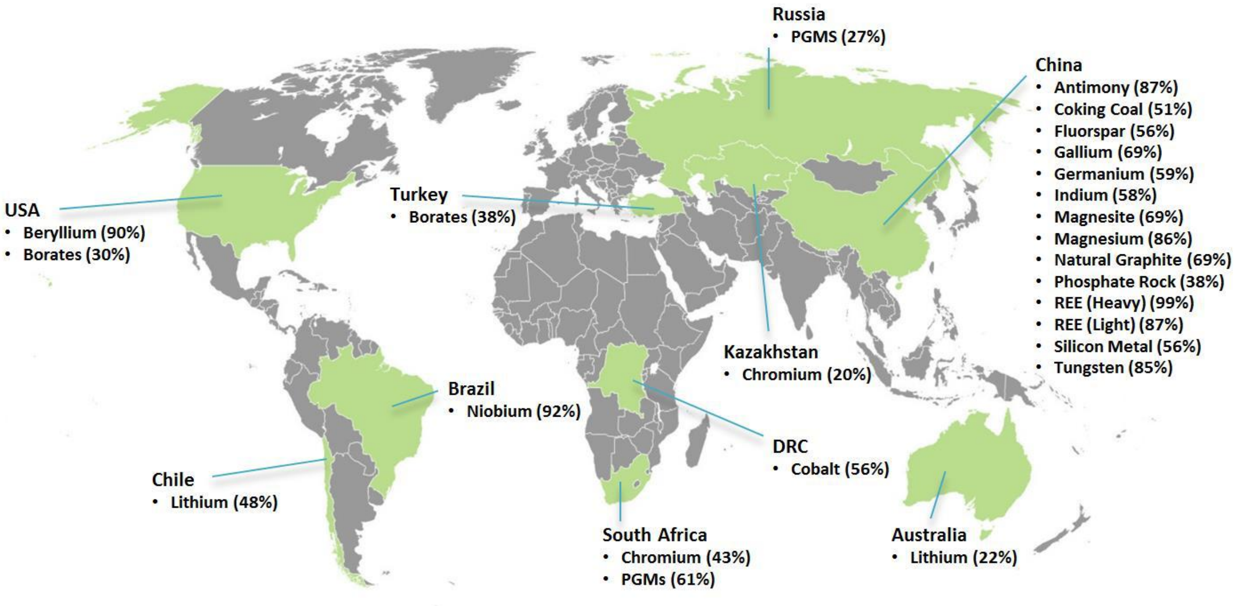
La civilisation des lingots construit la rareté des métaux





World primary supply of the 54 candidate raw materials

World primary supply of the 21 critical raw materials

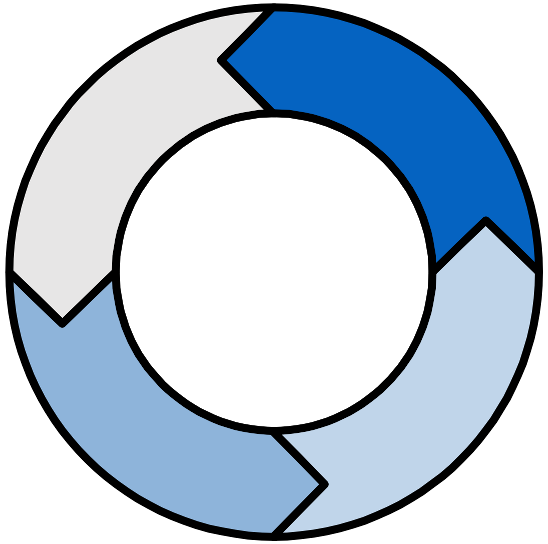


Study on Criticial Raw Materials at the EU Level, Fraunhofer, 2013

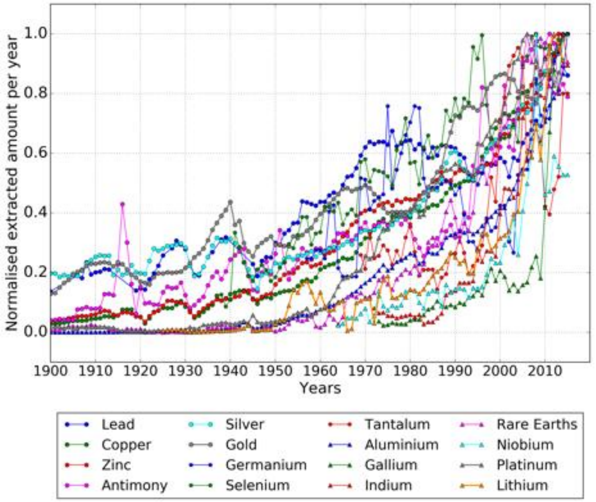
Mineraux & énergie: cercle vicieux

Extraction requiert plus d'énergie

Minéraux moins concentrés



Plus de nouveaux matériaux nécessaires



Energie moins accessible