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MODELLING THE DEMAND AND ACCESS OF MINERAL RESOURCES IN A CHANGING WORLD

Olivier Vidal ^{1,*}, Hugo Le Boulzec ^{1,2} , Baptiste Andrieu ^{1,3} and François Verzier ¹

¹ Institut de Sciences de la Terre (ISTerre), CNRS-University of Grenoble, 1381 rue de la Piscine, 38041 Grenoble, France

² Grenoble Applied Economics Laboratory (GAEL), 1241 Rue des Résidences, 38400 Saint-Martin-d'Hères, France

³ The Shift Project, 16-18, rue de Budapest, 75009 Paris, France

* Correspondence: olivier.vidal@univ-grenoble-alpes.fr

Abstract: Humanity is using mineral resources at an unprecedented level and demand will continue to grow over the next few decades before stabilizing by the end of the century, due to the economic development of populated countries and the energy and digital transitions. The demand for raw materials must be estimated with a bottom-up and regionalized approach, and the supply capacity with approaches coupling long-term prices with energy and production costs controlled by the quality of the resource and the rate of technological improvement that depends on thermodynamic limits. Such modelling provides arguments in favour of two classically opposed visions of the future of mineral resources: an unaffordable increase in costs and prices following the depletion of high quality deposits or, on the contrary, a favourable compensation by technological improvements. Both views are true, but not at the same time. After a period of energy and production cost gains, we now appear to be entering a pivotal period of long-term production cost increases as we approach the minimum practical energy and thermodynamic limits for many metals.

Keywords: Raw materials; Mineral resources; Demand; Production energy; Price

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1. Introduction

The per-capita consumption of global resource has doubled between 1950 and 2010 [1] and the consumption of raw materials and mineral resources (gravel and sand, cement, ores, industrial minerals) used to build the urban, energy, and transportation infrastructure and consumer goods of modern societies has increased at an average rate of 2-5%/year over the past century. Humanity is now using mineral resources at an unprecedented level, with 70 billion tons of material extracted from the ground per year [2-6]. This acceleration naturally raises the question of supply sustainability, which has been discussed repeatedly since the 1950s [7-16]. Repeated predictions of short-term depletion of fossil resources have so far not been verified by actual shortages. On the contrary, and despite the exponential growth in consumption observed for more than a century, metal reserves have never been higher than they are today. The increase in reserves, despite the strong growth in consumption, can be explained by technological progress, which makes it possible to exploit new fossil resources of lower quality at the same cost. Unconventional hydrocarbons, which were undevelopable at a competitive cost a few decades ago, are now a major source and most metal deposits developed today are less concentrated than those developed in the past [17]. Because the amount of low-grade deposits is much greater than concentrated deposits, reserves have increased with technological improvements. This trend gives the misleading impression that perpetual growth is possible in a finite world, the Earth. Misleading because there is a thermodynamic limit to the potential of technological improvements and what was possible in the past will not necessarily be possible in the future.

37 The future availability of fossil resources depends on production capacity, which
38 in turn depends on production technologies, the type and quality of ore deposits con-
39 trolling production costs, and the proportion of recycled products at the end of their
40 life. It also depends on demand, which in turn depends on population and standard of
41 living, economic and geopolitical cycles, and technological development associated with
42 energy and digital transitions. All these parameters define the conditions for economi-
43 cally viable production. They vary over time, are coupled and should not be analysed
44 separately. Over the past decades, the demand for non-energy materials has been in-
45 tensively studied through material flow or input-output analyses. The development of
46 materials databases [18–21] has enabled a comprehensive understanding of metal and
47 mineral stocks and flows within society at different scales through top-down studies (e.g.
48 [22–27]). Many recent efforts have been devoted to estimating future demand for raw
49 materials through bottom-up stock-based analysis in the energy sectors (e.g. [28–37]),
50 transportation (e.g. [31,38–42]) and construction (e.g. [39,43–47]), its energy demand
51 and production cost (e.g. [6,39]), environmental impacts (e.g. [39,48–50]) or to reserve
52 estimation (e.g. [51–53]) and production capacities. However, very few studies have at-
53 tempted to combine all these dimensions into single models. Notable exceptions are the
54 dynamic models World7 [54,55] and MEDEAS-World [56], which couple global GDP and
55 demographic changes with commodity and energy demand. These models are valuable
56 and powerful tools for discussing the global resource issue in relation to socioeconomic
57 changes. However, they sometimes rely on disputable empirical assumptions such as the
58 linear dependence of the total demand of metals on GDP evolution assumed in MEDEAS
59 [56]. This assumption, based on an empirical fit of global historical data covering too
60 short a period, is in conflict with the historical evolution in developed countries [57–59].
61 Moreover, it assumes that the future demand for metal per GDP will be the same as in
62 the past, whereas new technologies that did not exist two decades ago are developing
63 fast in the sector of energy, transport, information and communications. The estimation
64 of global demand requires a comprehensive bottom-up approach, i.e., by technologies
65 whose material intensities, use intensities, energy consumption and efficiencies change
66 at different rates over time, and by geographic regions with contrasting transportation
67 patterns and material intensities. The modelling of raw material supply can also be
68 improved by developing standardized approaches coupling long-term resource prices
69 with energy and production costs [60]. The minimum production energy and the mini-
70 mum practical production energies can be estimated from the quality of the resource
71 exploited (ore grade) and on technological improvement constrained in the last resort
72 by thermodynamic limits that cannot be overstepped. Finally, and before attempting
73 to apply the models to future developments, it must be demonstrated that they are
74 capable of reproducing the historical evolution of the demand for infrastructure and
75 raw materials over long periods of time, by country or geographical region. These
76 different points are discussed in the present contribution, along with a brief review of
77 anticipated future needs and production capacities. Our objective is not to provide a
78 single answer to the complex issues raised by the consumption and supply of mineral
79 resources, but rather to identify some of the key points that seem important to consider
80 in their modelling.

81 **2. The drivers of mineral resources consumption**

82 *2.1. The base metals and cement consumption from traditional applications*

83 The prospective analysis of metals and minerals in society requires a dynamic
84 model describing the evolution of stocks and flows. An inverted U-shape of demand
85 with economic growth was first proposed in the late 20th century [61] and later validated
86 for steel for middle-income countries [59]. Growing stock analysis has led to a better
87 understanding of stock and flow dynamics, and to the identification of a three-stage
88 model of the stock curve in use: growth, maturation, and saturation [57]. The first
89 stage of economic growth in all countries is characterized by the construction of raw

90 materials demanding infrastructures of heavy industry, housing, transport, commu-
91 nications and energy. This phase of development mainly consumes "structural" raw
92 materials produced in present global quantities of more than one million tons per year
93 (Mt/yr), such as sand and aggregates, concrete, steel and iron, aluminium, copper,
94 manganese, zinc, chromium, lead, titanium and nickel. Then, the annual consumption
95 of structural raw materials levels off when the gross domestic product (GDP) per capita
96 reaches about 15,000 US\$/cap (maturing stage) and eventually declines as the in-use
97 stock reaches its saturation limit (saturation stage) [57,58]. When saturation level of
98 in-use stocks is reached, the size of the infrastructure becomes mainly controlled by
99 the evolution of population and the material content of technologies. The number of
100 technological units per capita (number of cars, trucks, planes, ships, m² building, etc) as
101 a function of GDP/capita thus follows the sigmoidal pattern of a logistic function, whose
102 parameters can be constrained by fitting the historical evolution of each technology
103 by countries (e.g. [46,62,63]). These parameters depend on the geography, population
104 density and lifestyle of the countries, with average values in the order of 0.7 LDV/cap,
105 $7 \cdot 10^{-5}$ locomotive/cap, $1.5 \cdot 10^{-5}$ aircraft/cap and 90 m²/cap. From these figures, the
106 future evolution of infrastructure can be estimated for given future GDP and popula-
107 tion evolutions. This is illustrated in Figure 1, which shows the number of observed
108 and estimated light vehicles, locomotives, airplanes and the surface of buildings in
109 the USA and China from 1950 until 2100. The results were obtained with the model
110 DyMEMDS (dynamic modelling of energy and matter demand and supply) [available](#)
111 [online](#). DyMEMDS is a stock and flow model that links the energy consumption, GDP,
112 population with the raw materials consumption, greenhouse gases emissions, global
113 warming and additional environmental impacts such as the consumption of water and
114 used land for mining. It includes about fifty technologies of transportation, construction
115 and energy, ten metals, cement and gravel, and nine geographical regions covering the
116 world. From the evolution of infrastructure calculated for imposed future GDP and
117 population evolutions (Figure 1), the stocks of materials by technologies are estimated
118 using dynamic raw materials intensities in kg of material per technological unit.

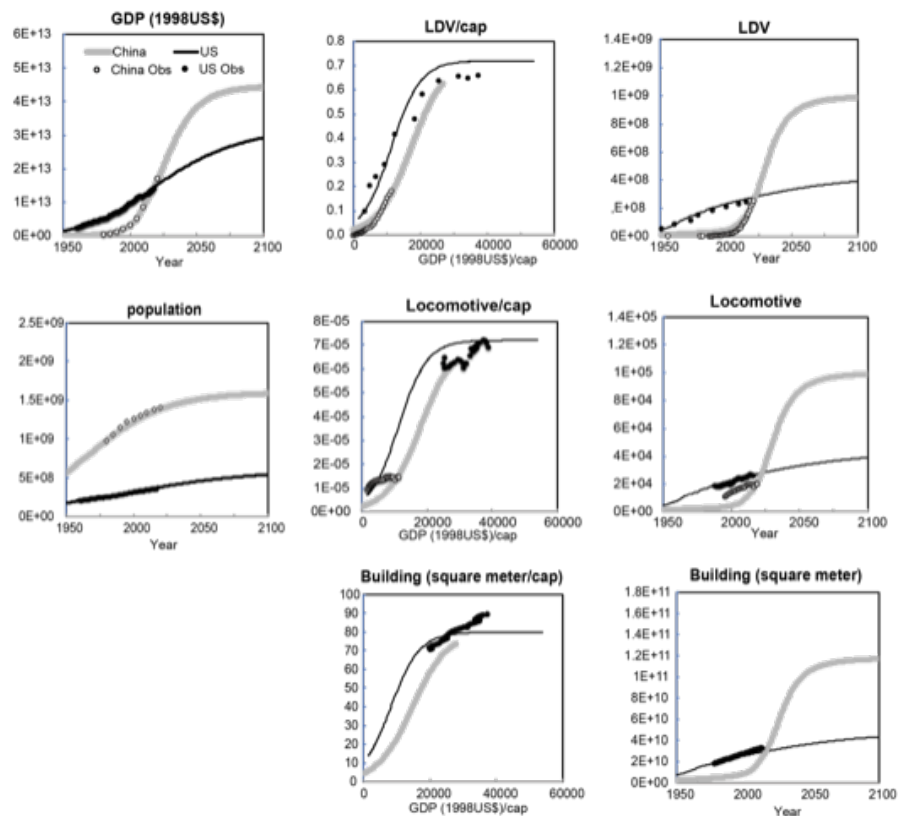


Figure 1. Evolution of the demand in infrastructure per capita in function of GDP/cap or time in China (grey lines and open circles) and USA (black line and black circles).

119 The same material intensities were used for all countries except for the building
 120 sector, which shows strong disparities between countries. The concrete and steel intensi-
 121 ties are for instance lower in the US than in China [64]. The stocks of materials in the
 122 infrastructure of all regions are obtained by adding up the needs of all technologies, and
 123 the global demand by adding up the demand of each geographical region (Figure 2).
 124 The annual consumptions are then obtained by deriving the stocks over time and the
 125 annual flows of primary, recycled and lost materials are calculated for imposed lifetimes
 126 of goods, collection and recycling rates (Figure 3). This full bottom-up approach starting
 127 from regional GDP and population evolutions makes it possible to link the global raw
 128 material consumptions with the economic development, population and technological
 129 evolutions of each geographical region. It reproduces the step increase of demand for
 130 base metals, cement and gravels observed since World War II. The period 1950-1970 was
 131 marked by a strong increase in global consumption driven by the construction of the
 132 infrastructure of currently developed countries. Consumption growth declined during
 133 the 1970-2000 period, as saturation thresholds were approached in rich countries and
 134 no poor country was economically emerging. Then the rapid economic emergence of
 135 China in the late 1990s led to a second period of increase in global consumption (Figure
 136 3). China's consumption is expected to level off over the next decade, and then decline
 137 between 2030 and 2050. After 2050, the need for new infrastructure in this country is
 138 no longer controlled by the evolution of GDP/capita because the saturation thresholds
 139 are reached. Moreover, the amount of recyclable material that was negligible before
 140 2030 increases after 2030 as fast as the increase of consumption observed between 2000
 141 and 2025. The amount of steel available for recycling between 2050 and 2075 is even
 142 higher than the apparent consumption. A peak in steel consumption was also observed
 143 in the US in the 1970's, although less pronounced than in China in 2030, because previ-
 144 ous growth was slower. Since then, the US steel consumption has remained relatively
 145 constant, which is a common observation made for all rich countries, as well as in China

146 after 2050. A step evolution of demand is also observed for Ni, Cr and Mn, which are
 147 mainly used as alloying elements of steel. The step evolution is less clear for other
 148 base metals such as copper and aluminium involved in a variety of new applications
 149 with lower lifetimes than steel since the fifties. The decrease of Chinese consumption in
 150 2030-2050 is likely to be compensated by the increase due to the economic emergence
 151 Indian and African countries. Assuming that these countries will achieve their economic
 152 development within the century, the Indian peak of cement and steel consumption might
 153 occur in 2050 and 2100, and those of copper and aluminium one or two decades latter.
 154 The African consumption peaks are expected to occur fifteen years latter. In this scenario,
 155 the yearly global demand in steel and cement in 2100 is fourfold the present value, and
 156 six fold the present consumption for aluminium and copper.

157 2.2. The new applications and high-tech metals

158 In parallel or after building its basic infrastructure, countries' economies are moving
 159 towards advanced technologies, which use many properties resulting from the electronic
 160 structure, catalytic, quantum or semiconductor properties specific to almost all the
 161 elements of the periodic table. Rapid changes in the use of metals have emerged during
 162 the last decades in the Information and Communication Technology (ICT) sector: in
 163 2019, there were approximately 13 billion mobile phones and tablets [65] and 2 billion
 164 computers (1 billion in 2008) in use, Facebook had more than 1 billion users and global
 165 data centre traffic was estimated at 4.8 zettabytes, representing more than 26,000 centuries
 166 of streaming video. This ICT sector is a large consumer of rare and high-purity substances
 167 (Cu, In, Ga, Sb, Ge, Co, Li, Ge, Ta, Nb, Au, Ag, rare earths, etc.) with dispersive uses
 168 resulting from high dilution in many short-lived devices, which limits the potential
 169 for recycling on the order of one percent. While the base metal consumption since
 170 1990 has increased by 2-5%/year, the annual growth of rare metals production is about
 171 10%/year. These huge growth rates and possible supply problems have attracted most
 172 the attention over the last decade. However, assessing the future of high-technology
 173 metals demand is difficult, because it depends on rapid technical innovation and the
 174 use of high technologies is much less dependent on GDP/cap than base metals. New
 175 technologies also concern the energy sector, which is evolving to reduce our GHG
 176 emissions and comply with the Paris agreements. These agreements of COP21 aim at
 177 achieving the "carbon neutrality" in the second half of the 21st century, which implies a
 178 deep review of the existing fossil-based energy system. Unfortunately, solar and wind
 179 infrastructures require more raw materials per installed capacity and energy supplied
 180 than fossil fuel-based facilities [34,37,66–68]. The same observation is made for the
 181 storage of energy, its transport and use at the end of the energy chain. It follows that
 182 large amounts of structural and high-tech mineral commodities will be consumed for
 183 the energy transition.

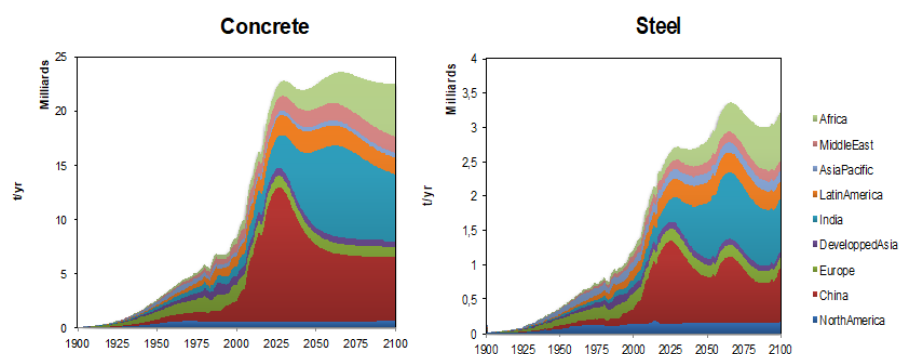


Figure 2. Concrete and steel consumption by geographical regions based on a logistic growth of regional infrastructures calculated for logistic GDP and population growths (Figure 1).

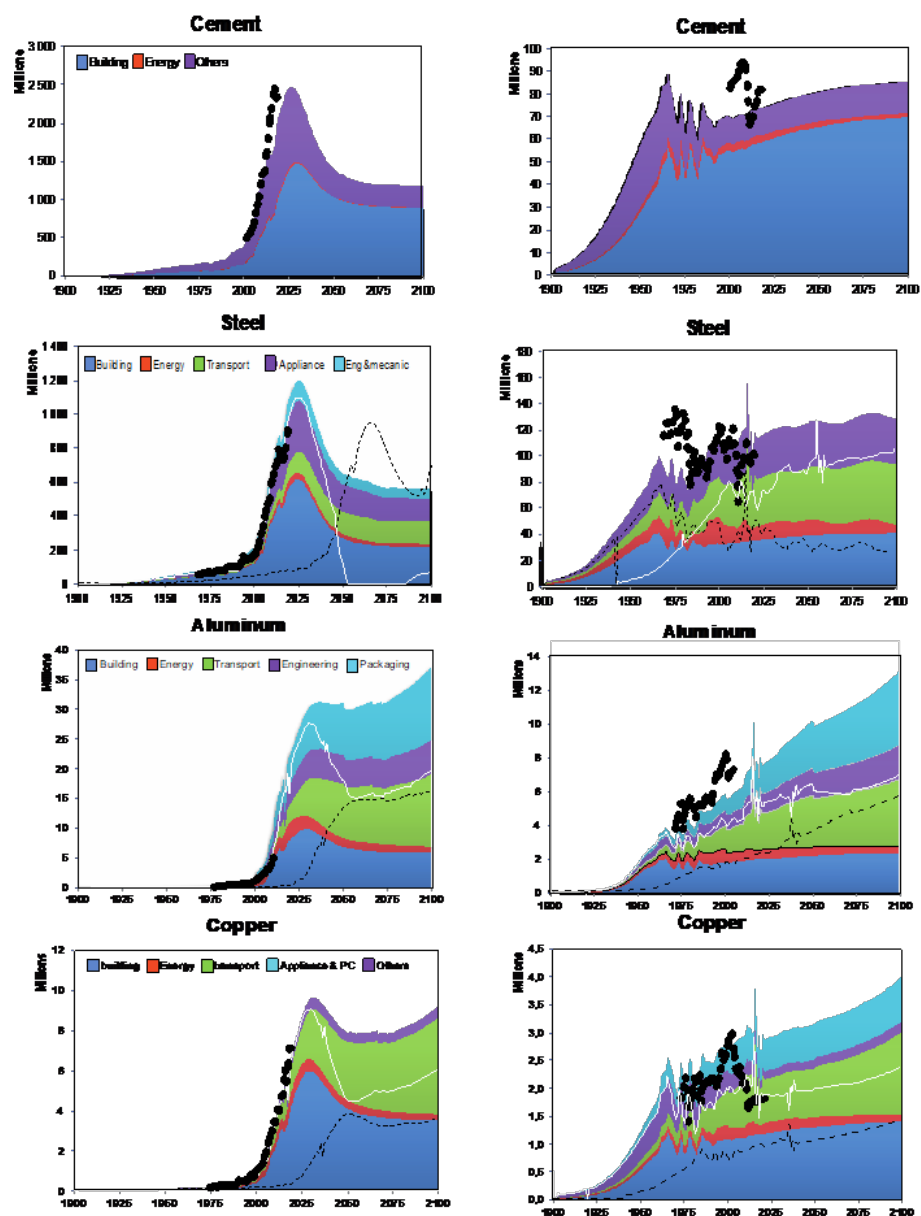


Figure 3. Raw material demand by sectors (Mt/year) calculated from the evolution of infrastructure (Figure 1) for the China (Left panel) and USA (Right panel). The white and dashed black lines show, respectively, the input and theoretical recycled flows (assuming no export or import of scrap). The dots show the historical data (USGS).

184 Figures 2 and 3 have been calculated under the assumption that the penetration of
 185 low-carbon energy technologies will remain moderate. For the same evolution of GDP
 186 and population, and thus of building, transport and energy infrastructure, the demand
 187 for metals will be different for a higher penetration of renewables. Examples are shown in
 188 Figure 4, which illustrate the differences in global Cu, Li, Co and Ni consumption for the
 189 two contrasted energy scenarios RTS (Reference Technology Scenario) and B2DS (Beyond
 190 2°C Scenario) of the International Energy Agency (IEA) [69]. In contrast to previous
 191 estimates based on GDP/cap evolutions (Figures 2 and 3), the demand in raw materials
 192 in Figure 4 is calculated from the consumed energies listed in the scenarios, which
 193 are transformed into an infrastructure for assumed evolutions of energy consumption
 194 (-1%/yr) and material content. The evolution of infrastructure is then transformed into
 195 raw materials demand using the same material intensities as those used to built Figures
 196 2 and 3. The demands in Cu, Li, Co and Ni are noticeably higher for the B2DS scenario,

197 which foresees a massive incorporation of renewable energy in the energy mix. Rare
198 earth elements (REE) and in particular neodymium are also elements of concern, as
199 they are used in the permanent magnets of a wide variety of technologies using electric
200 motors and in the generators of off-shore wind turbines. The estimates in Figure 4 must
201 be handle with care because the present technologies, intensity of use and recycling rates
202 are not necessarily representative of the future situation. The price of cobalt, used as a
203 cathode in lithium-ion batteries, increased from 55,000 to 83,000 \$/t between March 2017
204 and February 2018. This situation has prompted the manufacturers to find solutions to
205 reduce or ban the use of cobalt in lithium batteries¹ and to develop efficient recycling
206 solutions². Similarly, during the rare earth elements (REE) crisis in 2011, engineers were
207 able to find solutions to either reduce the amount of used REE while maintaining the
208 efficiency of technologies, or to change technologies. This illustrates the high potential
209 of technological innovation to reduce the use of rare elements in high or/and energy
210 technologies. For this reasons, it is extremely difficult to provide reliable estimates of
211 their future demand.

¹ Increasing investments into cobalt-free batteries research and development and production are currently observed by [small to large companies](#).

² Such as the development of [closed loop recycling processes](#).

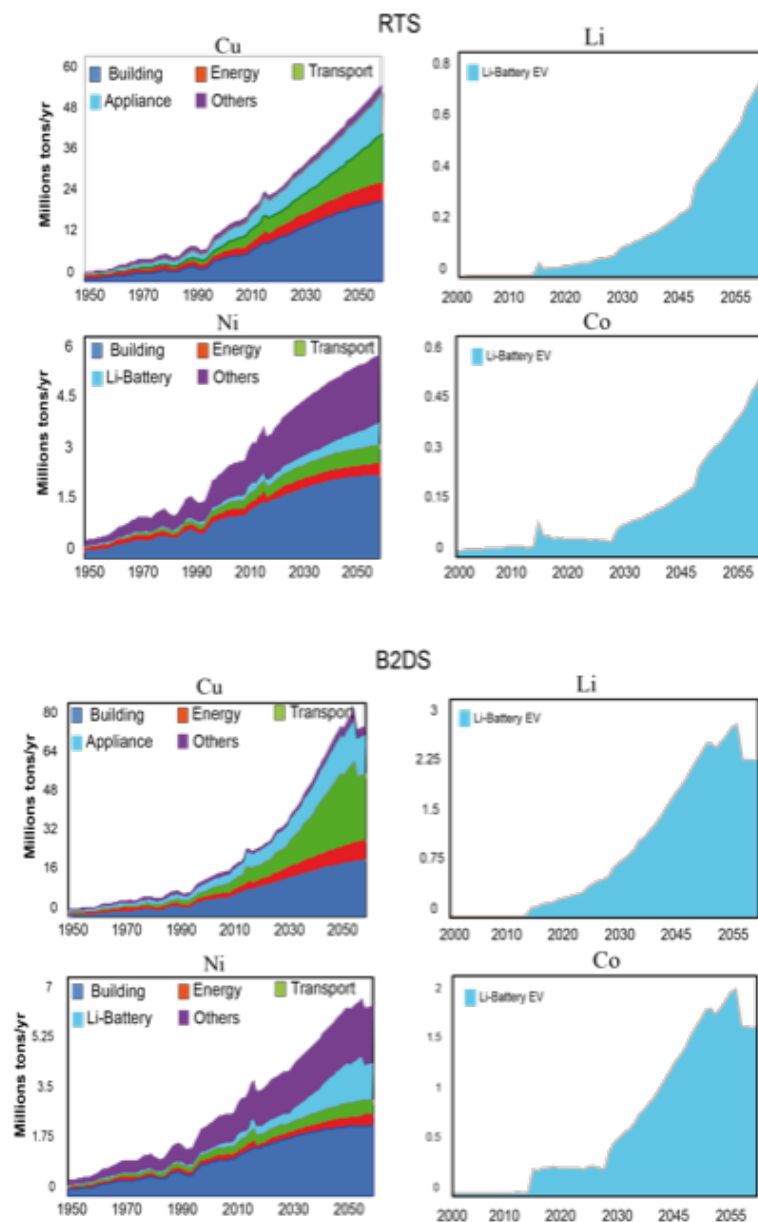


Figure 4. Annual demand for Cu, Li, Ni and Co calculated for the evolution of infrastructure in the reference technology (RTS) (**Top panel**) and the "Beyond 2°C" scenario (B2DS) (**Bottom panel**) of the International Energy Agency.

212 Even though it will depend on the rate of economical development, energy and
 213 numerical transitions, the estimated cumulative amount of metals to be produced over
 214 the next 35 years is likely to be equivalent or exceed the cumulative amount produced
 215 from antiquity to the present. These dizzying figures, which are consistent with previous
 216 estimates [2,3], illustrate the reality of a forever growth of GDP. For a constant growth
 217 rate of 5%/year, the quantity doubles every 12 years. It has been possible to double
 218 aluminium production since 2000, will it be possible to quadruple it in the next 40 years?
 219 This question is addressed in the following section.

220 3. Can future production meet the demand?

221 Several studies suggest that the future supply of raw materials will not be able to
 222 keep pace with demand, because the stock of exploitable fossil resources is declining
 223 over time and the production of several metals has already peaked or will peak in the
 224 near future [8,10–13,16,70,71]. Although it was initially developed for the oil production,

225 application of the Hubbert's theory to mineral resources led Sverdrup et al.[71] to the
 226 conclusion that the production of gold, silver, copper, nickel, zinc, molybdenum, iron,
 227 platinum and indium should peak at or before 2050. The same authors described a similar
 228 situation for conventional fossils energy resources, and a peak of non-conventional oil
 229 by 2075. However, a major flaw of the Hubbert's approach lies in the assumption
 230 that production is limited by the sole availability of resources at continuously growing
 231 demand. According to this logic, the observed decline in the growth rate of steel
 232 production between 1970 and 2000 (Figure 2) could have been misinterpreted as a sign
 233 of resource depletion, while it was actually resulting from temporarily declining growth
 234 of demand. Another pitfall is the assumption that the "ultimate recoverable resource"
 235 (URR) is finite and quantifiable. Metals and minerals are currently exploited from a small
 236 fraction of the continental crust. The maximum value of reserves can be estimated from
 237 the log-Gaussian ore-tonnage (OT) versus ore grade (OG) relationship of ore deposits
 238 [72,73]:

$$OT = \frac{A}{OG \cdot \sigma \cdot \sqrt{2\pi}} \cdot \exp\left(\frac{-\log(OG) - \mu^2}{2 \cdot \sigma^2}\right) \quad (1)$$

239 where μ is the central tendency, σ the dispersion and A the scaling factor that
 240 determines the function amplitude. The additional amount of metal M_{OG} that can be
 241 extracted with varying OG reads:

$$M_{OG} = OT \cdot \frac{OG}{100} \quad (2)$$

242 M_{OG} is the amount of additional available metal deduced from its geological
 243 distribution in the crust, whatever the cost of its extraction. The integral of M_{OG} gives
 244 the evolution of reserves plus cumulative production, which increases exponentially as
 245 long as the average OG remains below the value of the peak of OT vs OG (Equation
 246 1). By combining equations 1 and 2 with the expected evolution of demand (Section
 247 2), it is possible to estimate the required evolution of average OG and thus OT and
 248 metal reserves. Based on the historical evolution of copper reserves, production, ore
 249 tonnage and OG with time, Vidal et al.[74] have estimated an URR of copper between 5
 250 and 7.5 Gt in 2100 for a copper price ranging between 10 and 15 thousands US\$1998/t.
 251 Although these estimated reserves are within the range of those made by [75–78], the
 252 approach is fraught with large uncertainties arising from equally large uncertainties in
 253 the distribution of metals in the earth's crust. Vidal et al.'s estimates assumed a bimodal
 254 distribution [74], one centred at the average grade of copper in the crust ($OG \approx 30$ ppm
 255 [79]) and another corresponding to the peak OT of ore deposits centred at $OG \approx 0.3\%$
 256 [72]. However, the bimodal OT vs OG distribution is questionable [75], and if a unimodal
 257 distribution centred at the average crustal concentration is assumed, future reserves
 258 could be at least an order of magnitude higher. Estimates of future reserves and resource
 259 availability from geologic criteria and OT vs. OG distributions are thus quite uncertain.
 260 The question of availability is above all a question of price and environmental impacts
 261 we will be willing to pay. Historical data show that so far, technological improvements
 262 have made it possible to mine less and less concentrated and accessible ores (deeper,
 263 offshore) without unaffordable increases in production costs and metal prices. Is this
 264 trend sustainable in the future? To answer the question, we must now understand the
 265 links between energy and production costs, between metal prices and OG, and between
 266 technological improvements and thermodynamic limits.

267 3.1. Energy of metal primary production, prices and reserves

268 Currently, about 12% of global energy consumption and about 35% of the energy
 269 consumed by the industry worldwide is used for the production of iron and steel, cement,
 270 aluminium and non-ferrous metals [80]. The production of mineral resources is therefore
 271 very energy-intensive. Several studies have shown that the average price of metals is

272 proportional to the energy of their production, which varies as a power law of dilution
 273 (inverse of ore grade) [60,68,81–83]. A plot of the production energies $E(2005)$ of twenty
 274 metals diluted from 1.9 (iron) to $2 \cdot 10^5$ (gold, platinum) as a function of their price in 2005
 275 ($P(2005)$) confirms this proportionality. The following relationships are derived between
 276 $E(2005)$ and $P(2005)$ [84]:

$$P(2005) = 26 \cdot \alpha \cdot E(2005)^{1.1} \quad (3)$$

277 with $\alpha = \frac{2}{C(2005)^{0.2}}$, and

$$E(2005) = \overline{\eta(2005)} \cdot (-\Delta G_{fi}^{\circ} + Es_i + \frac{a_i}{C(2005)}) \quad (4)$$

278 with $\overline{\eta(2005)}$ the inverse of energy efficiency compared to the thermodynamic
 279 minimum ($\eta=1$ at the thermodynamic minimum, an average value $\overline{\eta(2005)}=3$ is obtained
 280 for 20 metals), $-\Delta G_{fi}^{\circ}$ the Gibb's free energy of formation of the ore mineral from its
 281 constituents (minimum energy of metallurgy), Es_i the mixing entropy of an ideal mixture
 282 of two components with no interaction (minimum energy to separate the metal-bearing
 283 minerals the from the disaggregated ore), $a_i = 0.2$ and C the mass concentration of metal
 284 in $\text{kg}_{\text{metal}}/\text{kg}_{\text{ore}}$. The evolution of production energy with time can be estimated with
 285 Equation 4 by replacing the 2005 values of $\overline{\eta(2005)}$ and $C(2005)$ by the values at year t .
 286 In order to account for the variations of energy price, Equation 3 must be corrected by
 287 the price of energy at time t ($PE(t)$) relative to 2005 ($PE(2005)$):

$$P(t) = 26 \cdot \frac{2}{C(2005)^{0.2}} \cdot E(t)^{1.1} \cdot \left(\frac{PE(t)}{PE(2005)}\right)^{\gamma} \quad (5)$$

288 with γ the elasticity of metals prices variations relative to the variation of energy
 289 price. Using the price of crude oil as a proxy of energy price, $\gamma = 0.7$ for copper and $\gamma =$
 290 0.1 for aluminum.

291 At $C < 1\%$, the metallurgy and separation energies are negligible compared to the
 292 term $\frac{a_i}{C}$ that represents the comminution energy. It means that at constant technology
 293 and price of energy, the energy of primary production of precious metals, copper or
 294 nickel are expected to increase exponentially with the decrease in ore grade observed
 295 over the last century [17,85]. Proponents of a looming shortage of metals often use this
 296 argument to claim that production will become prohibitively expensive in the future.
 297 However, long-term historical data do not support this figure and the inflation-adjusted
 298 commodity prices have actually been falling between 1900 and 2000 [86]. This fall,
 299 also observed for copper or nickel, indicates that the expected increase in production
 300 energy due to falling ore grades has actually been offset by the improvements of energy
 301 efficiency and productivity at constant ore grade (EC in the Figure 5a). The improvement
 302 of energy efficiency was 1-2%/year between 1900 and 2000 [83,84,87] and until 2000, the
 303 energy gains of all metals production have more than compensated the decrease of ore
 304 quality. Since the regeneration of reserves increases with falling grade (Equations 1 and
 305 2), these figures explain why both the produced quantities of metals and their reserves
 306 have grown exponentially since 1900. However, this trend is not sustainable on the long
 307 term because there is a thermodynamic limit (ETL) to the extraction of metals, which is
 308 given by Equation 4 with $\eta = 1$. This physical limit cannot be overstepped, whatever
 309 the technological improvement. Steel production consumed about 50 MJ/kg in the 1950
 310 and it has been halved between the 1950s and 2000 [87]. It will most likely not be halved
 311 again by 2050 to reach the thermodynamic limit equal to about 10 MJ/kg for iron oxide
 312 ore³ ($-\Delta G_f^{\circ} = 7$ MJ/kg of hematite), as the investment required to gain a few MJ when
 313 approaching this limit becomes prohibitive. More worrying, the thermodynamic limit of

³ For metals at high concentration in ore deposits such as iron ($C = 30\text{-}50\%$) or aluminium (15-30%), the energy demand of crushing and grinding ore ($\frac{a_i}{C}$) is negligible compared to the energy of metallurgy ($-\Delta G_f^{\circ}$) in Equation 4.

314 metals at $C < 1\%$ is expected to increase exponentially with falling ore grade due to the
 315 term $\frac{a_i}{C}$. In practice, this limit cannot be reached because industrial processes cannot be
 316 100% efficient, and the minimum value of η in Equation 4 is unlikely to be lower than 1.5
 317 (PME = 1.5 · ETL). In the case of copper, η decreased at an annual rate of -1.5%/yr from
 318 about 10 in 1930 to 2 in 2000 (dashed line in Figure 5b). It will not be possible to continue
 319 on this trend because the minimum value of $\eta = 1.5$ will be reached before the end of
 320 the century (continuous line in Figure 5c). For an average ore grade of copper deposits
 321 decreasing at 1.5%/yr since 1900, improving current mechanical crushing and grinding
 322 technologies will thus not compensate for the additional energy to switch to lower grade
 323 ore in the future, as it has been the case during the 20th century. The energy of copper
 324 production, which declined between 1900 and 2000, is thus expected to increase from
 325 2000 onward and parallels the PME in the second half of the century (Figure 5a). Similar
 326 conclusions are drawn for precious metals and nickel, zinc and manganese.

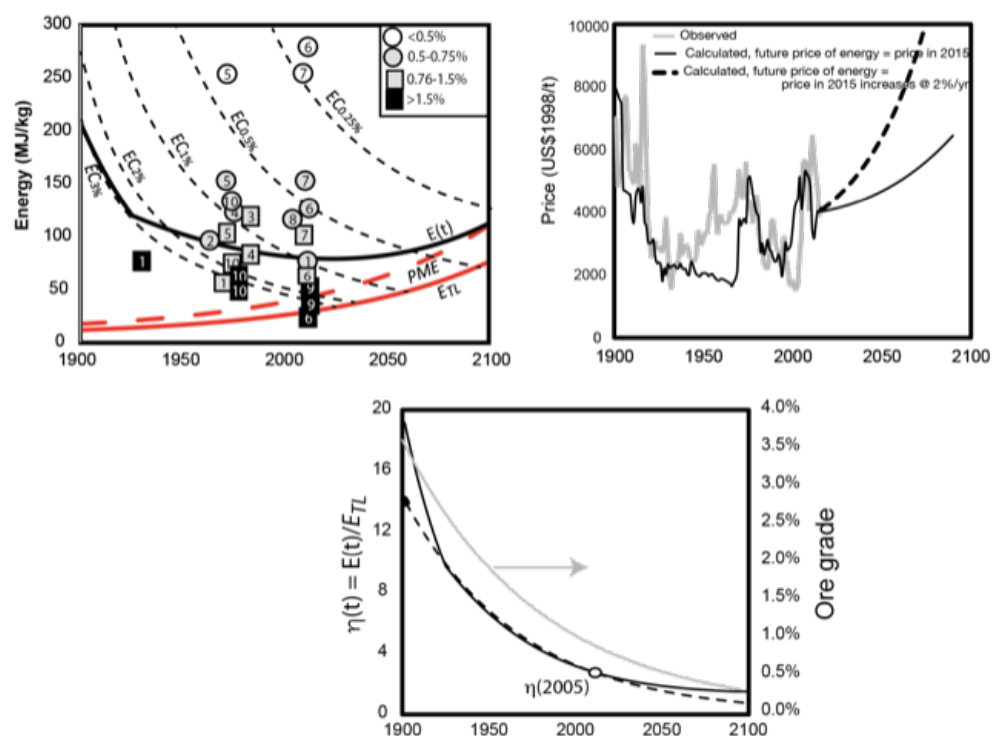


Figure 5. a) Calculated and observed (numbers) energies of copper production: the heavy black line shows the energy of copper production with varying ore grade and technology $E(t)$, the thin black dashed line show the energy at constant ore grade with varying technology (EC), and the red dashed and continuous lines show the practical minimum energy (PME) and thermodynamic limit (ETL), respectively. The observed data are plotted at the time of publication and reported ore grades: 1) Rötzer and Schmidt[88]; 2) Rosenkranz[89]; 3) Gaines[90]; 4) Kellogg[91]; 5) Page and Creasy[92]; 6) Norgate and Jahanshahi[85]; 7) Marsden[93]; 8) Office of Energy Efficiency & Renewable Energy[94]; 9) Rankin[95]; 10) Chapman[96]. **b)** Observed copper price (grey line) and calculated price (black line). The future price is calculated at constant future price of energy (=PE2015, continuous line) or at 2%/yr increasing price of energy after 2015 (dashed line). **c)** $\eta(t)$ (black continuous line, left scale) and ore grade (grey line, right scale) used to compute a) and b). The black dashed line in c) shows $\eta(t)$ calculated from $\eta(2005)$ and a -1.5%/yr of change.

327 4. Discussion

328 The above overview of some parameters controlling the demand and primary
 329 production provides arguments for two classically opposed views of the future of
 330 mineral resources: an unaffordable increase in costs and prices following the depletion
 331 of high quality deposits or, on the contrary, a favourable compensation by technological
 332 improvements. Both visions are true, but not at the same time. After a period of gains

333 in energy and production costs, it seems that we are now entering a pivotal period of
334 long-term increasing production costs as we approach the practical minimum energy
335 and thermodynamic limits for several metals. To reduce this increase of price, unknown
336 breakthrough but affordable grinding technologies based on non-mechanical processes
337 will have to be found. Another possibility is to reduce the price of energy. Renewable
338 energies are virtually unlimited and once the infrastructure of production is built, they
339 are cheap. If we could use renewable energy sources at a low and stable price in the
340 future, the increasing weight of energy intensity in the cost of production would no
341 longer be an issue. This is illustrated by Iceland, which became in 2016 the world's ninth
342 largest producer of aluminium from imported bauxite thanks to cheap geothermal and
343 hydroelectric power, even though it has no ore and most of its production is destined
344 to foreign markets. If the use of renewable energy sources were to become significant
345 enough to cover the needs of the raw material production sector, it would become
346 possible to exploit low-grade resources that cannot be exploited at an affordable cost
347 today. However, energy transition scenarios present another constrain: in order to cope
348 with the targeted decrease of CO₂ emissions, they generally assume a strong reduction
349 in energy consumption. For example, the amount of energy available for the industrial
350 sector in the scenario B2DS already used in Figure 2 is 65% that of RTS, while the energy
351 consumed for the production of raw materials is similar. The future share of industrial
352 energy consumed to produce the raw materials is thus higher in B2DS than RTS and
353 the remaining energy available for the other industrial sectors is lower. These figures
354 will impact the intensive industries and in particular the raw material production sector,
355 which will already face the problem of declining resource quality. It thus seems extremely
356 difficult to switch to renewable energies while reducing global energy demand. Neither
357 the developed countries, which are expected to replace their fossil fuel-based energy
358 infrastructure in two nor three decades, nor the developing countries that produce
359 raw materials to build their basic infrastructure will spontaneously follow this path.
360 Until 2050, the demand for energy will thus continue to grow on a global scale. On
361 the longer term, the energy demand for the production of raw materials is expected
362 to decrease after 2050 in both scenarios B2DS and RTS. This is due to the combined
363 effects of: **i)** approaching the saturation levels of infrastructure at the global scale, which
364 entails a reduction of the annual demand in raw materials, **ii)** completing the energy
365 transition, and **iii)** increasing rapidly the share of less energy-intensive recycled metals
366 at the saturation levels and unaffordable prices of primary metals.

367 The above overview of the parameters controlling the demand and primary produc-
368 tion also indicates that the question of the future of mineral resources cannot be based
369 solely on knowledge of current geological availability for a constant rate of growth in
370 demand and technology. It must be studied using dynamic models that integrate the
371 value chain from primary production to recycling, coupling energy requirements and
372 thermodynamic limits, geological, environmental, technological, social, economic and
373 and geopolitical dimensions. Such models are intrinsically complex, but it is illusory
374 to address complex issues with empirical and deterministic models such as Hubbert's
375 model, or any model neglecting the role of technological improvement, change in re-
376 source quality and variations of energy prices with time. Coupling material flows with
377 GDP and population evolution is quite straightforward using sigmoid evolutions of
378 the infrastructure/cap with GDP/cap, and assumptions on the materials contents. The
379 consumed energy can also be estimated for assumed intensities of use and energy ef-
380 ficiencies. In contrast, coupling the materials and energy flows with economic models
381 is more difficult, because economic models lack physical basis and constrains and are
382 derived from observations made in growing economies. Since the industrial activities
383 and consuming sectors are strongly coupled, it is difficult to analyse one sector of metal
384 production isolated from the whole economic system. To circumvent the problem, a pos-
385 sible approach based on a prey-predator dynamics has been proposed by Vidal et al.[74],
386 in line of previous study by Bardi and Lavacchi[8]. This approach is also empirical, but

387 it allows one to combine physical units (tons) with monetary units without requiring a
388 detailed and comprehensive description of all economic sectors. It analyses the evolution
389 of industrial capital (the predator, in monetary units) and the metal reserves (the prey, in
390 tonnes) with two coupled differential equations involving four parameters controlling to
391 the yearly regeneration of reserves, metal production, regeneration and erosion of capital.
392 Interestingly, the cost (price) of metal production is given by the ratio of two of them,
393 corresponding to the capital growth to metal production. Applying the model to the
394 case of copper, we showed that the expected price evolution is similar to the production
395 energy-based independent estimate reported in Figure 5. Independently of any eco-
396 nomic consideration, the long-term price of metals derived from the production energy
397 calculated with the simple thermodynamic formalism proposed in Equations 3 to 5 thus
398 provides first order constraints on the future evolution of metals production. In the case
399 of copper, Vidal et al. [74] predicted a peak in primary production by 2050, followed by a
400 rapid collapse if the future demand is assumed to follow the historical trends (+3%/year).
401 In contrast, a scenario no longer based on a steady growing demand but on the need for a
402 population stabilizing at 11 billion inhabitants in 2100 and an average GDP per capita of
403 10,000\$ provides more optimistic results. A peak of primary production is still observed,
404 but it is a peak of demand. A decrease of primary production occurs in the second
405 half of the century, when the saturation of infrastructures is approached and recycled
406 copper becomes the major source. Here again, this example shows that the future of
407 natural resources cannot be dissociated from a scenario of demand, which is another
408 illustration of the limit of Hubbert-like approaches. The prey-predator model applied to
409 other metals suggests that the supply of most base and precious metals (except gold)
410 should also meet the demand until the end of the century. The situation is much less
411 clear for rare metals, as historical data on reserves and production are missing, imprecise
412 or cover too short a time period to be used as reliable constraints for the models.

413 In addition to the reserves, price and energy production issues, the environmental
414 impacts of raw materials and energy production must also be integrated in the models.
415 These impacts might become a limiting factor to production in the future. An emblematic
416 example is given by El Salvador that made history as first nation to impose blanket
417 ban on metal mining in response to diminishing water sources from polluting mining
418 projects⁴. The huge expected increase in mineral resources consumption and primary
419 production will increase conflicts and social opposition. The surface occupied by mines
420 and quarries at the world level has been estimated to be about 400,000 km² [97], it
421 could be double by 2050 and quadruple by 2100. The embodied water consumption and
422 other environmental impacts are expected to follow the same trends. These figures are
423 naturally concerning, especially in arid production areas. To our knowledge, no model
424 currently exists that describes the local societal response to water and land use and more
425 broadly to environmental impacts, even though this is a major constraint on the future
426 production of resources. This response is expected to depend on the level of GDP/capita
427 and population density, the industrial typology, the level of agricultural production
428 and geographical characteristics of the producing countries, such as the availability of
429 water. Modelling the feedback of resource consumption and environmental changes
430 on social opposition is a very important research topic to address the issue of future
431 mineral resource availability in a world of increasing environmental constraints, and
432 increasingly compromised access to water and arable land.

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⁴ This decision was approved by the Parliament of El Salvador in [early 2017](#).

437 **References**

- 438 1. Schaffartzik, A.; Mayer, A.; Gingrich, S.; Eisenmenger, N.; Loy, C.; Krausmann, F. The global
439 metabolic transition: Regional patterns and trends of global material flows, 1950–2010. *Global*
440 *Environmental Change* **2014**, *26*, 87–97. doi:10.1016/j.gloenvcha.2014.03.013.
- 441 2. Graedel, T.E.; Cao, J. Metal spectra as indicators of development. *Proceedings of the National*
442 *Academy of Sciences* **2010**, *107*, 20905–20910. doi:10.1073/pnas.1011019107.
- 443 3. Graedel, T.E. On the future availability of the energy metals. *Annual Review of Materials*
444 *Research* **2011**, *41*, 323–335.
- 445 4. Wiedmann, T.O.; Schandl, H.; Lenzen, M.; Moran, D.; Suh, S.; West, J.; Kanemoto, K. The
446 material footprint of nations. *Proceedings of the National Academy of Sciences* **2015**, *112*, 6271–
447 6276. doi:10.1073/pnas.1220362110.
- 448 5. Elshkaki, A.; Graedel, T.E.; Ciacci, L.; Reck, B.K. Resource Demand Scenarios for the Major
449 Metals. *Environmental Science & Technology* **2018**, *52*, 2491–2497. doi:10.1021/acs.est.7b05154.
- 450 6. Elshkaki, A. Materials, energy, water, and emissions nexus impacts on the future contribution
451 of PV solar technologies to global energy scenarios. *Scientific Reports* **2019**, *9*, 19238. doi:
452 10.1038/s41598-019-55853-w.
- 453 7. *Nuclear Energy and the Fossil Fuel*, Vol. All Days, *Drilling and Production Practice*,
454 1956, [[https://onepetro.org/APIDPP/proceedings-pdf/API56/All-API56/API-56-
455 007/2059843/api-56-007.pdf](https://onepetro.org/APIDPP/proceedings-pdf/API56/All-API56/API-56-007/2059843/api-56-007.pdf)]. API-56-007.
- 456 8. Bardi, U.; Lavacchi, A. A Simple Interpretation of Hubbert’s Model of Resource Exploitation.
457 *Energies* **2009**, *2*, 646–661. doi:10.3390/en20300646.
- 458 9. Bardi, U.; Pagani, M. *Peak Minerals*, 2007.
- 459 10. Meadows, D.H.; Meadows, D.L.; Randers, J.; Behrens, W.W. *The Limits to Growth: A report*
460 *for the Club of Rome’s Project on the Predicament of Mankind*; Universe Books, 1972. doi:
461 10.1349/ddlp.1.
- 462 11. Sverdrup, H.; Ragnarsdóttir, K.V. Natural Resources in a Planetary Perspective. *Geochemical*
463 *Perspectives* **2014**, pp. 129–341. doi:10.7185/geochempersp.3.2.
- 464 12. Kerr, R.A. The Coming Copper Peak. *Science* **2014**, *343*, 722–724. doi:10.1126/sci-
465 ence.343.6172.722.
- 466 13. Northey, S.; Mohr, S.; Mudd, G.; Weng, Z.; Giurco, D. Modelling future copper ore grade de-
467 cline based on a detailed assessment of copper resources and mining. *Resources, Conservation*
468 *and Recycling* **2014**, *83*, 190–201. doi:10.1016/j.resconrec.2013.10.005.
- 469 14. Bardi, U. Energy Prices and Resource Depletion: Lessons from the Case of Whaling in the
470 Nineteenth Century. *Energy Sources, Part B: Economics, Planning, and Policy* **2007**, *2*, 297–304.
471 doi:10.1080/15567240600629435.
- 472 15. Bardi, U.; Lavacchi, A.; Yaxley, L. EROEI and Net Energy in the Exploitation of Natural
473 Resources. A Study based on the Lotka-Volterra Model **2018**. p. 7.
- 474 16. Laherrère, J. Copper peak. *The Oil Drum: Europe* **2010**, pp. 1–27.
- 475 17. Mudd, G.M. *The sustainability of mining in Australia: key production trends and environmental*
476 *implications*; Monash University, Department of Civil Engineering: Clayton, 2009. OCLC:
477 511439437.
- 478 18. UN. UN Comtrade - International Trade Statistics Database, 2021.
- 479 19. Worldsteel. Steel Statistical Yearbook, 2021.
- 480 20. Copper Alliance. Annual Reports - Copper Alliance. Technical report, 2021.
- 481 21. USGS. Mineral Commodity Summaries. Technical report, USGS, 2021.
- 482 22. Li, Q.; Dai, T.; Gao, T.; Zhong, W.; Wen, B.; Li, T.; Zhou, Y. Aluminum material flow analysis
483 for production, consumption, and trade in China from 2008 to 2017. *Journal of Cleaner*
484 *Production* **2021**, *296*, 126444. doi:10.1016/j.jclepro.2021.126444.
- 485 23. Streeck, J.; Dammerer, Q.; Wiedenhofer, D.; Krausmann, F. The role of socio-economic
486 material stocks for natural resource use in the United States of America from 1870 to 2100.
487 *Journal of Industrial Ecology* **2021**, p. jiec.13166. doi:10.1111/jiec.13166.
- 488 24. Ciacci, L.; Fishman, T.; Elshkaki, A.; Graedel, T.; Vassura, I.; Passarini, F. Exploring future
489 copper demand, recycling and associated greenhouse gas emissions in the EU-28. *Global*
490 *Environmental Change* **2020**, *63*, 102093. doi:10.1016/j.gloenvcha.2020.102093.
- 491 25. Wiedenhofer, D.; Fishman, T.; Lauk, C.; Haas, W.; Krausmann, F. Integrating Material
492 Stock Dynamics Into Economy-Wide Material Flow Accounting: Concepts, Modelling,
493 and Global Application for 1900–2050. *Ecological Economics* **2019**, *156*, 121–133. doi:
494 10.1016/j.ecolecon.2018.09.010.

- 495 26. Pfaff, M.; Glöser-Chahoud, S.; Chrubasik, L.; Walz, R. Resource efficiency in the German cop-
496 per cycle: Analysis of stock and flow dynamics resulting from different efficiency measures.
497 *Resources, Conservation and Recycling* **2018**, *139*, 205–218. doi:10.1016/j.resconrec.2018.08.017.
- 498 27. Krausmann, F.; Schandl, H.; Eisenmenger, N.; Giljum, S.; Jackson, T. Material Flow Ac-
499 counting: Measuring Global Material Use for Sustainable Development. *Annual Review of*
500 *Environment and Resources* **2017**, *42*, 647–675. doi:10.1146/annurev-environ-102016-060726.
- 501 28. Deetman, S.; de Boer, H.; Van Engelenburg, M.; van der Voet, E.; van Vuuren, D.
502 Projected material requirements for the global electricity infrastructure – generation,
503 transmission and storage. *Resources, Conservation and Recycling* **2021**, *164*, 105200. doi:
504 10.1016/j.resconrec.2020.105200.
- 505 29. Ren, K.; Tang, X.; Wang, P.; Willerström, J.; Höök, M. Bridging energy and metal sustainability:
506 Insights from China’s wind power development up to 2050. *Energy* **2021**, *227*, 120524. doi:
507 10.1016/j.energy.2021.120524.
- 508 30. Li, F.; Ye, Z.; Xiao, X.; Xu, J.; Liu, G. Material stocks and flows of power infrastructure devel-
509 opment in China. *Resources, Conservation and Recycling* **2020**, *160*, 104906. doi:Development
510 and validation of a dynamic material flow analysis model for French copper cycle.
- 511 31. Watari, T.; McLellan, B.C.; Giurco, D.; Dominish, E.; Yamasue, E.; Nansai, K. Total material
512 requirement for the global energy transition to 2050: A focus on transport and electricity.
513 *Resources, Conservation and Recycling* **2019**, *148*, 91–103. doi:10.1016/j.resconrec.2019.05.015.
- 514 32. Moreau, V.; Dos Reis, P.; Vuille, F. Enough Metals? Resource Constraints to Supply a Fully
515 Renewable Energy System. *Resources* **2019**, *8*, 29. doi:10.3390/resources8010029.
- 516 33. Dong, D.; Tukker, A.; Van der Voet, E. Modeling copper demand in China up to 2050: A
517 business-as-usual scenario based on dynamic stock and flow analysis. *Journal of Industrial*
518 *Ecology* **2019**, *23*, 1363–1380. doi:10.1111/jiec.12926.
- 519 34. Vidal, O.; Boulzec, H.L.; François, C. Modelling the material and energy costs of the transition
520 to low-carbon energy. *EPJ Web of Conferences* **2018**, *189*, 00018. Publisher: EDP Sciences, doi:
521 10.1051/epjconf/201818900018.
- 522 35. Tokimatsu, K.; Wachtmeister, H.; McLellan, B.; Davidsson, S.; Murakami, S.; Höök, M.;
523 Yasuoka, R.; Nishio, M. Energy modeling approach to the global energy-mineral nexus: A
524 first look at metal requirements and the 2 °C target. *Applied Energy* **2017**, *207*, 494–509. doi:
525 10.1016/j.apenergy.2017.05.151.
- 526 36. Elshkaki, A.; Graedel, T. Dynamic analysis of the global metals flows and stocks in
527 electricity generation technologies. *Journal of Cleaner Production* **2013**, *59*, 260–273. doi:
528 10.1016/j.jclepro.2013.07.003.
- 529 37. Vidal, O.; Goffé, B.; Arndt, N. Metals for a low-carbon society. *Nature Geoscience* **2013**,
530 *6*, 894–896. doi:10.1038/ngeo1993.
- 531 38. Dunn, J.; Slattey, M.; Kendall, A.; Ambrose, H.; Shen, S. Circularity of Lithium-Ion Battery
532 Materials in Electric Vehicles. *Environmental Science & Technology* **2021**, *55*, 5189–5198. doi:
533 10.1021/acs.est.0c07030.
- 534 39. Pauliuk, S.; Heeren, N. Material efficiency and its contribution to climate change mitigation
535 in Germany: A deep decarbonization scenario analysis until 2060. *Journal of Industrial Ecology*
536 **2021**, *25*, 479–493. doi:10.1111/jiec.13091.
- 537 40. Yang, H.; Song, X.; Zhang, X.; Lu, B.; Yang, D.; Li, B. Uncovering the in-use metal stocks
538 and implied recycling potential in electric vehicle batteries considering cascaded use: a case
539 study of China. *Environmental Science and Pollution Research* **2021**, *28*, 45867–45878. doi:
540 10.1007/s11356-021-13430-7.
- 541 41. Zhu, Y.; Chappuis, L.B.; De Kleine, R.; Kim, H.C.; Wallington, T.J.; Luckey, G.; Cooper,
542 D.R. The coming wave of aluminum sheet scrap from vehicle recycling in the United States.
543 *Resources, Conservation and Recycling* **2021**, *164*, 105208. doi:10.1016/j.resconrec.2020.105208.
- 544 42. Liu, M.; Chen, X.; Zhang, M.; Lv, X.; Wang, H.; Chen, Z.; Huang, X.; Zhang, X.; Zhang,
545 S. End-of-life passenger vehicles recycling decision system in China based on dynamic
546 material flow analysis and life cycle assessment. *Waste Management* **2020**, *117*, 81–92. doi:
547 10.1016/j.wasman.2020.08.002.
- 548 43. Deetman, S.; Marinova, S.; van der Voet, E.; van Vuuren, D.P.; Edelenbosch, O.; Heijungs, R.
549 Modelling global material stocks and flows for residential and service sector buildings to-
550 wards 2050. *Journal of Cleaner Production* **2020**, *245*, 118658. doi:10.1016/j.jclepro.2019.118658.
- 551 44. Marinova, S.; Deetman, S.; van der Voet, E.; Daioglou, V. Global construction materials
552 database and stock analysis of residential buildings between 1970–2050. *Journal of Cleaner*
553 *Production* **2020**, *247*, 119146. doi:10.1016/j.jclepro.2019.119146.

- 554 45. Liu, Y.; Li, J.; Duan, L.; Dai, M.; Chen, W.q. Material dependence of cities and implications for
555 regional sustainability. *Regional Sustainability* **2020**, *1*, 31–36. doi:10.1016/j.regsus.2020.07.001.
- 556 46. Cao, Z.; Shen, L.; Zhong, S.; Liu, L.; Kong, H.; Sun, Y. A Probabilistic Dynamic Material Flow
557 Analysis Model for Chinese Urban Housing Stock: A Probabilistic Dynamic MFA Model.
558 *Journal of Industrial Ecology* **2018**, *22*, 377–391. doi:10.1111/jiec.12579.
- 559 47. Wiedenhofer, D.; Steinberger, J.K.; Eisenmenger, N.; Haas, W. Maintenance and Expansion:
560 Modeling Material Stocks and Flows for Residential Buildings and Transportation
561 Networks in the EU25. *Journal of Industrial Ecology* **2015**, *19*, 538–551. _eprint:
562 <https://onlinelibrary.wiley.com/doi/pdf/10.1111/jiec.12216>, doi:10.1111/jiec.12216.
- 563 48. Kalt, G.; Thunshirn, P.; Wiedenhofer, D.; Krausmann, F.; Haas, W.; Haberl, H. Material
564 stocks in global electricity infrastructures – An empirical analysis of the power sector’s
565 stock-flow-service nexus. *Resources, Conservation and Recycling* **2021**, *173*, 105723. doi:
566 10.1016/j.resconrec.2021.105723.
- 567 49. Beylot, A.; Guyonnet, D.; Muller, S.; Vaxelaire, S.; Villeneuve, J. Mineral raw material
568 requirements and associated climate-change impacts of the French energy transition by 2050.
569 *Journal of Cleaner Production* **2019**, *208*, 1198–1205. doi:10.1016/j.jclepro.2018.10.154.
- 570 50. Huang, T.; Shi, F.; Tanikawa, H.; Fei, J.; Han, J. Materials demand and environmental impact
571 of buildings construction and demolition in China based on dynamic material flow analysis.
572 *Resources, Conservation and Recycling* **2013**, *72*, 91–101. doi:10.1016/j.resconrec.2012.12.013.
- 573 51. Hunt, C.; Romero, J.; Jara, J.; Lagos, G. Copper demand forecasts and predictions of future
574 scarcity. *Resources Policy* **2021**, *73*, 102123. doi:10.1016/j.resourpol.2021.102123.
- 575 52. Sverdrup, H.U.; Olafsdottir, A.H.; Ragnarsdottir, K.V. On the long-term sustainability of
576 copper, zinc and lead supply, using a system dynamics model. *Resources, Conservation &
577 Recycling: X* **2019**, *4*, 100007. doi:10.1016/j.rcrx.2019.100007.
- 578 53. Ayres, R.U.; Ayres, L.W. The Life Cycle of Copper, its Co-Products and By-Products, 2002.
- 579 54. Olafsdottir, A.H.; Sverdrup, H.U. Modelling Global Mining, Secondary Extraction, Supply,
580 Stocks-in-Society, Recycling, Market Price and Resources, Using the WORLD6 Model; Tin.
581 *BioPhysical Economics and Resource Quality* **2018**, *3*, 11. doi:10.1007/s41247-018-0041-8.
- 582 55. Sverdrup, H.U.; Olafsdottir, A.H. System Dynamics Modelling of the Global Extraction,
583 Supply, Price, Reserves, Resources and Environmental Losses of Mercury. *Water, Air, & Soil
584 Pollution* **2020**, *231*, 439. doi:10.1007/s11270-020-04757-x.
- 585 56. Capellán-Pérez, I.; Blas, I.d.; Nieto, J.; Castro, C.d.; Miguel, L.J.; Carpintero, O.; Mediavilla,
586 M.; Lobejón, L.F.; Ferreras-Alonso, N.; Rodrigo, P.; Frechoso, F.; Álvarez Antelo, D. MEDEAS:
587 a new modeling framework integrating global biophysical and socioeconomic constraints.
588 *Energy & Environmental Science* **2020**, *13*, 986–1017. Publisher: Royal Society of Chemistry
589 (RSC), doi:10.1039/c9ee02627d.
- 590 57. Bleischwitz, R.; Nechifor, V.; Winning, M.; Huang, B.; Geng, Y. Extrapolation or saturation
591 – Revisiting growth patterns, development stages and decoupling. *Global Environmental
592 Change* **2018**, *48*, 86–96. doi:10.1016/j.gloenvcha.2017.11.008.
- 593 58. Bleischwitz, R.; Nechifor, V. Saturation and Growth Over Time: When Demand for Minerals
594 Peaks **2016**. p. 37.
- 595 59. Wårell, L. Trends and developments in long-term steel demand – The intensity-of-use
596 hypothesis revisited. *Resources Policy* **2014**, *39*, 134–143. doi:10.1016/j.resourpol.2013.12.002.
- 597 60. Vidal, O. Modeling the Long-Term Evolution of Primary Production Energy and Metal Prices.
598 In *Mineral Resources Economics 1: Context and Issues*, Fizaine, F.; Galiègue, X. ed.; Wiley, 2021.
599 doi:10.1002/9781119850861.
- 600 61. Malenbaum, W. World Resources for the Year 2000. *The Annals of the American Academy of
601 Political and Social Science* **1973**, *408*, 30–46.
- 602 62. Huo, H.; Wang, M. Modeling future vehicle sales and stock in China. *Energy Policy* **2012**,
603 *43*, 17–29. doi:10.1016/j.enpol.2011.09.063.
- 604 63. Shi, F.; Huang, T.; Tanikawa, H.; Han, J.; Hashimoto, S.; Moriguchi, Y. Toward a Low
605 Carbon-Dematerialization Society: Measuring the Materials Demand and CO₂ Emissions of
606 Building and Transport Infrastructure Construction in China. *Journal of Industrial Ecology*
607 **2012**, *16*, 493–505. doi:10.1111/j.1530-9290.2012.00523.x.
- 608 64. IEA. Global Status Report 2018. Technical report, IEA, 2018.
- 609 65. Radicati. Mobile Statistics Report, 2019–2023. Technical report, Radicati, London, 2019.
- 610 66. Kleijn, R.; van der Voet, E.; Kramer, G.J.; van Oers, L.; van der Giesen, C. Metal
611 requirements of low-carbon power generation. *Energy* **2011**, *36*, 5640–5648. doi:
612 10.1016/j.energy.2011.07.003.

- 613 67. Hertwich, E.G.; Gibon, T.; Bouman, E.A.; Arvesen, A.; Suh, S.; Heath, G.A.; Bergesen, J.D.;
614 Ramirez, A.; Vega, M.I.; Shi, L. Integrated life-cycle assessment of electricity-supply scenarios
615 confirms global environmental benefit of low-carbon technologies. *Proceedings of the National
616 Academy of Sciences* **2015**, *112*, 6277–6282.
- 617 68. Vidal, O.; Rostom, F.; François, C.; Giraud, G. Global Trends in Metal Consumption and
618 Supply: The Raw Material–Energy Nexus. *Elements* **2017**, *13*, 319–324. doi:10.2138/gsele-
619 ments.13.5.319.
- 620 69. IEA. Energy Technology Perspectives 2017. Technical report, IEA, 2017.
- 621 70. Laherrère, J. Peak Gold, Easier to Model than Peak Oil?, 2009.
- 622 71. Sverdrup, H.U.; Koca, D.; Ragnarsdóttir, K.V. Peak metals, minerals, energy, wealth, food and
623 population: urgent policy considerations for a sustainable society. *Journal of Environmental
624 Science and Engineering. B* **2013**, *2*, 189.
- 625 72. Gerst, M.D. Revisiting the Cumulative Grade-Tonnage Relationship for Major Copper Ore
626 Types. *Economic Geology* **2008**, *103*, 615–628. doi:10.2113/gsecongeo.103.3.615.
- 627 73. Singer, D.A. The lognormal distribution of metal resources in mineral deposits. *Ore Geology
628 Reviews* **2013**, *55*, 80–86. doi:10.1016/j.oregeorev.2013.04.009.
- 629 74. Vidal, O.; Rostom, F.Z.; François, C.; Giraud, G. Prey–Predator Long-Term Modeling of
630 Copper Reserves, Production, Recycling, Price, and Cost of Production. *Environmental Science
631 & Technology* **2019**, *53*, 11323–11336. doi:10.1021/acs.est.9b03883.
- 632 75. Arndt, N.T.; Fontboté, L.; Hedenquist, J.W.; Kesler, S.E.; Thompson, J.F.; Wood, D.G.
633 Future Global Mineral Resources. *Geochemical Perspectives* **2017**, pp. 1–171. doi:
634 10.7185/geochempersp.6.1.
- 635 76. Johnson, K.; Hammarstrom, J.; Zientek, M.; Dicken, C. Estimate of Undiscovered Copper
636 Resources of the World, 2013. Fact Sheet 2014, USGS, 2014. Series: Fact Sheet.
- 637 77. Henckens, M.; van Ierland, E.; Driessen, P.; Worrell, E. Mineral resources: Geological
638 scarcity, market price trends, and future generations. *Resources Policy* **2016**, *49*, 102–111. doi:
639 10.1016/j.resourpol.2016.04.012.
- 640 78. Singer, D.A. Future copper resources. *Ore Geology Reviews* **2017**, *86*, 271–279. doi:
641 10.1016/j.oregeorev.2017.02.022.
- 642 79. Rudnick, R.; Gao, S. Composition of the Continental Crust. In *Treatise on Geochemistry*;
643 Elsevier, 2003; pp. 1–64. doi:10.1016/B0-08-043751-6/03016-4.
- 644 80. IEA. IEA Sankey Diagram, 2021.
- 645 81. Phillips, W.G.B.; Edwards, D.P. Metal prices as a function of ore grade. *Resources Policy* **1976**,
646 *2*, 167–178. doi:10.1016/0301-4207(76)90016-7.
- 647 82. Johnson, J.; Harper, E.M.; Lifset, R.; Graedel, T.E. Dining at the Periodic Table: Metals
648 Concentrations as They Relate to Recycling. *Environmental Science & Technology* **2007**, *41*, 1759–
649 1765. doi:10.1021/es060736h.
- 650 83. Gutowski, T.G.; Sahni, S.; Allwood, J.M.; Ashby, M.F.; Worrell, E. The energy required to
651 produce materials: constraints on energy-intensity improvements, parameters of demand.
652 *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*
653 **2013**, *371*, 20120003–20120003. doi:10.1098/rsta.2012.0003.
- 654 84. Vidal, O.; Andrieu, B.; Le Boulzec, H.; Fizaine, F. Modeling the production energy and metal
655 prices from 1900 to 2100. *Manuscript submitted for publication* **2021**.
- 656 85. Norgate, T.; Jahanshahi, S. Low grade ores – Smelt, leach or concentrate? *Minerals Engineering*
657 **2010**, *23*, 65–73. doi:10.1016/j.mineng.2009.10.002.
- 658 86. Mariscal, R.; Powell, A. Commodity Price Booms and Breaks: Detection, Magnitude and Im-
659 plications for Developing Countries. *SSRN Electronic Journal* **2014**. doi:10.2139/ssrn.2384422.
- 660 87. Yellishetty, M.; Ranjith, P.; Tharumarajah, A. Iron ore and steel production trends and
661 material flows in the world: Is this really sustainable? *Resources, Conservation and Recycling*
662 **2010**, *54*, 1084–1094. doi:10.1016/j.resconrec.2010.03.003.
- 663 88. Rötzer, N.; Schmidt, M. Historical, Current, and Future Energy Demand from Global Copper
664 Production and Its Impact on Climate Change. *Resources* **2020**, *9*, 44. doi:10.3390/re-
665 sources9040044.
- 666 89. Rosenkranz, R.D. Energy Consumption in Domestic Primary Copper Production **1976**. p. 40.
- 667 90. Gaines, L. Energy and materials flows in the copper industry. Technical Report ANL/CNSV-
668 11, 6540399, 1980. doi:10.2172/6540399.
- 669 91. Kellogg, H.H. Energy efficiency in the Age of Scarcity. *JOM* **1974**, *26*, 25–29. doi:
670 10.1007/BF03355879.

-
- 671 92. Page, N.J.; Creasy, S.C. Ore grade, metal production, and energy. *Journal of Research of the US*
672 *Geological Survey* **1975**, *3*, 1–13.
- 673 93. Marsden, J.O. Energy Efficiency & Copper Hydrometallurgy. Society for Mining, Metallurgy,
674 and Exploratio, 2008, p. 41.
- 675 94. Office of Energy Efficiency & Renewable Energy. ITP Mining: Energy and Environmental
676 Profile of the U.S. Mining Industry. Technical report, Office of Energy Efficiency & Renewable
677 Energy, 2002.
- 678 95. Rankin, W. *Minerals, Metals and Sustainability: Meeting Future Material Needs*; CSIRO Publish-
679 ing, 2011. doi:10.1071/9780643097278.
- 680 96. Chapman, P.F. The Energy Costs of Producing Copper and Aluminium from Primary Sources.
681 Technical report, Research Report ERG001, Open University, 1973.
- 682 97. Hooke, R.L.; Martín-Duque, J.F. Land transformation by humans: A review. *GSA Today* **2012**,
683 *12*, 4–10. doi:10.1130/GSAT151A.1.

