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Modelling the Demand and Access of Mineral Resources in a Changing World

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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 regionalised 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 resources 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 energy, transportation, and building infrastructures 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]. Recurring predictions of the 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.

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

2. The Drivers of Mineral Resources Consumption

2.1. The Base Metals and Cement Consumption from Traditional Applications

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

phase of development mainly consumes "structural" raw materials produced in present global quantities of more than one million tons per year (Mt/yr), such as sand and aggregates, concrete, steel and iron, aluminium, copper, manganese, zinc, chromium, lead, titanium, and nickel. Then, the annual consumption of structural raw materials levels off when the gross domestic product (GDP) per capita reaches about 15,000 USD/cap (maturing stage) and eventually declines as the in-use stock reaches its saturation limit (saturation stage) [57,58]. When the saturation level of in-use stocks is reached, the size of the infrastructure becomes mainly controlled by the evolution of population and the material content of technologies. The number of technological units per capita (number of cars, trucks, planes, ships, m^2 building, etc.) as a function of GDP/capita thus follows the sigmoidal pattern of a logistic function, whose parameters can be constrained by fitting the historical evolution of each technology by countries (e.g., [46,62,63]). These parameters depend on the geography, population density and lifestyle of the countries, with average values in the order of 0.7 LDV/cap, 7×10^{-5} locomotive/cap, 1.5×10^{-5} aircraft/cap, and 90 m^2/cap. From these figures, the future evolution of infrastructure can be estimated for given future GDP and population evolutions. This is illustrated in Figure 1, which shows the number of observed and estimated light vehicles, locomotives, airplanes, and the surface of buildings in the USA and China from 1950 until 2100. The results were obtained with the model DyMEMDS (dynamic modelling of energy and matter demand and supply) available online https://www.dropbox.com/sh/ws85dgbelt9ceyf/AAC8fYnglzzINREp27xvwFnra?dl=0 (accessed on 13 December 2021). DyMEMDS is a stock and flow model that links the energy consumption, GDP, and population with raw materials consumption, greenhouse gases emissions, global warming, and additional environmental impacts such as the consumption of water and used land for mining. It includes about 50 technologies of transportation, construction, and energy; 10 metals, cement, and gravel; and 9 geographical regions covering the world. From the evolution of infrastructure calculated for imposed future GDP and population evolutions (Figure 1), the stocks of materials by technologies are estimated using dynamic raw material intensities in kg of material per technological unit.

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

all rich countries, as well as in China after 2050. An incremental evolution of demand is also observed for Ni, Cr, and Mn, which are mainly used as alloying elements of steel. The incremental evolution is less clear for other base metals such as copper and aluminium involved in a variety of new applications with lower lifetimes than steel since the 1950s. The decrease in Chinese consumption in 2030–2050 is likely to be compensated by the increase due to the economic emergence India and African countries. Assuming that these countries will achieve their economic development within the century, the Indian peak of cement and steel consumption might occur in 2050 and 2100, and those of copper and aluminium one or two decades latter. The African consumption peaks are expected to occur 15 years latter. In this scenario, the yearly global demand for steel and cement in 2100 is fourfold the present value and sixfold the present consumption for aluminium and copper.

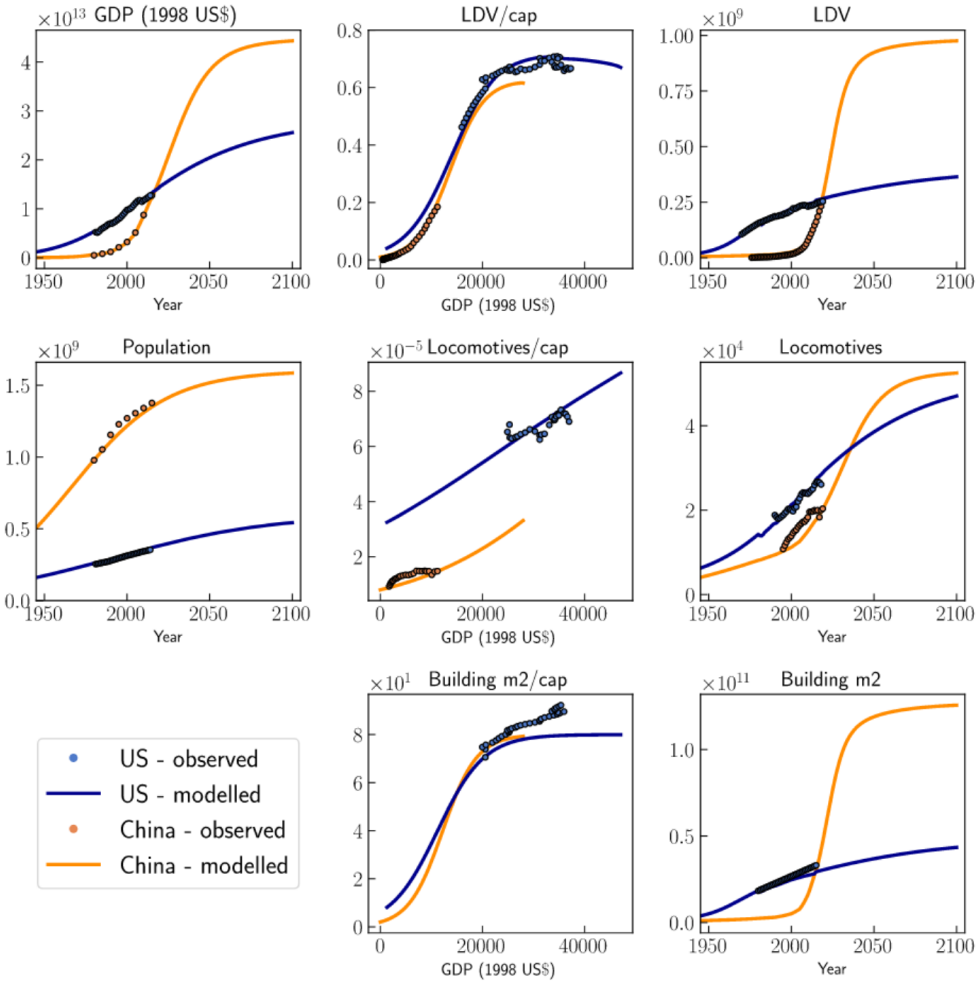


Figure 1. Evolution of the demand in infrastructure per capita in function of GDP/cap or time in China (grey lines and open circles) and the USA (black line and black circles).

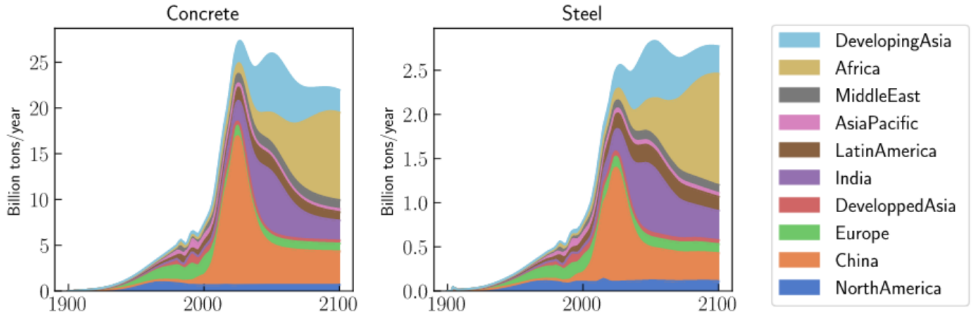


Figure 2. Concrete and steel consumption by geographical regions based on a logistic growth of regional infrastructures calculated for logistic GDP and population growths (Figure 1).

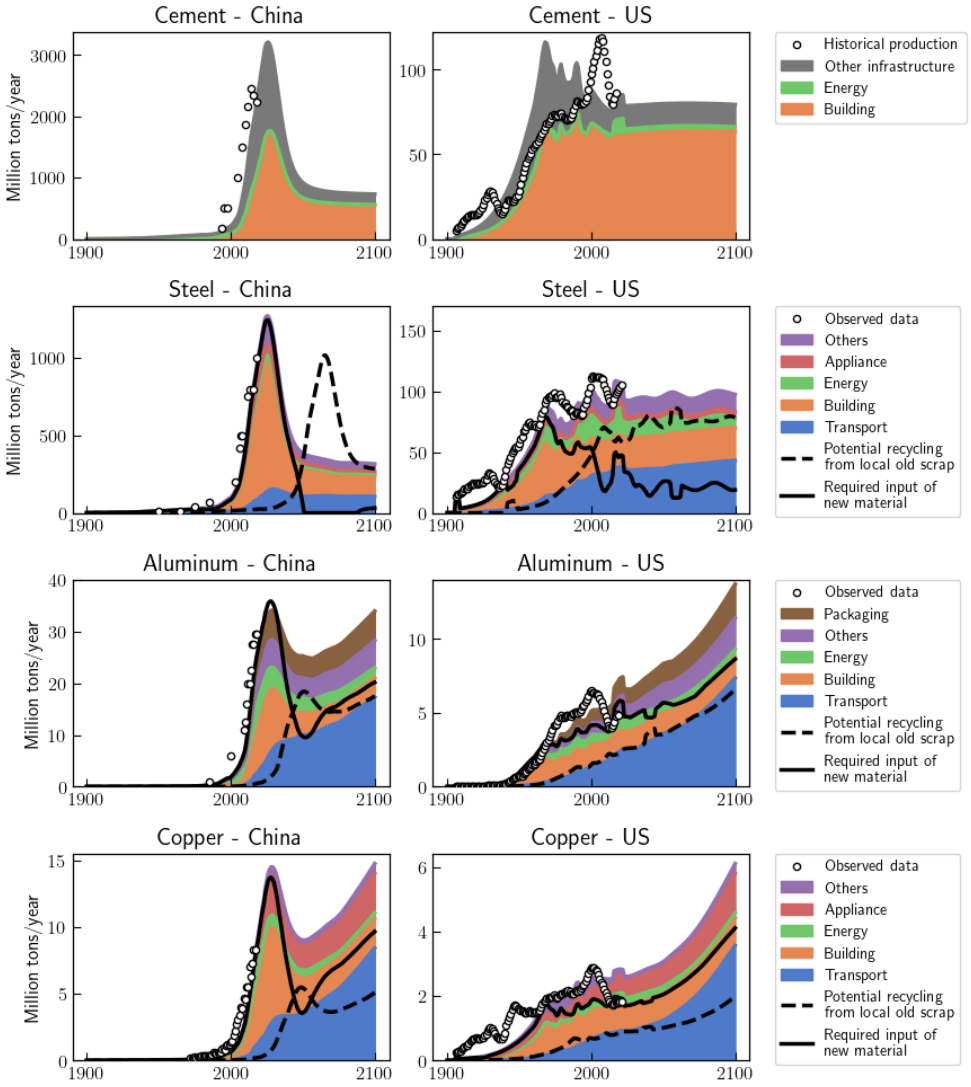


Figure 3. Raw material demand by sectors (Mt/year) calculated from the evolution of infrastructure (Figure 1) for China (**Left panel**) and the USA (**Right panel**). The plain and dashed black lines show the input and theoretical recycled flows, respectively (assuming no export or import of scrap).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

2.2. The New Applications and High-Tech Metals

In parallel or after building its basic infrastructure, economies are moving towards advanced technologies, which use many properties resulting from the electronic structure, catalytic, quantum, or semiconductor properties specific to almost all the elements of

the periodic table. Rapid changes in the use of metals have emerged during the last decades in the Information and Communication Technology (ICT) sector: In 2019, there were approximately 13 billion mobile phones and tablets [65] and 2 billion computers (1 billion in 2008) in use, Facebook had more than 1 billion users, and global data centre traffic was estimated at 4.8 zettabytes, representing more than 26,000 centuries of streaming video. This ICT sector is a large consumer of rare and high-purity substances (Cu, In, Ga, Sb, Ge, Co, Li, Ge, Ta, Nb, Au, Ag, rare earths, etc.) with dispersive uses resulting from high dilution in many short-lived devices, which limits the potential for recycling in the order of one percent. While the base metal consumption since 1990 has increased by 2–5%/year, the annual growth of rare metals production is about 10%/year. These huge growth rates and possible supply problems have attracted most of the attention over the last decade [66]. However, assessing the future of high-technology metals demand is difficult because it depends on rapid technical innovation, and the use of high technologies is much less dependent on GDP/capita than base metals. New technologies also concern the energy sector, which is evolving to reduce our greenhouse gases (GHG) emissions and comply with the Paris agreement. This agreement of COP21 aims at achieving the "carbon neutrality" in the second half of the 21st century, which implies a deep review of the existing fossil-based energy system. Unfortunately, solar and wind infrastructures require more raw materials per installed capacity and energy supplied than fossil fuel-based facilities [34,37,67–69]. The same observation is made for the storage of energy, its transport, and its use at the end of the energy chain. It follows that large amounts of structural and high-tech mineral commodities will be consumed for the energy transition.

Figures 2 and 3 have been calculated under the assumption that the penetration of low-carbon energy technologies will remain moderate. For the same evolution of GDP and population, and thus of building, transport, and energy infrastructure, the demand for metals will be different for a higher penetration of renewables. Examples are shown in Figure 4, which illustrate the differences in global Cu, Li, Co, and Ni consumption for the two contrasted energy scenarios RTS (Reference Technology Scenario) and B2DS (Beyond 2 °C Scenario) of the International Energy Agency (IEA) [70]. In contrast to previous estimates based on GDP/capita evolutions (Figures 2 and 3), the demand in raw materials in Figure 4 is calculated from the consumed energies listed in the scenarios, which are transformed into an infrastructure for assumed evolutions of energy consumption (−1%/yr) and material content. The evolution of infrastructure is then transformed into raw materials demand using the same material intensities as those used to build Figures 2 and 3. The demands in Cu, Li, Co, and Ni are noticeably higher for the B2DS scenario, which foresees a massive incorporation of renewable energy in the energy mix. Rare earth elements (REE), and in particular neodymium, are also elements of concern, as they are used in the permanent magnets of a wide variety of technologies using electric motors and in the generators of off-shore wind turbines. The estimates in Figure 4 must be handled with care because the present technologies, intensity of use and recycling rates are not necessarily representative of the future situation. The price of cobalt, used as a cathode in lithium-ion batteries, increased from 55,000 to 83,000 USD/t between March 2017 and February 2018. This situation has prompted manufacturers to find solutions to reduce or ban the use of cobalt in lithium batteries (increasing investments into cobalt-free batteries research and development and production are currently observed by small to large companies https://cleantechnica.com/2018/07/03/tesla-panasonic-investments-in-cobalt-free-batteries-not-the-only-game-in-town/ (accessed on 13 December 2021)) and to develop efficient recycling solutions (such as the development of closed loop recycling processes https://www.umicore.com/en/media/press/new-power-from-old-cells-audi-and-umicore-develop-closed-loop-battery-recycling (accessed on 13 December 2021)). Similarly, during the rare earth elements (REE) crisis in 2011, engineers were able to find solutions to either reduce the amount of used REE while maintaining the efficiency of technologies or to change technologies. This illustrates the high potential of technological innovation to

reduce the use of rare elements in high or/and energy technologies. For these reasons, it is extremely difficult to provide reliable estimates of their future demand.

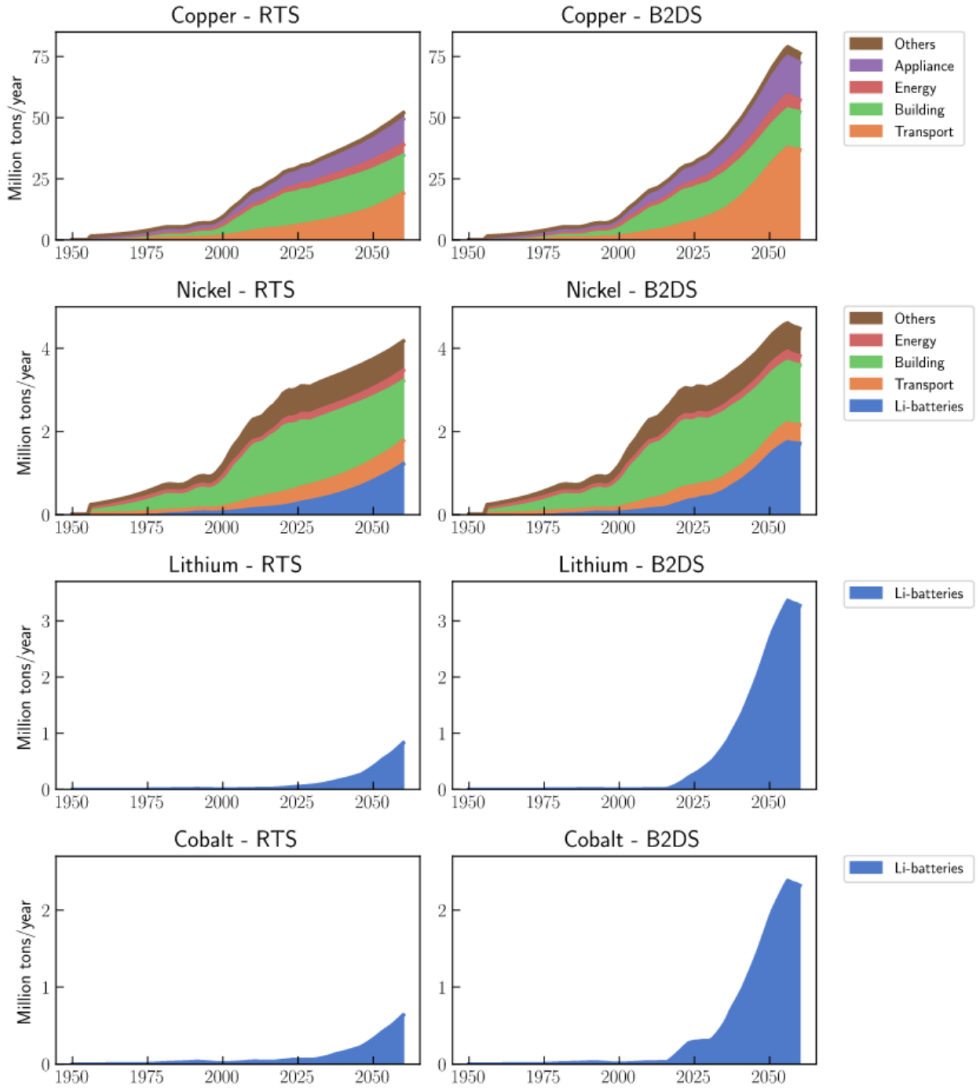


Figure 4. Annual demand for Cu, Li, Ni, and Co calculated for the evolution of infrastructure in the reference technology (RTS) (**Left panel**) and the "Beyond 2 °C" scenario (B2DS) (**Right panel**) of the International Energy Agency.

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

3. Can Future Production Meet the Demand?

Several studies suggest that the future supply of raw materials will not be able to keep pace with demand because the stock of exploitable non-renewable resources is declining over time and the production of several metals has already peaked or will peak in the near future [8,10–13,16,71,72]. Although it was initially developed for oil production, the application of Hubbert's theory to mineral resources led Sverdrup et al. [72] to the

conclusion that the production of gold, silver, copper, nickel, zinc, molybdenum, iron, platinum, and indium should peak at or before 2050. The same authors described a similar situation for conventional fossil energy resources, and a peak of non-conventional oil by 2075. However, a major flaw of Hubbert's approach lies in the assumption that production is limited by the sole availability of resources at continuously growing demand. According to this logic, the observed decline in the growth rate of steel production between 1970 and 2000 (Figure 2) could have been misinterpreted as a sign of resource depletion, while it was actually resulting from the temporarily declining growth of demand. Another pitfall is the assumption that the "ultimate recoverable resource" (URR) is finite and quantifiable. Metals and minerals are currently exploited from a small fraction of the continental crust. The maximum value of reserves can be estimated from the log-Gaussian ore-tonnage (OT) versus ore grade (OG) relationship of ore deposits [73,74]:

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

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

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

M_{OG} is the amount of additional available metal deduced from its geological distribution in the crust, whatever the cost of its extraction. The integral of M_{OG} gives the evolution of reserves plus cumulative production, which increases exponentially as long as the average OG remains below the value of the peak of OT vs. OG (Equation (1)). By combining Equations (1) and (2) with the expected evolution of demand (Section 2), it is possible to estimate the required evolution of average OG and thus OT and metal reserves. Based on the historical evolution of copper reserves, production, ore tonnage, and OG with time, Vidal et al. [75] have estimated an URR of copper between 5 and 7.5 Gt in 2100 for a copper price ranging between 10 and 15 thousands USD(1998)/t. Although these estimated reserves are within the range of those made by [76–79], the approach is fraught with large uncertainties arising from equally large uncertainties in the distribution of metals in the Earth's crust. Vidal et al.'s estimates assumed a bimodal distribution [75], one centred at the average grade of copper in the crust (OG $\approx$ 30 ppm [80]) and another corresponding to the peak OT of ore deposits centred at OG $\approx$ 0.3% [73]. However, the bimodal OT vs. OG distribution is questionable [76], and if a unimodal distribution centred at the average crustal concentration is assumed, future reserves could be at least an order of magnitude higher. Estimates of future reserves and resources availability from geologic criteria and OT vs. OG distributions are thus quite uncertain. The question of availability is above all a question of price and environmental impacts we will be willing to pay. Historical data show that, so far, technological improvements have made it possible to mine less and less concentrated and accessible ores (deeper, offshore) without unaffordable increases in production costs and metal prices. Is this trend sustainable in the future? To answer the question, we must now understand the links between energy and production costs, between metal prices and OG, and between technological improvements and thermodynamic limits.

Energy of Metal Primary Production, Prices, and Reserves

Currently, about 12% of global energy consumption and about 35% of the energy consumed by industry worldwide is used for the production of iron and steel, cement, aluminium, and non-ferrous metals [81]. The production of mineral resources is therefore very energy-intensive. The energy of primary metal production can be estimated as the sum of three contributions [60,69]: (i) the comminution energy proportional to the inverse of the mass concentration of metals in ore deposits ($\frac{1}{C}$), (ii) the minimum energy to separate the metal-bearing minerals from the disaggregated ore given by the mixing entropy of an

ideal mixture of two components with no interaction (Es_i), and (iii) the minimum energy of metallurgy given by the Gibb's free energy of formation of the ore mineral from its constituents ($-\Delta G^{\circ}_{fi}$):

$$E_i(2005) = \overline{\eta(2005)} \cdot (-\Delta G^{\circ}_{fi} + Es_i + \frac{a}{C_i(2005)}) \quad (3)$$

where $\overline{\eta(2005)}$ is the inverse of the energy efficiency compared to the thermodynamic minimum (η = 1 at the thermodynamic minimum). Based on the observed evolution of the production energies of 20 metals (i) diluted from 1.9 (iron) to 2×10^5 (gold, platinum), average values of $\overline{\eta(2005)} = 3$ and $a = 0.2$ are obtained (Figure 5a). Several studies have shown that the average price of metals is proportional to the energy of their production, which also varies as a power law of dilution ($\frac{1}{C}$) [60,69,82–84]. For the 20 metals used to derive the values $\overline{\eta(2005)}$ and a in Equation (3), a plot of the observed production energies E(2005) as a function of their price in 2005 (P(2005)) confirms this proportionality, and the following relationship is derived [85] (Figure 5c):

$$P(2005) = 26 \cdot \alpha \cdot E(2005)^{1.1} \quad (4)$$

A systematic deviation is observed between the observed and calculated price evaluated with Equation (4). The ratio of the observed to the calculated price is proportional to the metal dilution (Figure 6b), which suggests that the share of energy cost in price also depends on metal dilution. This effect is taken into account by multiplying the RHS of Equation (3) by $\alpha = \frac{2}{C(2005)^{0.2}}$ (Figure 5b).

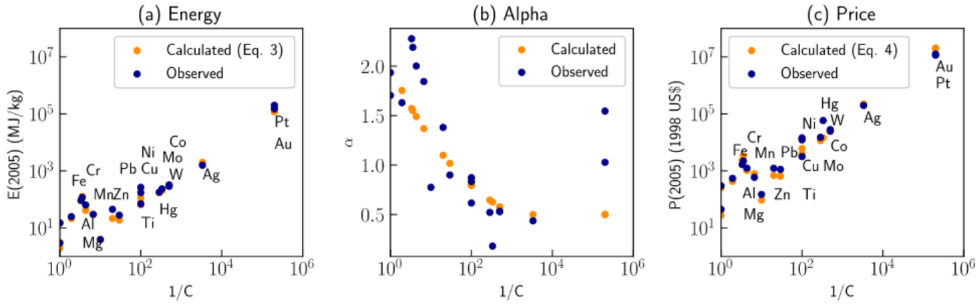


Figure 5. Energy (**a**), α in year 2005 (**b**), and price (**c**).

The evolution of production energy with time can be estimated with Equation (3) by replacing the 2005 values of η and C by their values at year t. In order to account for the variations of energy price with time, Equation (3) must also be corrected by the price of energy at time t (PE(t)) relative to 2005 (PE(2005)):

$$P(t) = 26 \cdot \alpha \cdot E(t)^{1.1} \cdot (\frac{PE(t)}{PE(2005}))^{\gamma} \quad (5)$$

where γ is the elasticity of metals' price variations relative to the variation in energy price. Using the price of crude oil as a proxy of energy price, γ = 0.7 for copper and γ = 0.1 for aluminum.

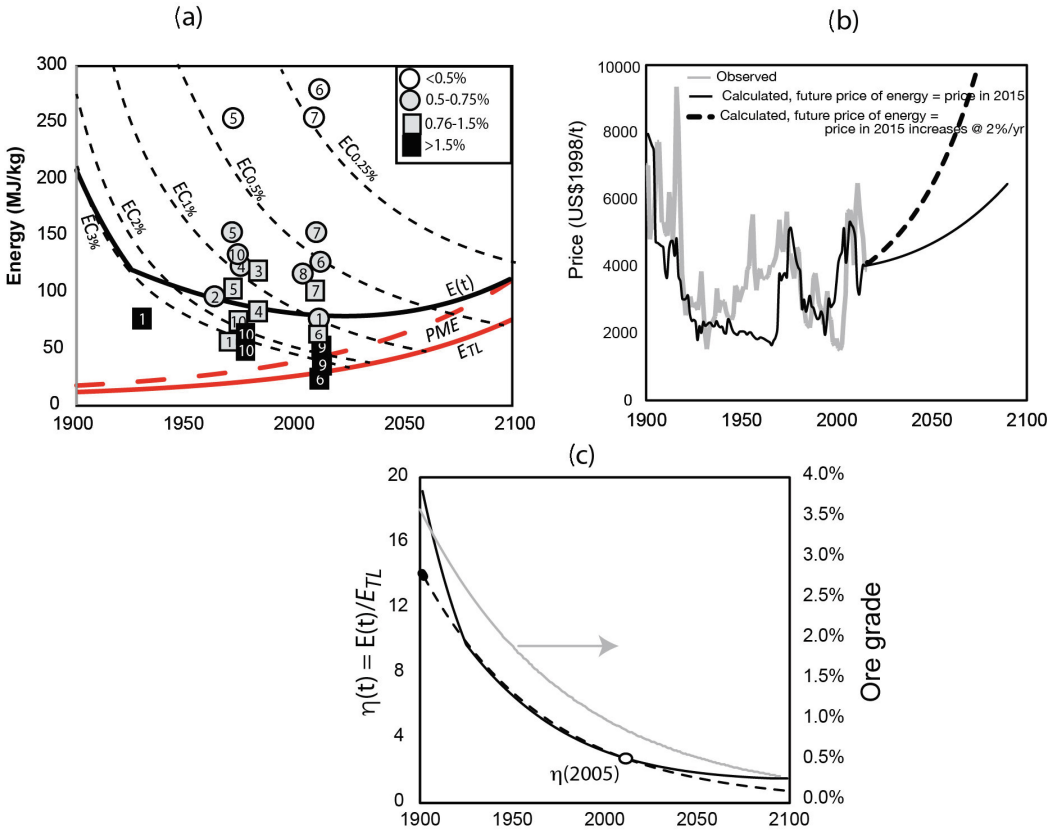


Figure 6. (**a**) Calculated and observed (numbers) energies of copper production: The heavy black line shows the energy of copper production with varying ore grade and technology E(t), the thin black dashed line shows the energy at constant ore grade with varying technology (EC), and the red dashed 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 [89]; (2) Rosenkranz [90]; (3) Gaines [91]; (4) Kellogg [92]; (5) Page and Creasy [93]; (6) Norgate and Jahanshahi [86]; (7) Marsden [94]; (8) Office of Energy Efficiency and Renewable Energy [95]; (9) Rankin [96]; (10) Chapman [97]. (**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**) η(t) (black continuous line, left scale) and ore grade (gray line, right scale) used to compute (**a**,**b**). The black dashed line in (**c**) shows η(t) calculated from η(2005) and a -1.5%/yr change.

At C < 1%, the metallurgy and separation energies are negligible compared to the term $\frac{a_i}{C}$ that represents the comminution energy. It means that at constant technology and price of energy, the energy of primary production of precious metals, copper, or nickel are expected to increase exponentially with the decrease in ore grade observed over the last century [17,86]. Proponents of a looming shortage of metals often use this argument to claim that production will become prohibitively expensive in the future. However, long-term historical data do not support this figure, and the inflation-adjusted commodity prices have actually been falling between 1900 and 2000 [87]. This fall, also observed for copper or nickel, indicates that the expected increase in production energy due to falling ore grades has actually been offset by the improvements in energy efficiency and productivity at constant ore grade (EC in the Figure 6a). The improvement in energy efficiency was 1–2%/year between 1900 and 2000 [84,85,88], and until 2000, the energy gains of all metals production have more than compensated the decrease in ore quality. Since the regeneration of reserves increases with falling grade (Equations (1) and (2)), these figures explain why both the produced quantities of metals and their reserves have grown exponentially since 1900. However, this trend is not sustainable in the long term

because there is a thermodynamic limit (ETL) to the extraction of metals, which is given by Equation (3) with η = 1. This physical limit cannot be overstepped, whatever the technological improvement. Steel production consumed about 50 MJ/kg in the 1950 and it has been halved between the 1950s and 2000 [88]. It will most likely not be halved again by 2050 to reach the thermodynamic limit equal to about 10 MJ/kg for iron oxide ore (for metals at high concentration in ore deposits such as iron (C = 30–50%) 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 (3)) ($-\Delta G_f^\circ$ = 7 MJ/kg of hematite), as the investment required to gain a few MJ when approaching this limit becomes prohibitive. More worrying, the thermodynamic limit of metals at C < 1% is expected to increase exponentially with falling ore grade due to the term $\frac{a_i}{C}$. In practice, this limit cannot be reached because industrial processes cannot be 100% efficient, and the minimum value of η in Equation (3) is unlikely to be lower than 1.5 (PME = 1.5·ETL). In the case of copper, η decreased at an annual rate of −1.5%/yr from about 10 in 1930 to 2 in 2000 (dashed line in Figure 6b). It will not be possible to continue on this trend because the minimum value of η = 1.5 will be reached before the end of the century (continuous line in Figure 6c). For an average ore grade of copper deposits decreasing at 1.5%/yr since 1900, improving current mechanical crushing and grinding technologies will thus not compensate for the additional energy to switch to lower grade ore in the future, as it has been the case during the 20th century. The energy of copper production, which declined between 1900 and 2000, is thus expected to increase from 2000 onward and parallels the PME in the second half of the century (Figure 6a). Similar conclusions are drawn for precious metals and nickel, zinc, and manganese.

4. Discussion

The above overview of some parameters controlling the demand and primary production provides arguments for two classically opposed views 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 visions are true, but not at the same time. After a period of gains in energy and production costs, it seems that we are now entering a pivotal period of long-term increasing production costs as we approach the practical minimum energy and thermodynamic limits for several metals. To reduce this increase in price, unknown breakthrough, but affordable, grinding technologies based on non-mechanical processes will have to be found. Another possibility is to reduce the price of energy. Renewable energies are virtually unlimited, and once the infrastructure of production is built, they are cheap. If we could use renewable energy sources at a low and stable price in the future, the increasing weight of energy intensity in the cost of production would no longer be an issue. This is illustrated by Iceland, which became in 2016 the world's ninth largest producer of aluminium from imported bauxite thanks to cheap geothermal and hydroelectric power, even though it has no ore and most of its production is destined to foreign markets. If the use of renewable energy sources were to become significant enough to cover the needs of the raw material production sector, it would become possible to exploit low-grade resources that cannot be exploited at an affordable cost today. However, energy transition scenarios present another constraint: In order to cope with the targeted decrease in CO_2 emissions, they generally assume a strong reduction in energy consumption. For example, the amount of energy available for the industrial sector in the scenario B2DS already used in Figure 2 is 65% that of RTS, while the energy consumed for the production of raw materials is similar. The future share of industrial energy consumed to produce the raw materials is thus higher in B2DS than RTS, and the remaining energy available for the other industrial sectors is lower. These figures will impact the intensive industries and in particular the raw material production sector, which will already face the problem of declining resource quality. It thus seems extremely difficult to switch to renewable energies while reducing global energy demand. Neither the developed countries, which are expected to replace their fossil fuel-based

energy infrastructure in two or three decades, nor the developing countries that produce raw materials to build their basic infrastructure will spontaneously follow this path. Until 2050, the demand for energy will thus continue to grow on a global scale. On the longer term, the energy demand for the production of raw materials is expected to decrease after 2050 in both scenarios B2DS and RTS. This is due to the combined effects of: (i) approaching the saturation levels of infrastructure at the global scale, which entails a reduction of the annual demand in raw materials; (ii) completing the energy transition; and (iii) rapidly increasing the share of less energy-intensive recycled metals at the saturation levels and unaffordable prices of primary metals.

The above overview of the parameters controlling the demand and primary production also indicates that the question of the future of mineral resources cannot be based solely on the knowledge of current geological availability for a constant rate of growth in demand and technology. It must be studied using dynamic models that integrate the value chain from primary production to recycling, coupling energy requirements and thermodynamic limits, geological, environmental, technological, social, economic, and geopolitical dimensions. Such models are intrinsically complex, but it is illusory to address complex issues with empirical and deterministic models such as Hubbert's model or any model neglecting the role of technological improvement, including the development of advanced exploration technologies, changes in resource quality, and variations in energy prices with time. Coupling material flows with GDP and population evolution is quite straightforward using sigmoid evolutions of the infrastructure/capita with GDP/capita and assumptions on the materials contents. The consumed energy can also be estimated for assumed intensities of use and energy efficiencies. In contrast, coupling the materials and energy flows with economic models is more difficult because economic models lack physical bases and constraints and are derived from observations made in growing economies. Since the industrial activities and consuming sectors are strongly coupled, it is difficult to analyse one sector of metal production isolated from the whole economic system. To circumvent the problem, a possible approach based on a prey–predator dynamic has been proposed by Vidal et al. [75], in line of the previous study by Bardi and Lavacchi [8]. This approach is also empirical, but it allows one to combine physical units (tons) with monetary units without requiring a detailed and comprehensive description of all economic sectors. It analyses the evolution of industrial capital (the predator, in monetary units) and the metal reserves (the prey, in tonnes) with two coupled differential equations involving four parameters controlling the yearly regeneration of reserves, metal production, regeneration and erosion of capital. Interestingly, the cost (price) of metal production is given by the ratio of two of them, corresponding to the capital growth to metal production. Applying the model to the case of copper, we showed that the expected price evolution is similar to the production energy-based independent estimate reported in Figure 6. Independently of any economic consideration, the long-term price of metals derived from the production energy calculated with the simple thermodynamic formalism proposed in Equations (4) and (5), thus providing first order constraints on the future evolution of metals production. In the case of copper, Vidal et al. [75] predicted a peak in primary production by 2050, followed by a rapid collapse if the future demand is assumed to follow the historical trends (+3%/year). In contrast, a scenario no longer based on a steady growing demand but on the need for a population stabilizing at 11 billion inhabitants in 2100 and an average GDP per capita of USD 10,000 provides more optimistic results. A peak in primary production is still observed, but it is a peak in demand. A decrease in primary production occurs in the second half of the century, when the saturation of infrastructures is approached and recycled copper becomes the major source. Here, again, this example shows that the future of natural resources cannot be dissociated from a scenario of demand, which is another illustration of the limit of Hubbert-like approaches. The prey–predator model applied to other metals suggests that the supply of most base and precious metals (except gold) should also meet the demand until the end of the century. The situation is much less clear

for rare metals, as historical data on reserves and production are missing, imprecise, or cover too short a time period to be used as reliable constraints for the models.

In addition to the reserves, price, and energy production issues, the environmental impacts of raw materials and energy production must also be integrated in the models. These impacts might become a limiting factor to production in the future. An emblematic example is given by El Salvador that made history as first nation to impose a blanket ban on metal mining in response to diminishing water sources from polluting mining projects (this decision was approved by the Parliament of El Salvador in early 2017 https://www.theguardian.com/global-development/2017/mar/30/el-salvador-makes-history-first-nation-to-impose-blanket-ban-on-metal-mining (accessed on 13 December 2021)). The huge expected increase in mineral resources consumption and primary production will increase conflicts and social opposition. The surface occupied by mines and quarries at the world level has been estimated to be about 400,000 km^2 [98]; it could be doubled by 2050 and quadrupled by 2100. The embodied water consumption and other environmental impacts are expected to follow the same trends. These figures are naturally concerning, especially in arid production areas. To our knowledge, no model currently exists that describes the local societal response to water and land use and more broadly to environmental impacts, even though this could significantly hamper future resource supplies. This response is expected to depend on the level of GDP/capita and population density, the industrial typology, the level of agricultural production, and the geographical characteristics of the producing countries, such as the availability of water. Modelling the feedback of resource consumption and environmental changes on social opposition is a very important research topic to address the issue of future mineral resource availability in a world of increasing environmental constraints and increasingly compromised access to water and arable land.

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