



What we have learned from the past and how we should look forward

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Abstract

From the vantage point of more than 50 years' work in the raw material field, as well as working in the private sector, in the German federal ministry of economics, at a geological survey, and engaged in teaching and supervising research at a university, I draw a number of conclusions about the following aspects of the fields: development of long-term prices, the long-term supply situation, especially the expectation of an imminent peaking of supply, the frequent and mistaken prediction of shortfalls in supply, our understanding of reserves and resources, and the cyclic nature of success in exploration. I am solely dealing with geological aspects, not taking into account political inferences and supply disruptions. This is followed by an attempt to look into the future of raw materials demand within the framework of the accelerating green energy transition. These conclusions are:

- Conclusion 1: When two amplifying effects overlap, long-term price trends can be broken.
- Conclusion 2: All growth rates flatten eventually. Never extrapolate high growth rates too far! However, growth rates are learning curves that move in waves and can steepen again. In general, the higher the production the lower the growth rates, even in exceptional cases.
- Conclusion 3: It is unclear, whether we have already reached the stage when growth rates of the major metals have flattened, but sooner or later it will come.
- Conclusion 4: Sooner or later we shall see demand peaking for primary metals of all commodities (in contrast to peak supply) because the share of secondary metals will grow and the consumption per capita reaches saturation levels.
- Conclusion 5: The reserve/ production ratio (R/P-ratio) is only a snapshot of a dynamically evolving reserve/ resources system. The learning effects during exploration so far are in step with ever-increasing consumption. Serious limits to reserves are nowhere to be seen.
- Conclusion 6: Rapid changes in production rates may be accompanied by significant decreases in R/P-ratios and it would appear justified to suspect that advances in exploration cannot always keep pace with consumption. However, as long as the R/P-ratios do not fall below 50 for stratabound deposits and 25 for other deposits and exploration activities continue apace as normal there is no reason to worry about future supply bottlenecks.
- Conclusion 7: The R/P-ratios are useless as indicators for lifetime; however, they are helpful as early warning indicators for looming problems of supply and for indicating the need for boosting exploration.
- Conclusion 8: Exploration discoveries show episodic behaviour. Therefore it is difficult to extrapolate into the future. So far all pessimistic forecasts have been proven wrong by ingenious advances to detect new ore bodies to replace mined-out reserves.
- Conclusion 9: Supply shortages have been forecast frequently in the past. They never actually happened. The self-regulating feedback control cycle of mineral supply safeguards adequate supply over time. There is no reason to assume that this system of self-correcting forecasts will not work in the future.

Keywords Price developments · Technological breakthroughs · Growth rates · Reserve to production ratio · Exploration success · Raw materials for the green energy transition · Innovation · Substitution · Learning curves

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Preface—a personal note at the beginning

I wish to thank Peter Buchholz, Magnus Ericsson and Volker Steinbach who on the occasion of my 80th birthday organized this impressive Special Volume: “Breakthrough technologies and innovations along the mineral raw materials supply chain—from exploration towards a sustainable and secure supply”. I am as moved as grateful to all the authors who generously put in time and efforts to contribute to this volume.

In my career, I straddled boundaries. I started in 1970 in the mining department of Metallgesellschaft AG, known as MG, the then-largest German non-ferrous mining, smelting and trading company. I took leave to work for 3 years for the raw materials branch of the German Federal Ministry of Economics. I then returned to MG, resp. MG’s Australian subsidiary, having previously worked also for MG’s Canadian subsidiary. In 1987, I again switched sides and joined the Federal Institute of Geosciences and Natural Resources, i.e. the German Federal Geological Survey. Since 1982, I was teaching part time and supervising research projects at the Technical University Berlin. This bouncing into the terrain of different institutions taught me to delve into more disciplines and to focus on aspects relevant for mineral economics, especially in economics, mining, metallurgy and marketing. Therefore, I am pleased that Peter Buchholz, Magnus Ericsson and Volker Steinbach structured this volume according to the value adding chain from exploration to markets.

I beg to understand that I cannot thank individually everybody who discusses important facets along this chain, but instead be permitted to personally extend special thanks to those colleagues with whom I cooperated very intensively to advance international cooperation in the geoscience field, especially in the field of natural resources: Peter Cook from the UK/Australia, John DeYoung Jr. from the USA, Patrice Christmann, Pierre Toulhoat and Jacques Varet from France, and Leopold Weber from Austria. I should also give credit to and extend special thanks to those who put me on this path and helped to sharpen and widen my perception when I started my career with Metallgesellschaft AG: Max von Müller, John D. Weisser, and Dietrich Wolff.

Thanks to all of you who contributed. I am overwhelmed by this honorary gift.

Introduction

When I worked for Metallgesellschaft AG, then the largest German non-ferrous metal mining and smelting company, and talked in the seventies of the last century to metal and ore traders—metal prices at the time were about 14 US-cts/lb for lead, about 16 US-cts/lb for zinc and between 45 to 60 US-cts/lb for copper—there was only one overwhelming message: metal prices have only one way to go, and that is

up, even in real, inflation-adjusted terms. In 1980 there was the celebrated scientific wager between business professor Julian L. Simon and biologist Paul Ehrlich, whether resource scarcity and population explosion would lead to real price increases of metals in the following decade, a bet the sceptical Ehrlich lost (Sabin 2013; von Weizsäcker and Ayres 2013). The eighties of the last century was also the time of common belief that real commodity prices would in the long run rise in step with the real rate of interest (Radetzki and Wårell 2017). The growth in world population and the parallel exponential growth of raw material consumption made these assumptions seem imperative. The increase of the world population from 1 to 2 billion took about 120 years (occurred in 1928); the increase from 6 to 7 billion took just 12 years (occurred in 2011) (Roser et al. 2019). The concomitant increase in consumption of raw materials shall be scrutinized stepwise to see what happened really and what conclusions can be drawn from the facts.

Geogenic raw materials occur as ore deposits in the Earth’s crust, i.e. natural enrichments of metals and minerals that can be exploited economically. The economics of ore deposits are determined on the one hand by the cost of producing a marketable commodity and on the other hand by the prevailing market price for the commodity. I shall therefore examine in turn price developments, followed by the cost of production, focussing on base metals.

In the next step, I will question the perception of a looming raw material scarcity, which stems from a misunderstanding of the interplay between exponential growth of both production and consumption, as well as from the confusion prevalent among many geoscientists not versed in resource economics as to what reserves and resources really mean. In this context, I shall examine what the reserve-to-production ratio (R/P-ratio)—frequently misunderstood as lifetime—really means and what R/P-ratios are useful for. I will then examine the cyclic nature of exploration successes, the development of extraction technologies and their combined influence on the balance between reserves and production, discussing various learning effects which I also experienced during my career. Finally, I shall venture to take a look forward into the future.

I shall solely deal with geological aspects, not taking into account those political inferences and supply disruptions which can only be solved politically.

Price developments

Price developments from the end of World War II to today

In the 75 years since the end of World War II metal prices showed the normal cyclical behaviour due to commodity

Fig. 1 Development of nominal and real metal prices since the Second World War, based on the CRB Metals sub-index adjusted for inflation by the Consumer Price Index (CPI) Basis 06.2000, from Wellmer et al. 2019, p.36, updated by DERA 2021



price volatility, a swinging pendulum between buyer's and seller's market (Stuermer 2018), demonstrating that Ehrlich lost the bet because he picked the wrong decade (Worstell 2013) (Fig. 1). From 2000 to 2010 he would have had won. The nominal metal prices, in particular those of the metals traded on metal exchanges, increase over the long term. However, the real prices decrease or stay constant over time (Fig. 1). Economic and political events repeatedly interrupt this decreasing trend with upward spikes. Typical examples are the cobalt crisis in 1978 triggered by the Shaba conflict in the Democratic Republic of Congo (formerly Zaire) or the tantalum peak of 1980 triggered by the surge of the electronics industry, examples used to illustrate the benevolent effect of the feedback control cycle of mineral supply, explained in detail in "How the balance between success in exploration and exploitation technology can keep up with rising production and result in a stable relationship between reserves and production (R/P-ratios), declining grades and constant prices in real terms" below (Bräuninger et al. 2013; Wellmer and Dalheimer 2012; Wellmer and Hagelüken 2015). The real prices increased very strongly during, for example, the oil crises in the 1970s or more recently during the raw materials boom that was set off by China in 2003. These price jumps are important to give the impetus for new investments and the chances for new mine developments to cope with the large initial investment burden at the start-up of a mine. For example, thanks to a jump in the zinc price in 1973 from 17 US-cents/lb to 38 US-cents/lb, the Nanisivik zinc-lead mine on Baffin Island/Canada could be brought into production and stayed in operation till 2002 (Wellmer 2008b). Once such mines are in production, experience and rationalization measures start a learning process, to compensate for the decrease in real prices and rising costs. However, if one examines the long-term trend, from 1947, practically from the end of World War II, to today, the real prices have remained approximately constant (Fig. 1).

Price developments since 1850

If we triple the time and examine a period from 1850 (Fig. 2) we can distinguish two very distinct periods: the time from 1850 to the end of World War I and from the end of World War I to today. In each period the prices stayed more or less constant over the long run. The graph of Fig. 2 suggests that it is, therefore, not meaningful to pick arbitrary starting points for trend extrapolations. One can derive positive or negative trends depending on the starting points. Choosing a starting point before the break of 1918 (e.g. at the beginning of the new century in 1900, Vogtländer et al. 2019, based on Henckens 2016) will always produce a declining price trend. For meaningful extrapolations, one should look for plateau periods (Buchholz et al. 2020) and try to understand breaks in the price development. Contrary to the assumptions of Ehrlich and Simon in their bet of 1980, described above, short time spans are unsuitable to derive valid price trends. However, long-term price trends can be helpful (von Weizsäcker and Ayres 2013). Long-run shortages would produce rising prices over many decades (Tilton et al. 2018). But picking the wrong starting points for price inter- and extrapolations often lead to wrong conclusions like early warning signs of scarcity or surplus supply. Therefore, before examining the long-term price trend since 1918 we will look at the price break 1918 in Fig. 2 and ask what actually happened.

The reason for the price break in 1918

In 1918 the huge demand for metals during World War I came to an end. An example from the United States: As a response to increased demand with the beginning of the war new copper mines opened in Arizona, New Mexico and Utah. Total capacity for electrolytic refineries nearly doubled between 1912 and 1917 (Delaney 2018, p. 160). At the end of the war, demand suddenly collapsed and

Fig. 2 Index of real prices of non-ferrous metals from 1850 to 2013 (normalized to 1900). The prices for aluminium, copper, lead, zinc and tin are weighted by means of the real value of the production. The data are derived from London Metal Exchange and its predecessors (after Stürmer 2013, Stürmer 2021 updated). The corrections for inflation are based on the British consumer price index

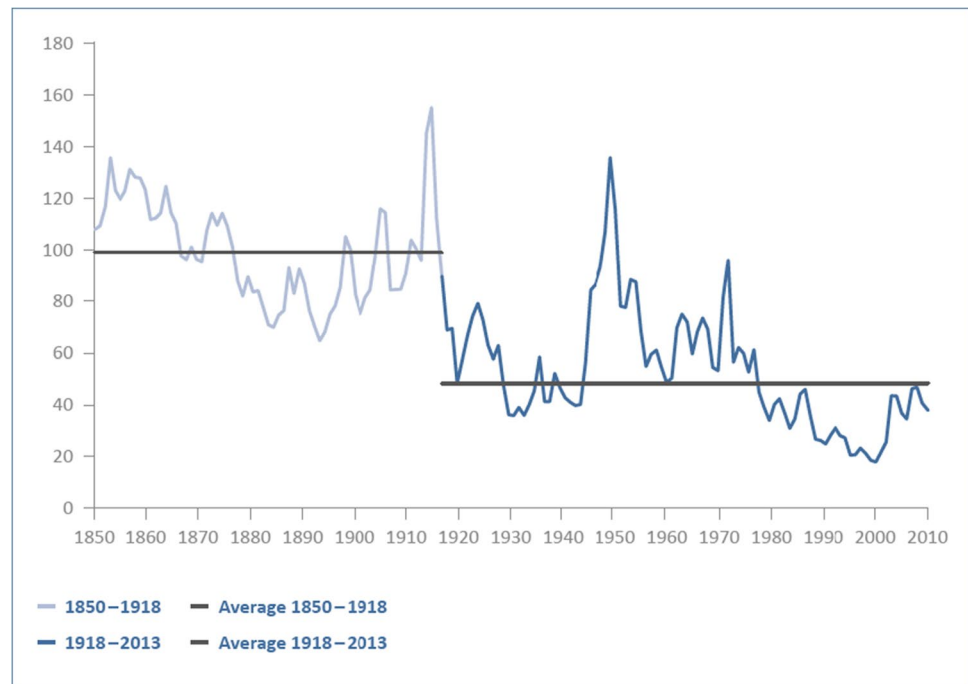


Table 1 Three production peaks with the following retraction in the twentieth century shown for the examples of copper and zinc

Copper			Zinc		
Production peak	Lowest production after peak	Recovery time till	Production peak	Lowest production after peak	Recovery time till
1917	1921: 36.5%	1925/26	1917	1921: 49.8%	1924/25
1929	1932: 46.1%	1936/37	1929	1932: 54.2%	1936
1943	1946: 68.6%	1951	1942	1946: 71.8%	1949/50

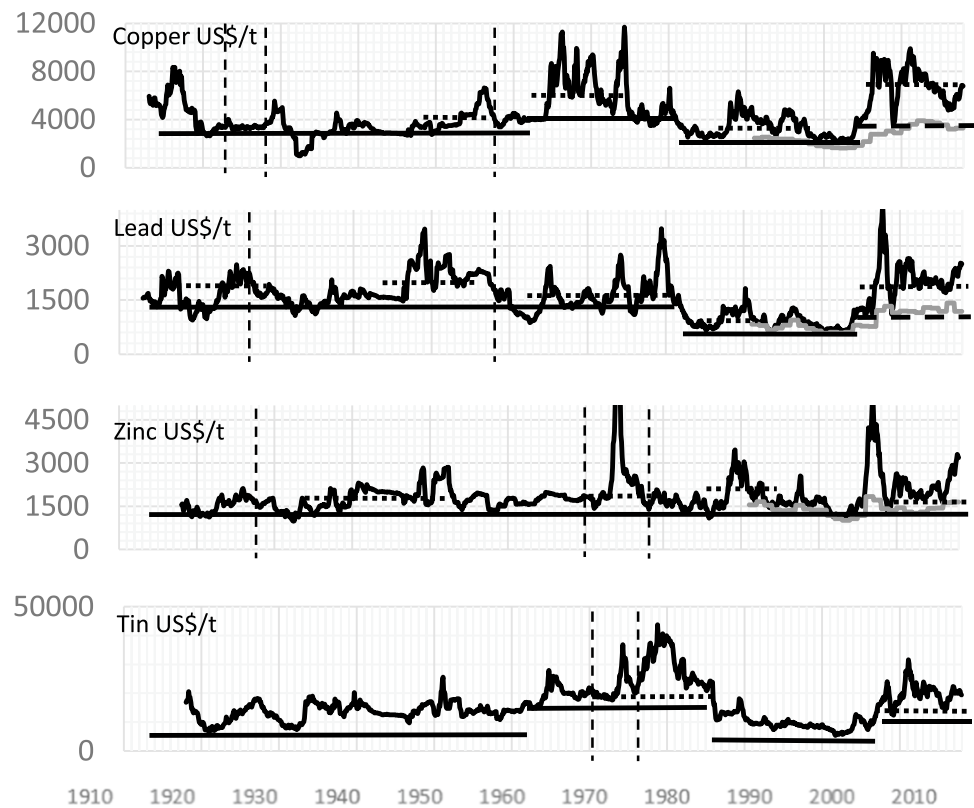
leftover copper stocks piled up to nearly half of the copper production in 1917 or 1918 (Delaney 2018, p. 166).

Now we want to compare the concomitant price collapse with other similar events. Between 1910 and 1950, there were two other peaks of metal production besides the one in 1918 followed by severe contractions as shown in Table 1: first during the world economic crisis of 1929, and then again at the end of WWII, both probably caused by the same effects of inflated demand during the war and reduced demand after the war. It took about 4 to 5 years to recover from each trough of production and to reach old production levels. Unlike these two cases of increasing production leading to price recovery, the period after WWI was different. Moreover, the crisis after WWI was not the most severe in comparison with the other two, illustrated in Table 1 with copper and zinc as examples.

What happened shortly after the end of World War I?

When looking for a cause for the difference in performance after 1918, when metal prices stabilized at a lower level despite increased production, innovation comes to mind. Indeed, several technological breakthroughs occurred at the beginning of the century. These included open-pit bulk-mining with big shovels, first introduced in the copper mines of Bingham/USA and Chuquibambilla/Chile, the refinement in flotation technology (Julihn 1932; Luyken and Bierbrauer 1931; Arrington and Hansen 1963; Lagos personal communication 2018), and other significant improvements in beneficiation like the Dorr rake classifier (Lynch 2018). Since the bulk mining technology is mainly used in copper mining, but not in zinc mining, which predominantly takes place underground, the decisive technological improvements that lowered the price plateau were probably beneficiation methods like flotation or the Dorr rake classifier.

Fig. 3 Base metals: real prices, lower and upper real price benchmarks, and real total cash costs (solid line for real price, solid horizontal line for lower real price benchmark, dashed line for upper real price benchmark, grey line for real total cash costs, real prices and cash costs deflated by using US Producer Price Index PPI, basis 2017, vertical dashed line indicates break in price specifications (from Buchholz et al. 2020)



Conclusion 1: When two amplifying effects (like reduced demand and breakthrough technologies) overlap, long-term price trends can be broken.

Real price development since 1918

If one looks now in detail at the price trends during the last 100 years, for example the ones of the base metals copper, lead, zinc, and tin (Fig. 3), one realizes that real prices which developed in long-term cycles or reacted to shocks, normally returned to a certain floor price (Schwerhoff and Stuermer 2016; Buchholz et al. 2020). Additional ore reserves are continuously added by new discoveries of resources and developed from them or by reserve growth of known deposits (to be discussed later); declining ore grades and increasing costs are compensated by technological improvements in mining and processing, often linked to economics of scale.

In contrast, it can be shown for ferroalloys, such as ferromolybdenum, ferrochrome, or ferromanganese that technological improvements comparable to the ones that took place before 1918 for base metals, as described above, continue to lead to decreasing prices without compensating upward price pressures. The prices of these ferroalloys shifted steadily towards lower real prices starting around 1975 to 1982 and continuing to the present day (Buchholz et al. 2020). The price erosion between 1975 and 1982 reflects a shift in ferroalloy production from higher-cost to lower-cost

locations, new steelmaking processes, and increased use of recycled materials. During this period, open hearth furnaces were phased out and replaced by basic oxygen and electric arc furnaces. For example, due to efficiency and substitution gains, the manganese unit consumption per tonne of crude steel production was reduced from 7.2 to 6.4 kg of manganese (de Linde 1995).

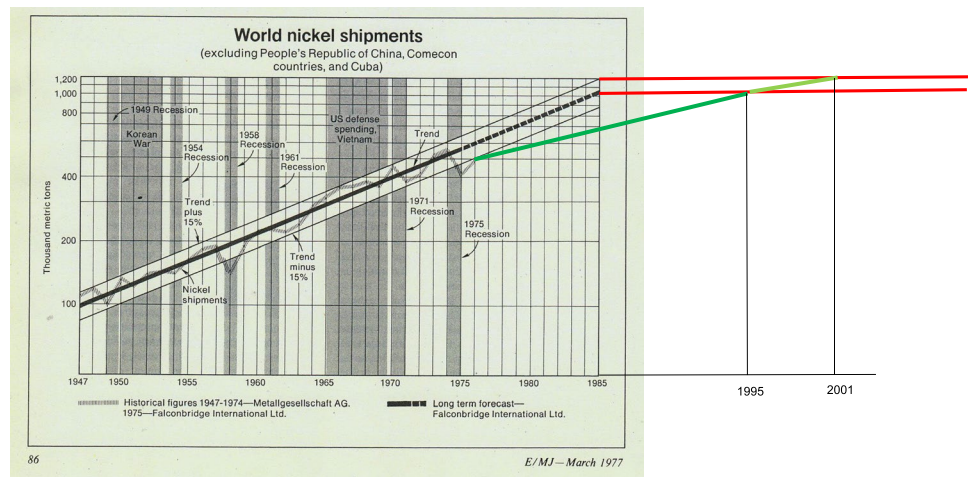
The perception of a looming raw material scarcity

The exponential growth of production and consumption of raw materials

The forecasts of the 1970s

The 1970s was the time when many people including many raw material practitioners and scientists anticipated a raw material supply crisis. Meadows et al. (1972) published its famous report to the Club of Rome “Limits to growth—Project on the predicament of mankind”. This book became quite influential and triggered an exploration boom. The Club of Rome was founded in 1968 amidst sociocultural and political upheaval in the developed world. The USA were about to lose the Vietnam War. Many high-level politicians, business leaders, and scientists were worried by

Fig. 4 Diagram from the March 1977 issue of the Journal E/MJ (Engineering and Mining Journal) (Dahl 1977), showing historic and anticipated nickel production. In green the trend after 1975 in red when an annual production of 1 and 1.2 million t was actually reached. (source BGR-raw materials databank)



runaway population growth and the accompanying increase in resource consumption. It was also the time when many experts thought that land-based resources would not suffice and marine resources such as manganese nodules rich in nickel and cobalt would need to be exploited. As a consequence, nearly every major mining company started to take an interest in marine mining activities (Gocht et al. 1988).

The study of Meadows et al. (1972) offers an excellent example for comparing predictions of the 1970s with the actual outcome 50 years later. Before I examine the forecasts of Meadows et al. (1972) in detail, however, I will scrutinize the exponential growth of metal consumption that took place in the twentieth century. Most people were only vaguely aware of exact growth rates, but had a general uneasy feeling because of growing consumption. Often too optimistic (or pessimistic, depending on the point of view) forecasts were made. A good example is the case of nickel much discussed during my time at Metallgesellschaft AG, because we were pursuing the nickel laterite project Barro Alto in Brazil (Wellmer 2008b). The journal E/MJ used to publish every year in its March issue an overview about the commodity markets. In the case of nickel, a diagram was shown (Fig. 4), displaying the historic consumption and a forecast by Falconbridge, one of the major nickel producers of the time (Dahl 1977). From 1947 to 1977 the average growth rate was about 6.3% per annum. Production fluctuated within a corridor of $\pm 15\%$. This was extrapolated to 1 million tonnes to be reached by 1985. In the end, the target was not reached until 1995, 10 years later than predicted (Fig. 4). Clearly, it is always dangerous to extrapolate high growth rates too far ahead. One could cite the Chief Economist of the British Government in 1952, Sir Alexander Cairncross: "A trend is a trend. But the question is: Will it bend? Will it alter its course through some unforeseen force and come to a premature end?"

Such growth curves can be considered as learning curves which often proceed in waves. (Later, learning curves will be further discussed in detail "The effect of learning curves based on incremental innovations" Learning curves may flatten, like the growth rate of

nickel described above, only to pick up later due to new demand brought about by structural changes in the world economy or a new invention. For example, after the first oil crisis in 1973, the demand curves for copper and zinc flattened but steepened in the 1990s driven by increasing demand from the BRIC-countries and boosted even more by increasing demand from China in the new century (Fig. 5). The same could be said of steel (see Wellmer et al. 2008, p.189, Fig. 14a–c). A similar trend can now be seen for nickel. Nickel is an essential component of lithium-ion batteries. With the coming green energy transition ("Energiewende") (see "The political framework: the green energy transition ("Energiewende")" below) a huge increase in nickel demand is expected. At present 85% of nickel is used in stainless steel and alloys, and only 5% for batteries. It is expected that by 2025 the battery share will increase to 25%. This increase of batteries for electrical vehicles is expected to be concomitant with an increase of nickel demand between 4.8 and 5.9 % annually (Szurles 2021). These growth rates, however, are still lower than the ones in the 1970s, i.e. when the total production was lower. This supports the observation that growth rates decrease the more a commodity is used and matures (Kürsten and Wellmer 1994).

Conclusion 2: All growth rates flatten eventually. Never extrapolate high growth rates too far! However, growth rates are learning curves that move in waves and can steepen again. In general, the higher the production the lower the growth rates, even in exceptional cases.

Critical examination of historical growth rates

Despite the general flattening of growth rates, we have to face the fact that we are living in a world of exponential growth of raw material consumption. Now we want to examine the uneasy feeling engendered by this kind of growth in detail and quantify it. We shall use accumulated production data of the BGR databank (BGR 2021) (see also Appendix). For copper, for example, data are available from 1800 on, further back historical data were reconstructed from Hong

Fig. 5 Relative growth of annual production of selected commodities since 1950. CAGR, compound annual growth rate; data from 1950 to 2019. For comparison the value for aluminium, not shown in the graph, CAGR = 5.54 % (source: BGR-raw materials databank)

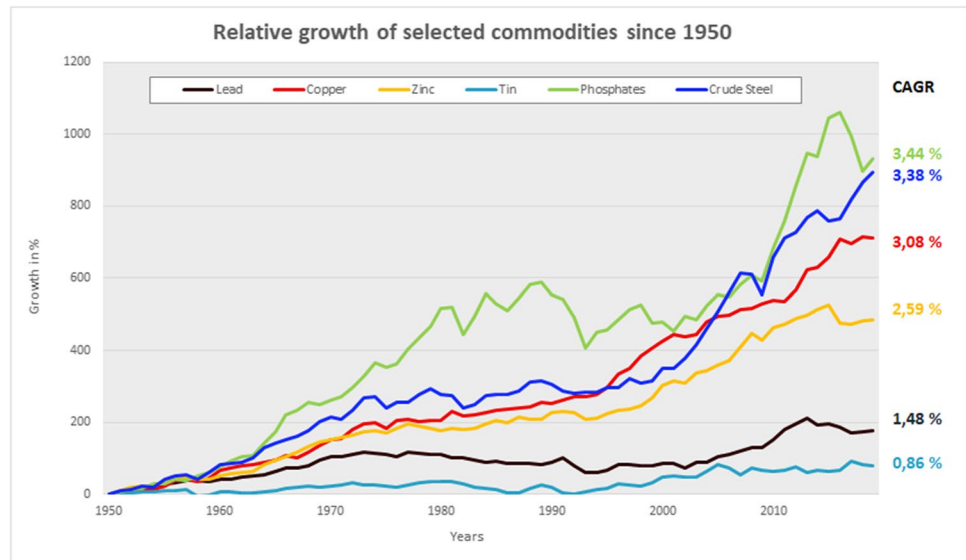


Table 2 Doubling periods of accumulated metal consumption for copper, bauxite (aluminium ore), zinc and nickel (see also [Appendix](#))

Commodity	Copper	Bauxite	Zinc	Nickel
Production 1970 (mio t/a)	6.402	60.710	5.561	0.663
Date and number of years from 1970 backwards in which as much metal was produced as the entire human history before	1949/1950 20.6 years	1961/1962 8.3 years	1949/1950 20.7 years	1958/1959 11.8 years
Production 2020 (mio t/a)	25.300	391.000	12.000	2.510
Date and number of years from 2020 backwards in which as much metal was produced as the entire human history before	1996 24 years	2003/2004 16.1 years	1992/1993 17.9 years	2000/2001 19.4 years

et al. (1996). One example of accelerating production is from 1800 to 1900: in the entire nineteenth century about 10 million t of copper were produced. This corresponds to about 19 months of production in 1970 and only 5 months of production in 2020. Accumulated production data can be used to answer the question: how long did it take in 1970 and does today in 2020 to produce as much metal as has been produced in the entire history before 1970, i.e. how long are the doubling periods (See model in [Appendix](#)). Table 2 shows that the doubling periods became longer for copper, bauxite and nickel, but still decreased for zinc.

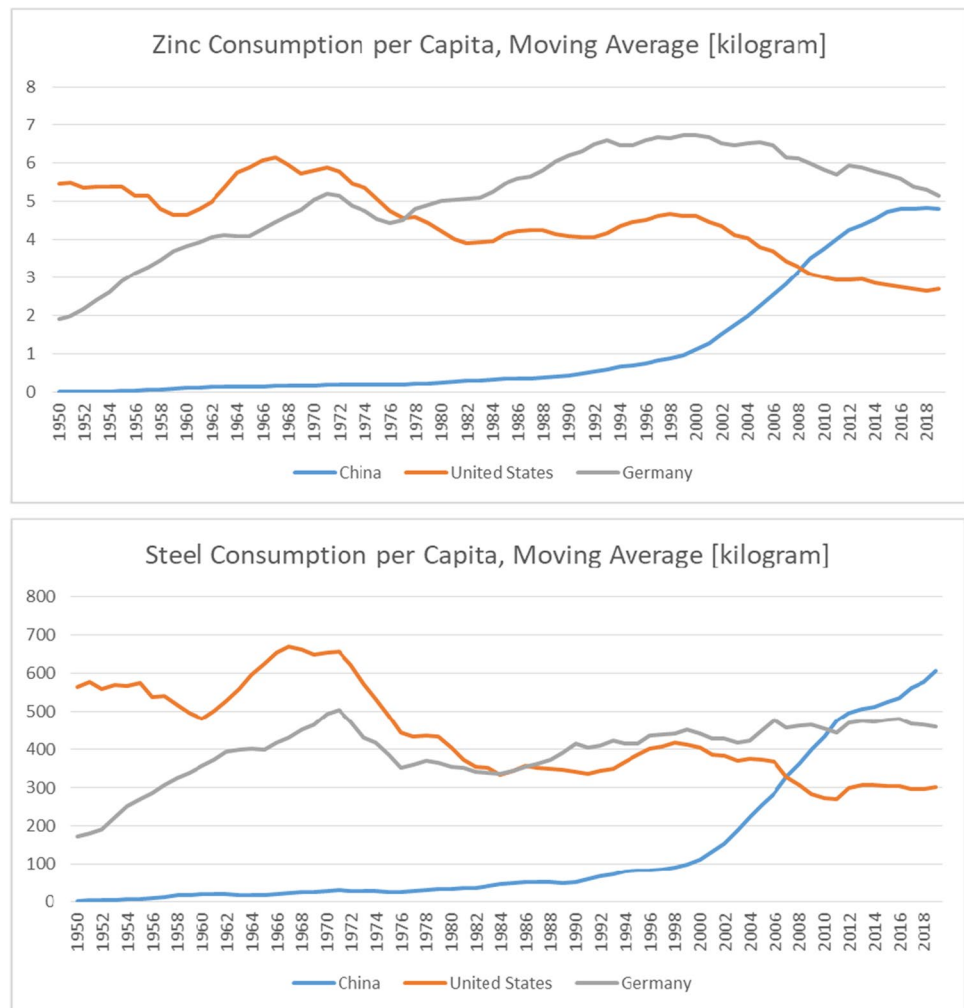
Conclusion 3: It is unclear, whether we have already reached the stage when growth rates of the major metals have flattened, but sooner or later it will come.

Can exponential growth continue forever?

The answer is clear: certainly not. No exponential growth can continue forever. The Earth has limits. However, growth can still continue for a long time, also stimulated by new

technologies to be discussed later (Fraunhofer ISI/DERA (2016, 2021)). All sceptics of the seventies so far have been proven wrong. Despite an optimistic view (critics may call it a cornucopian view) limits to the use of primary raw materials will become apparent sooner or later, not because of limits of resources, but because of the saturation of consumption and the flattening of the population growth curve due to decreasing birth rates. It is estimated that the world population will increase to 9.7 billion people by 2050 and 10.9 billion people by 2100 (Roser et al. 2019). At the same time, more and more countries will industrialize and the consumption per capita will flatten (Fig 6a and b as examples for zinc and steel) and then, due to learning effects, decrease. The sequence can be seen in examples from China, Germany and the USA. China as an industrializing nation shows still a continuous growth of per capita annual use for steel, whereas for zinc, the use per capita and year seem to flatten out. Germany shows steady growth for zinc up until 1992 and for steel up to 1972, followed by a flat development or even decline. The USA, as the most advanced industrial nation, has already been in the declining phase since 1950. It

Fig. 6 a (top): Annual per capita use of zinc for various countries (5 years—moving averages). Fig. 6 b (bottom): Annual per capita use of steel per capita (5 years—moving averages). (Source Use data—BGR—raw materials databank 2021, population data: The Conference Board (2020)) (Courtesy J. Perger, DERA, 18.5. 2021)



can be shown that for each nation a peak is reached. This is a peak demand curve and has nothing to do with the frequently discussed peak supply curve, like peak oil or peak phosphate (see “Forecast/actual comparison of the study “Limits to growth—Project on the predicament of mankind” of Meadows et al. (1972)”) (Scholz and Wellmer 2013).

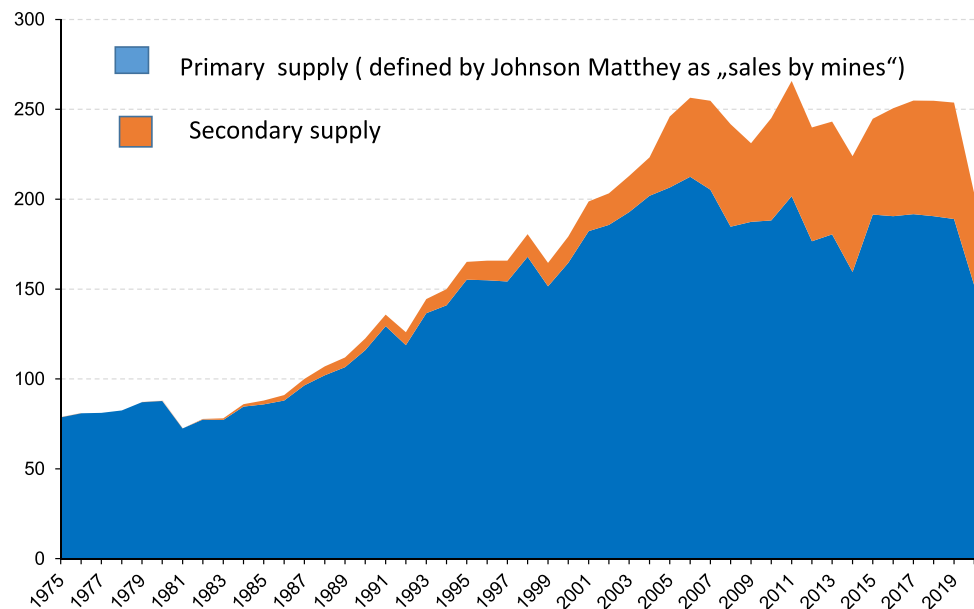
In addition, recycling of secondary material diminishes the use of primary materials. This effect can already be seen with the worldwide consumption of primary and secondary platinum¹ (Fig. 7). National policies aimed at

intensifying the circular economy are bound to contribute to attaining peak primary raw material demand for most metals in the not too distant future. An example could be the new circular economy action plan (CEAP) of the European Commission as an element of the European Green Deal (EU 2021).

It has been argued that during its industrial period humankind has produced so much raw materials from the geosphere and transferred them into the technosphere—as atoms do not disappear—that humankind could live solely off secondary raw materials. This, however, is a fallacy even for metals with high recycling rates. The collection rate for recycling is never 100%, some metals are used in a very dispersed form, making recovery and recycling impractical, the main reason being that 100% recovery is thermodynamically impossible (Wellmer et al. 2019, p. 78 ff).

¹ Concerning recycling of platinum: Shown in Fig. 7 are only the quantities of recycling of business-to-business activities, not of jewellery for example (a small market only). Of the business-to-business activities only those quantities are shown here which became available to the open market (mainly from auto catalysts and electronics). Before 1980 platinum was already used for example as catalysts in the petrochemical and glass manufacturers industry, which was already recycled. These quantities however stayed in the possession of the owner, the recycling was done on a toll basis and the quantities did not enter the free market (Hagelüken 2021; Hagelüken et al. 2009).

Fig. 7 Development of the supply of platinum from primary and secondary sources. Secondary sources exclude captive platinum supply from closed business-to-business applications such as chemical process catalysts or equipment for glass manufacturers (updated from Schmidt 2015, based on information from Johnson Matthey)



Conclusion 4: Sooner or later we shall see demand peaking for primary metals of all commodities (in contrast to peak supply) because the share of secondary metals will grow and the consumption per capita reaches a saturation level.

Forecast/actual comparison of the study “Limits to growth—Project on the predicament of mankind” of Meadows et al. 1972

At this point in time, it is appropriate to attempt a target/actual comparison of the report to the Club of Rome “Limits to growth—Project on the predicament of mankind” of Meadows et al. (1972), a cause célèbre of the 1970s. The data of this study are from 1970. So we have the benefit of half a century worth of statistics. Meadows et al. wrote in 1972: “... that the quantities of platinum, zinc, and lead are not sufficient to meet demand. At the present rate of consumption ... silver, tin, and uranium may be in short supply even at higher prices by the turn of the century”. They made reference to geology and wrote: “Despite spectacular recent discoveries, there are only limited numbers of places left to search for most minerals. Geologists disagree about finding large, new, rich ore deposits. Reliance on such discoveries would seem unwise in the long term” (Meadows et al. (1972) p. 54/55). With the last statement, they rely on a general 1970 report for the US Government (Council on Environmental Quality 1970).

How pessimistic and unrealistic from today’s perspective the view of Meadows et al. (1972) was, may be illustrated with the example of zinc, where the authors saw a gap between supply and demand looming. Among the base metals, zinc has one of the lowest reserve to production

ratios (R/P-ratio); using this tool of ratios in an incorrect way zinc supply may seem to be most precarious. Working with R/P-ratios then prevailing, the authors considered the situation in 1970 as well as the case for an escalating demand, and thirdly the case of escalating demand and concomitant increase of the reserves by a factor of five which they considered to be the maximum attainable reserve growth. For the static case, the R/P-ratio was 23 in 1970; for the latter case (growth of consumption rate and reserves) the R/P-ratio was calculated with 50, i.e. in the year 2020 the zinc reserves would have been used up. In retrospect, the situation turned out as follows (Scholz and Wellmer 2021):

The R/P-ratio of 23 in 1970 is today only slightly lower at 21, i.e. practically the same, despite a 2.1-fold increase in production, from 5.6 mio annual tonnes in 1970 to 12 mio tonnes in 2020. In the 50 years between 1970 and 2020, 442 mio tonnes of zinc were produced in total (BGR 2021); this is 3.6 times the reserves known to Meadows et al. (1972) in 1970. If we take the authors’ most optimistic case of reserve growth by a factor of 5 as the maximum, this in retrospect also turns out to be too pessimistic. The annual reserves reported did not decline, but grew by a factor of 2 from 1970 to 2020; 3.6 times the reserves of 1970 have been mined in the meantime i.e. the balance today is 5.6 times the reserves of 1970. In addition, the resources (a mineral substance category with less assured parameters) at present are estimated to be about 1.9 billion tonnes, i.e. 7.6 times present reserves and 15.4 times the reserves of 1970 of Meadows et al. (1972) (USGS 2021).

Table 3 Comparison of change of production from 1970 to 2020 and the development of the reserve to production ratios (sources: Meadows et al. 1972, Kelly and Matos (2018), USGS 2022, BGR 2021,

Uranium data: NEA 2020 and earlier issues, for uranium reserve definitions over time see Scholz and Wellmer 2013, p. 16, Table 1)

Commodity	Production 1970	Production 2020	Growth rate 1970 to 2020-Factor	Reserve to Production- Ratio 1970 (Meadows et al. 1972)	Reserve to Production- Ratio 2020 (USGS 2021).
Copper	5.9 million t	20.6 million t	3.5	36	43
Lead	3.39 million t	4.38 million t	1.3	26	21
Platinum	58 t	166 t	2.9	130	182
Silver	9.360 t	23.500 t	2.5	16	23
Tin	232.000 t	264.000 t	1.1	17	19
Uranium	34.088 t U	54.224 t U (2019 data)	1.6	75	113
Zinc	5.6 million t	12.0 million t	2.1	23	21
Bauxite	57.8 million t	391.0 million t	6.7	203	82

Clearly, this shows that reserves are a dynamic quantity and as yet there are no limits to be seen. To support this conclusion we will examine the reserve to production ratio for those commodities which Meadows et al. (1972) specifically mention (p. 56 and 58) as being in danger of depletion (Table 3, top part from copper to zinc).

The conclusion we can draw from Table 3, top part: The production from 1970 to 2020 grew between 1.2 for tin and up to 3.4 for copper. Despite this growth in production, the R/P-ratios more or less stayed constant or grew, meaning the exploration activities of mining and exploration companies were successful in keeping a balance between reserves and production. Exploration like research is a continuous learning process. Obviously, it was mastered by geoscientists since 1970 in the exploration field.

Conclusion 5: The reserve/ production ratio is only a snapshot of a dynamically evolving reserve/resources system. The learning effects during exploration so far are in step with ever-increasing consumption. Serious limits to reserves are nowhere to be seen.

Two instances of R/P-values shall be discussed in particular: the ones of lead and of bauxite:

R/P-values for lead: The R/P-ratio for lead declined from 26 to 20 over the 50 years between 1970 and 2020 by an increase of production of only 1.3 times in the same period. Lead is a commodity not very much in focus by mining companies anymore. About 80% of lead is used in batteries for internal combustion engines. With the changeover to electric vehicles we should see peak demand for lead probably in parallel with peak oil demand, which under reasonable assumptions is

expected to occur between 2025 and 2030 according to the World Energy Council (World Energy Council 2019). (For peak demand in contrast to peak supply, see Scholz and Wellmer 2013). We already saw a peak in demand for lead once in 1979 with the phase-out of lead in petrol (BGR 2021). Due to the growth of vehicle production, however, lead consumption increased again in the following years.

R/P-values for bauxite: For comparison, at the bottom of Table 3, the data for bauxite are included. Aluminium, and therefore also bauxite, the aluminium ore, shows a very high growth rate of annual production of 6.7 for aluminium and 6.4 for bauxite from 1970 to 2020, far higher than for the other commodities considered. Here the R/P-ratio declined significantly due to a very rapid increase in consumption in China in the new century. China has now become the biggest consumer in the world for all the significant raw materials except for oil and natural gas. A global boom in commodity prices occurred as early as 2003 because of increasing Chinese demand. The mining industry reacted to the new situation by expanding production capacities, primarily for iron and aluminium, which are by far the most used metals in the world. The production of iron ore increased by a factor of 3.2 from 2001 to 2011, that of bauxite increased by a factor of 1.8 (Wellmer et al. 2019). As the example of the Chinese boom shows, consumption increases can be quite sudden. If exploration can build on extension of known deposits or success in a brownfield environment, discoveries can keep pace with growing consumption. If, however, greenfield (grassroots) discoveries become necessary which are cyclic, as will be discussed below, time delays will occur. Such successes need learning time to develop new ideas and cannot be accelerated beyond a certain point by deploying ever more money, equipment and manpower. An excellent example for

this basic rule of exploration is the case history of hydrocarbon exploration in Germany, before and during World War II, when Germany needed every drop of oil it could find for the war effort. The peak of production was only achieved in 1968, 23 years after the end of WWII (Wellmer 2020). If we apply this rule of learning in exploration and consider the reduction in the R/P-ratio for bauxite from 203 to 81 in 49 years, it might not necessarily be a warning sign, but an indication that learning could not keep up with rapid production increases. Another aspect, however, cannot be overlooked: Significant bauxite deposits are tied to the present-day land surface. There are only few—and small—geologically ancient bauxite deposits known. It could well be that the reduction of the R/P-value for bauxite—at least partially—is also due to a new exploration situation finding new deposits on a well-explored Earth surface. However, the R/P-value of 81 is far from being a matter of concern, which will be discussed below.

Conclusion 6: It is obvious from the examples above that rapid changes in production rates may be accompanied by significant decreases in R/P-ratios and it would appear justified to suspect that advances in exploration cannot always keep pace with consumption. However, as long as the R/P-ratios do not fall below 50 for stratabound deposits and 25 for other deposits and exploration activities continue apace as normal there is no reason to worry about future supply bottlenecks.

The misunderstanding of the reserve/production ratio

The Total Resource Box

To better comprehend the reserve/production ratio (R/P-ratio) used by Meadows et al. (1972) and in “Forecast/actual comparison of the study “Limits to growth—Project on the predicament of mankind” of Meadows et al. (1972)” and its implications it is necessary to understand the categories of reserves, resources and geopotential that add up to a total global resource estimate. This is explained in Fig. 7, the Total Resource Box.

The concept of the Total Reserve Box has been developed from the McKelvey Box used by the US Geological Survey (see, e.g. USGS 2021). It has, however, been simplified and adapted to make it easier for politicians and non-technical people to apprehend. Three terms, namely reserves, resources, and geopotential, need to be understood. *Reserves* of a commodity are the share of the total resources that can be economically extracted with the available technology and energy under environmentally and socioeconomically acceptable conditions. *Resources* (sensu strictu) are known ore material (at various levels of confidence), but without

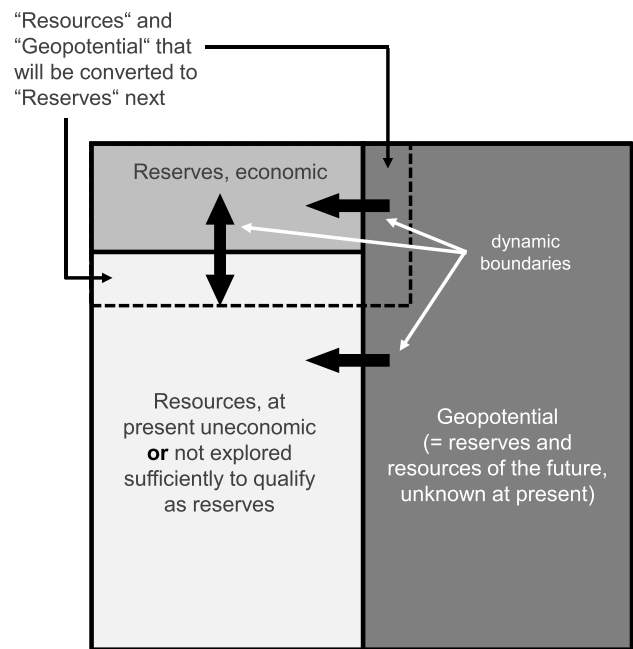
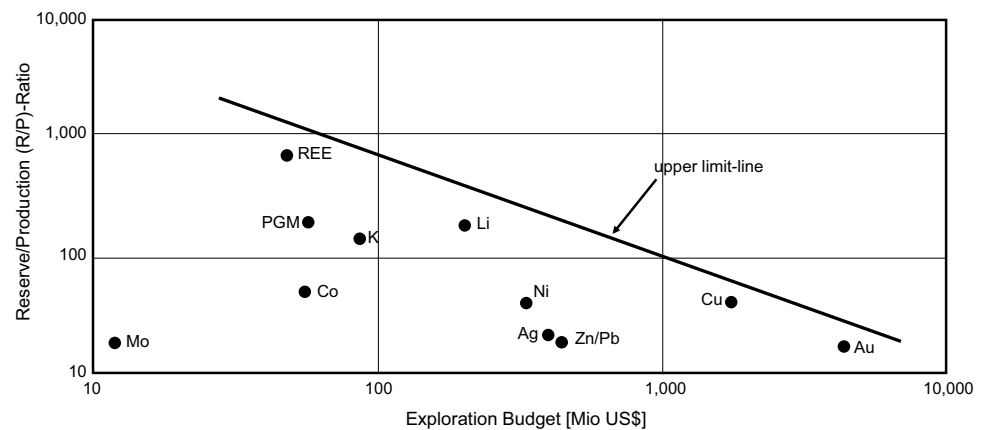


Fig. 8: Total Resource Box (amended from Scholz et al. 2014); *x-axis*: general trend of increasing knowledge, going from left to right; *y-axis*: general trend of increasing economic viability going from bottom to top

economic viability having been established. Some resources may be unviable under present economic conditions, some are not sufficiently explored to fulfil the requirements of reserves. Looking further ahead, we must consider a third category in addition to reserves and resources: the *geopotential*. The geopotential is the as yet unknown but promising portion of the Earth’s crust. By means of modern exploration techniques, geopotential may be converted into future reserves and resources (Fig. 8). The boundaries between reserves and resources are not fixed. Due to changing economic conditions and new technological developments resources can become reserves or reserves might fall back into the resource category. Due to ongoing exploration activities, the boundaries between geopotential and reserves and resources are also dynamic. Therefore, we have a source for future reserves and resources: the geopotential. How large could the *geopotential* be? Three raw materials experts of the US Geological Survey (Meinert et al. 2016) may provide an answer:

The adequacy of mineral resources in light of population growth and rising standards of living has been a concern since the time of Malthus (1798), but many studies erroneously forecast impending peak production or exhaustion because they confuse reserves with “all there is”. Reserves are formally defined as a subset of resources, and even current and potential resources are only a small subset of “all there is” (italics by the author).

Fig. 9 Global exploration expenditures vs. R/P-ratios (logarithmic scale). (Source BGR-raw materials databank, S&P. 2021, R/P-ratios calculated from USGS 2021). The black line shows an upper limit of the trend



R/P-ratio as an early warning indicator

As shown above in “Forecast /actual comparison of the study “Limits to growth—Project on the predicament of mankind” of Meadows et al. (1972)”, the R/P-ratios are unsuitable as an indicator of lifetime (Wellmer 2008a). However, they can be helpful as early warning indicators (Scholz and Wellmer 2013) when they are in continuous decline and come close to the 10 or 15 years lead time for new mining developments. This has so far been found only for antimony and tin (Wellmer et al. 2019, p. 22, 180, Fig. A2). Antimony is considered a critical raw material by the European Commission in its latest EU-20 list (EU 2020) because of high supply concentration from a single source country China. China is not only the main geological source for mining the ore material, but also the country where much of the remaining production is smelted; restricted possibilities for substitution, and limited possibilities for recycling. The U.S. Government too regards antimony as a critical mineral, mainly because of its use in military applications (Seal et al. 2017).

Tin also is listed as critical material by the U.S. Government, but not by the European Commission. In a U.S. Department of Defense study of strategic minerals published in 2013, tin has the greatest shortfall (insufficient supply to meet demand) of \$416 million; this amount is more than twice that for antimony (\$182 million), which is the strategic mineral with the next largest shortfall (Kamilli et al. 2017; U.S. Department of Defense 2013).

This leads to the next useful application of the R/P-ratio as an indicator for exploration needs.

R/P-ratio as an indicator for exploration needs

We have seen that reserve-to-production ratios (R/P-ratios) are useless to predict the lifetime of raw material reserves. They are more influenced by ore deposit type than possible lifetime. For instance, commodities that occur mainly in

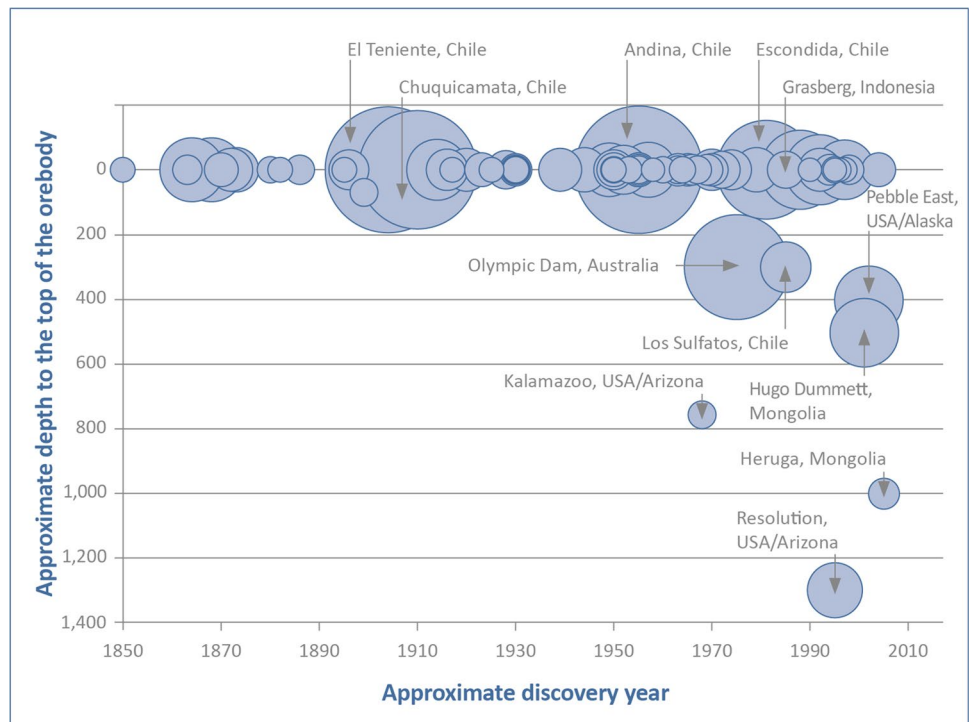
lenticular deposits like the base metals copper, lead and zinc, or precious metals like gold and silver in vein deposits, have low R/P-ratios below 50. On the other hand, commodities which occur in stratiform deposits, for which observations can be extrapolated quite far, have R/P-ratio above 100, or even higher like for example iron, potash or phosphate. Nevertheless, R/P-ratios can be quite helpful in revealing any need for exploration. To recognize the benefits of R/P-ratios we have to understand the planning process within mining companies, and return to the importance of the reserve category within the Total Reserve Box of Fig. 8.

Reserves are the result of exploration by natural resources companies. For them, reserves are part of strategic planning and serve to minimize financial risk and maximize returns. This information helps companies plan their activities for normally 30 to 50 years ahead². Therefore, it would not make sense for a company to explore and define reserves that could only be mined say 150 to 200 years hence. From this we can deduce an optimal value of the R/P-ratio as a guide to structure companies’ exploration budgets:

If the R/P-ratio is below 50, sustained exploration effort is necessary to keep the balance between reserves and production. If the ratio is around 100, as in the case of bauxite or iron ore, exploration effort can be kept flexible in keeping with specific company needs. Rosenau-Tornow et al. (2009) comment from the point of consumers. They are more optimistic and recommend to monitor exploration activities regularly, if the R/P-ratio falls below 25. Time series of the R/P-ratios from 1988 to 2012 actually show that for most non-stratabound metal deposits these ratios are in the range of 20–40 years (Wellmer et al. 2019).

² There are exceptions like cases where the planning horizon is much shorter, for example when companies are mining irregular vein deposits, like barite, fluor spar, antimony or gold vein deposits. Here sometimes the planning is often as short as 5 years (Wellmer and Drobe 2019).

Fig. 10 Depth of copper deposits that have been discovered during the period 1850–2010. Deposits containing more than four million tonnes of copper only are included (from Wellmer et al. 2019; p.74, modified after Finlayson 2009; Large 2014)



In consequence, one can see a general trend if one plots exploration expenditures against R/P-ratios (Wellmer and Becker-Platen 2002, p.731 and Fig. 9). If R/P-ratios are low, as for gold or copper, the expenditures are high; they are much lower when the ratios are high as for the lanthanides, the platinum group metals or lithium.

There are of course other influences on exploration expenditures: some commodities are simply “in”. Speculators who fund the exploration activities of junior companies - the main and most successful drivers of grass roots exploration today—back especially those companies that explore for “buzz” commodities in the hope of making a killing. For a long time in Canada, for example, such buzz word was “diamonds”. Other commodities which lie well below the upper trend line in Fig. 9 are by-product commodities such as cobalt or molybdenum, which are mainly produced along with copper.

Conclusion 7: The reserve to production (R/P) ratios are useless as indicators for lifetime; however, they are helpful as early warning indicators for looming problems of supply and for indicating the need for boosting exploration.

The perception of declining exploration successes

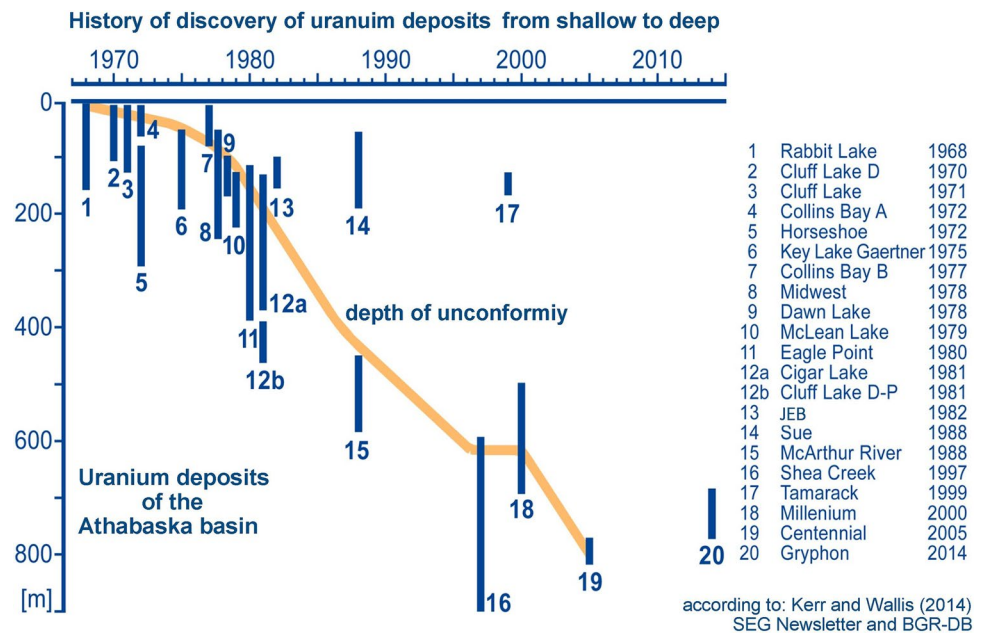
We saw in “Forecast /actual comparison of the study “Limits to growth—Project on the predicament of mankind” of Meadows et al. 1972. and “The misunderstanding of the reserve/production ratio” and Table 3 that the R/P-ratios stayed more or less constant, with successful exploration

guaranteeing a constant flow from the geopotential field to the reserve field in Fig. 8. The transfers were able to compensate not only for extracted resources but also for increased production necessitated by growing consumption. It should be pointed out that the R/P- ratio is also kept within a narrower corridor by improvements in mining methods and extractive technology that enable the mining of lower grades economically. But the decisive factor is exploration success.

Again and again there are warning voices that the success ratio is decreasing. Before examining the mistaken idea of declining exploration successes in a critical light we want to quote Meadows et al. (1972). The authors, relying on the 1970 report by the Council on Environmental Quality, wrote 50 years ago: “Despite spectacular recent discoveries, there are only limited number of places left to search for most minerals. Geologists disagree about finding large, new, rich ore deposits. Reliance on such discoveries would seem unwise in the long term” (Meadows et al. (1972) p. 54/55).

This statement is certainly true for finding deposits at or close to the surface. But it neglects the third dimension. Below 300 m depth, global exploration hardly has touched the Earth’s deeper crust, with the exception of locally confined areas mostly in the close vicinity of known deposits (Wellmer et al. 2019, p.30). The fact that despite growing consumption, by factors ranging from 1.2 to 3.4 for base metals and uranium (Table 3), the R/P-ratios have practically stayed constant, proves that exploration geoscientists in their persistent search for new deposits have learned to constantly improve their understanding of the processes of ore genesis

Fig. 11 Discovery history of the uranium deposits of the Athabasca Basin/Canada with depth ranges in relation to the unconformity (sources Kerr and Wallis 2014, BGR-databank)



in a given geological setting and adapted search methods to the new concepts. The outcome, refined ore deposit models, made exploration at depth—where expensive drilling is the decisive search method—and the discovery of ore deposits below 300 m possible.

Figure 10 shows copper deposit discoveries worldwide from 1850 to 2010; Fig. 11 shows the example of uranium deposits in the Athabasca basin in Canada. Major progress has been made in the field of exploration techniques. Forty years ago, airborne electromagnetic methods had a depth penetration of 200–300 m at best. Recent advances in the method have extended penetration all the way to 1000 m (e.g. Steuer et al. 2020).

The Athabasca Basin in Canada is the most important uranium district in the world. The occurrence of the uranium deposits is controlled by a discordance between strongly deformed Archaic and early Paleoproterozoic sequences and undeformed clastic Meso- and late Proterozoic sediments. Based on the unconformity-concept new deposits could be discovered at increasing depths, some very rich indeed. In most cases, geophysical methods were the decisive exploration tools (Dahlkamp 1993).

Another instance of the successful application of a geological model is the discovery of the giant Olympic Dam deposit in South Australia, the second-largest copper deposit and the largest single uranium deposit in the world. It was discovered in 1975 as a blind deposit below 325 m of barren rock.

These examples serve to show that the pessimism of Meadows et al. 1972 and the experts of the US Council on Environmental Quality 1970, claiming that it would be unwise to expect large, new, rich discoveries, were

unwarranted. They underestimated human creativity, the most important resource to mitigate anticipated raw material shortages (McKelvey 1972). The discovery of the Olympic Dam was based on the geologic model of altered basalts as the source of copper in stratiform copper deposits of Proterozoic age, combined with geophysical models (Woodall 1984; Upton 2010). It is the role model of a newly recognized category of ore deposits, the iron ore-copper-gold deposit class (IOCG) (Geoscience Australia 2014) stimulating further exploration activities.

Besides going deeper in the search for new ore deposits another option is to challenge traditional ore deposit models with new concepts. A brilliant example of this approach is the discovery of the very large and high grade copper deposit Kamo-a-Kakula in the Democratic Republic of Congo DRC in 2008 with reserves of 245 million tonnes of 4.63% Cu and resources of 1.3 billion tonnes with 2.74 % Cu, “the first new copper belt discovery in decades” (Gilchrist 2020). It has become the fourth largest copper deposit in the world after Escondida in Chile, Olympic Dam in Australia, Col-lahuasi in Chile, illustrating again how wrong the forecast of Meadows et al. (1972) was. It was discovered by conventional stream-sediment and soil geochemical and airborne magnetic-radiometric surveys (Broughton and Rogers 2010) after discarding the orthodox notion that copper mineralization in the Copper Belt can only occur in the traditional Mine series (Mines Subgroup of the Proterozoic Roan Group). It is also a breakthrough in the mostly unquestioned belief that metal grades continuously have to fall. We may find a lot of deep deposits of such kind through modern exploration technologies.

Amount of copper & by-products found in the World

Primary copper deposits >0.1 Mt Cu found : 1950-2011

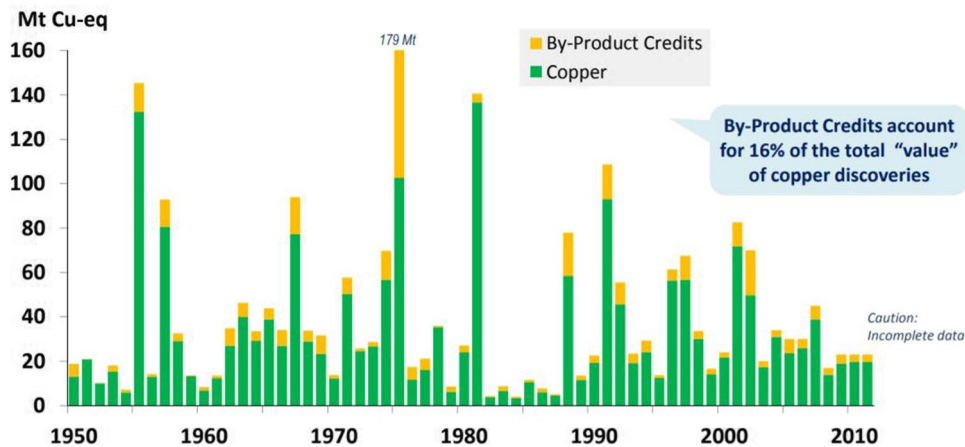


Fig. 12 Tonnage of copper and by-products in deposits with greater than 0.1 million tonnes contained copper that were discovered during the period 1950–2011 (presented in million tonnes copper-equivalent, Cu-eq.). Estimate includes adjustments for deposits with no discovery year and deposits missing from the database. The contribution of the by-products is calculated on basis of the monetary value of one tonne

of copper ore containing 1% copper which is taken to be equivalent to the value of one tonne of ore with 3.26% zinc, 4.76% lead, 0.30% nickel, 0.25% molybdenum, 0.43% cobalt, 0.94 lbs uranium oxide (U_3O_8), 0.44 tonnes magnetite, 3.0 g per tonne gold, or 156 g per tonne silver (Schodde 2012) (with permission of the author)

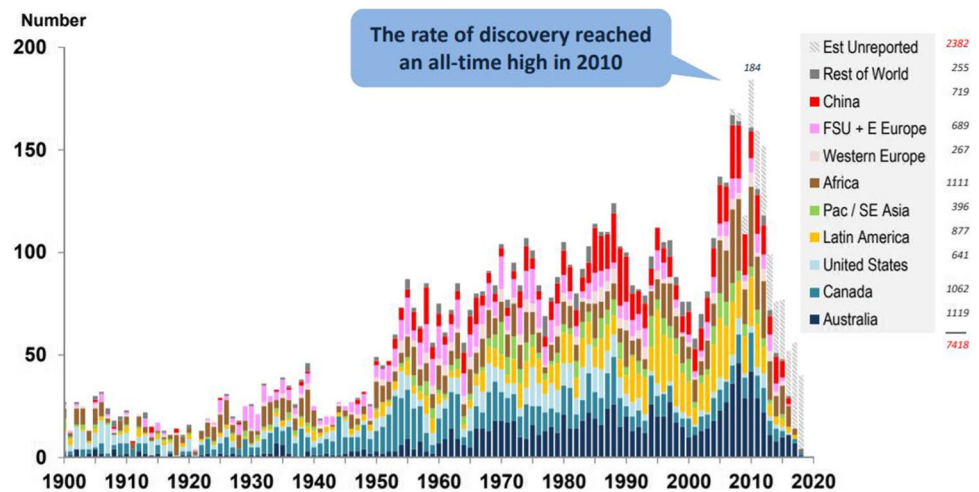
There has always been apprehension about diminishing exploration efficiency. For instance, early fears were aroused about uranium supply in the USA in the 1960s after a significant decrease in tonnes of U_3O_8 discovered per million meters drilled (Faulkner 1968), or about the general malaise in the exploration scene in the USA in 1971 (NN 1971). As to uranium, the anxiety was before the discoveries of the large, high-grade deposits of the unconformity-related vein-type deposits in the Athabasca basin in Canada (see Fig. 11) and in Northern Australia in the Alligator River Camp, which changed the market dramatically and led to the phasing out of the low-grade quartz-pebble conglomerate deposits in Canada and the exploitation of uranium as a by-product of gold mining in South Africa (Wellmer 2008a, p.584, Fig. 10). (Technological progress, of course, has also made an important contribution to the structural changes in uranium mining. In-situ leaching has become the most widespread treatment method. By 2019, 57% of uranium was produced by solution mining (NEA 2020).) In the new millennium, concern about decreasing exploration efficiency was expressed, for example, by Bizzi (2007), Large (2014) or Schodde (2019), while Carter (2010) saw conflicting evidence. Major reasons for the split in opinions about the decrease in exploration efficiency are the cyclic nature of exploration success and the reserve growth factor.

The cyclic nature of exploration successes

Since metal prices are fluctuating, as described above, earnings and profits of companies rise and fall in step. Since exploration expenditures of mining companies usually are paid out of profits, it follows that exploration budgets ebb and flow too. A large share of exploration today is driven by junior companies that raise their exploration funds by share issues on the stock exchanges. The ease of raising money is very much influenced by metal prices. Thus metal prices and exploration budgets usually are correlated, with a lag of one or two years (Ventura 1982; Eggert 1988). The higher the exploration budgets are, the more holes can be drilled and the higher the chance of a discovery. This, however, is only one cause of the cyclic nature of exploration success. Exploration is like research. Scientific breakthroughs, i.e. in our case exploration successes, do not occur regularly, even if the whole world is taken into account and not just individual countries. On a national scale, many examples are given in the book by Tilton et al. (1988) "World Mineral Exploration—Trend and Economic Issues" for the USA, Canada and Australia (also Cranstone 1988; Rose and Eggert 1988; Mackenzie and Woodall 1988). An outstanding example of the episodic nature of mineral discoveries is given by Rose (1982) for the discovery of major copper resources in the USA from 1840 to 1980, distinguishing four distinct phases of discoveries. Recent research by Schodde also shows this cyclicity (Fig. 12).

Typically, all graphs displaying exploration successes over time show a decrease in the latest reported years

Fig. 13 Number of significant mineral discoveries by region in the world from 1900 to 2018. Based on deposits large than moderate in size, i.e. > 100 000 oz gold, > 10 000 t nickel, > 100 000 t copper, > 250 000 t zinc plus lead, > 5 000 t U_3O_8 , > 5 million t heavy minerals, > 20 million t iron, > 20 million t thermal coal, > 10 million t metallurgical coal, > 3 million t P_2O_5 , > 3 million t K_2O (Schodde 2019) (with permission of the author)



(Figs. 12 and 13). In Fig. 12, the author Schodde (2012), therefore, flags the most recent data in the graph “Caution: incomplete data”. How justified this caution is, is shown by a graph of Schodde of 2019 (Fig. 13). It is a compilation of significant discoveries between 1900 and 2018 by region, demonstrating the cyclic nature of discoveries and the falling off in recent years.

The decline in the most recent reporting years might be due to a decline in exploration efficiency, but could also be caused by delay in reporting or, if the tonnages are plotted as in Fig. 11, could be due to the effect of reserve growth.

Reserve growth

It is a matter of course that reserves of a mine grow over time. Once a mine is in operation, the exploration efforts of near mine exploration of mine geologists usually pay off as shown by Wagner (1999) (Fig. 14). It is interesting to see that the critical point is arrived at when 60% of the initial reserves have been mined. It is the tipping point of a learning curve. In the studied cases, mostly from Canada, the reserve growth started at this point, on average. Wagner derived final multiplier factors, factors the initial reserves have to be multiplied by to arrive at the final reserves, i.e. the growth rates. These are 1.6 for porphyry copper deposits, 1.8 for Mississippi Valley-type lead-zinc deposits and 3 for volcanogenic base metal deposits. Cranstone (1988) arrived at somewhat different factors: 2 for porphyry copper, copper-molybdenum, and molybdenum deposits, 2 for non-porphyry, non-vein base metal sulphide deposits (excluding nickel-copper deposits), 3 for vein deposits of gold, silver, and other metals, 1.3 for nickel-copper deposits (other than those at Sudbury, Ontario, and the Thompson Nickel Belt in Manitoba).

Typically, reserve growth can be observed in mining camps where ore deposits occur in clusters of lenses, like

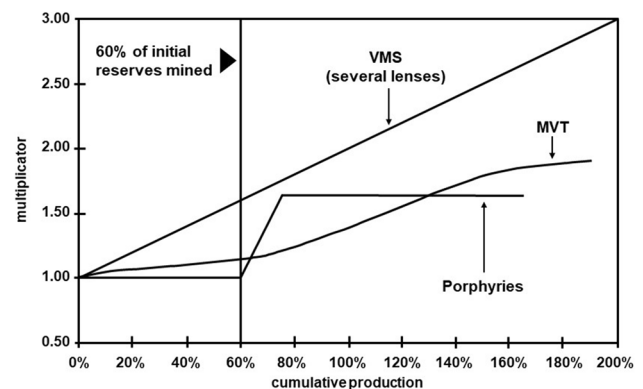
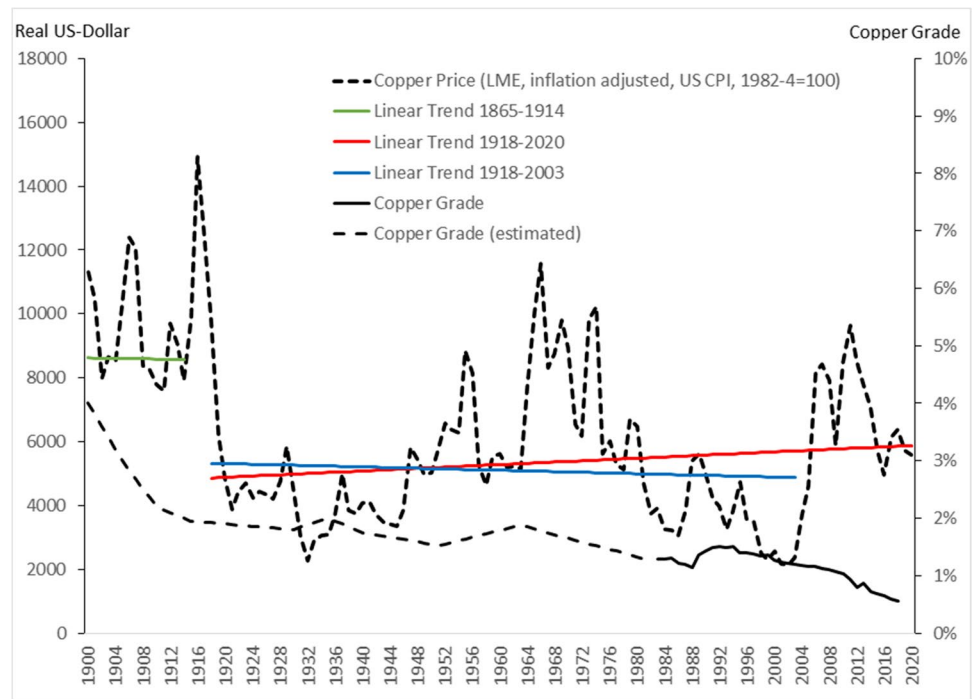


Fig. 14 Development of reserve growth over time for porphyry copper deposits, Mississippi Valley type lead-zinc deposits (MVT) and volcanogenic base metal deposits (VMS) (translated from Wagner 1999)

in Mississippi Valley lead-zinc-deposit districts where ore is hosted in carbonates, or volcanogenic massive sulphide deposits. For the first type, the Pine-Point district in the Northwestern Territory/Canada is a good example where about 80 deposits were discovered and mined from 1964 to 1987 (Osisko Metals 2019). In the meantime, Osisko Metals, by applying recent technological advances in exploration, outlined new reserves and resources of 13 and 38 mio tonnes respectively, with grades between 6.3 and 6.8% zinc equivalent. The company is now planning to revive production in the old district.

Conclusion 8: Exploration discoveries show episodic behaviour. Therefore it is difficult to extrapolate into the future. So far all pessimistic forecasts have been proven wrong by ingenious advances to detect new ore bodies to replace exploited reserves.

Fig. 15 Development of the worldwide average copper grades and the real copper price (Schodde 2019; Stuermer 2013, updated by Stuermer 2021). There are two trends interpolated after the price plateau shift in 1918 (see “The reason for the price break in 1918”): from 1918 to 2003, the start of the China boom, and from 1918 to the present, which has the steeper inclination. This will be discussed below in the conclusions (“Tentative conclusions for future metal prices” and “Discussion”)



How the balance between success in exploration and exploitation technology can keep up with rising production and result in a stable relationship between reserves and production (R/P-ratios), declining grades and constant prices in real terms

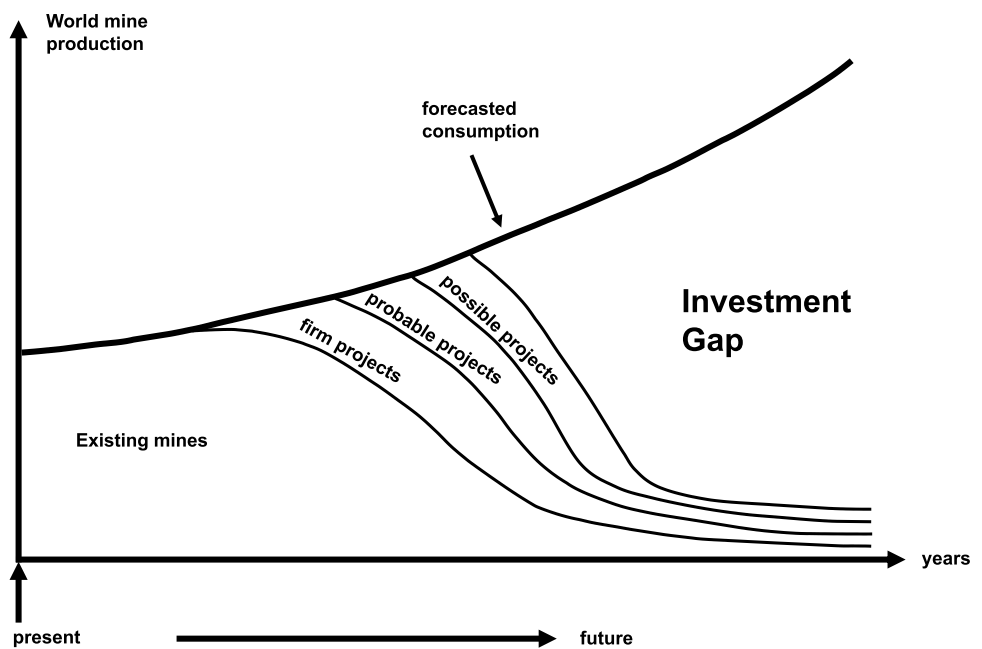
That the reserve to production ratios for the major commodities have remained constant (or even grown) over many decades has been shown in Table 3, with the exception of bauxite explained as a special case (see also Wellmer et al. 2019, p. 180, Fig. 2A). Hereby not only exploration successes were helpful but also the rationalization effects compensating for declining grades. There is a rule of thumb gained from practice that halving the cut-off grade will increase the ore tonnes by a factor of 4 and the contained metal 2 fold. (Schodde 2019). Figure 15 shows the outcome for copper. To demonstrate how far mining technology has progressed: The lowest grade copper concentrate producing mine of the world is the Aitik Mine in Sweden, mining 0.22% Cu with a cut-off grade of 0.06% Cu (Karlsson 2018). The cut-off is just 12 times the geological background of 50 ppm in the host rock (Rankin 2011). In the USA, 0.24% Cu are stated for the reserves of the operating Morenci copper porphyry deposit in Arizona (Mining Intelligence 2021).

Even the life-cycle assessment (LCA) science community, which uses the abiotic depletion potential (ADP) as a characteristic value to assess the environmental cost of material consumption, and which developed into a measure for raw material scarcity, accepted in a recent review paper the fact that so far a balance has always been maintained

between reserves and production (Berger et al. 2020 with 21 authors from the LCA community). The authors state: “Furthermore, the use of the economic reserves estimate is problematic because historically it has actually grown in absolute terms, and the extraction-to-economic-reserve ratios have been relatively stable, indicating no increase in resource scarcity” (Berger et al. 2020, p.805).

Reserves are one side of the coin of mineral supply. Nature offers us mineral enrichment in the Earth’s crust to produce tools for needed functions. The other side of the coin is the mining companies which develop resources, bring them to the market and satisfy supply needs. Supply shortfalls had been forecast during the last 50 years again and again. Typically, graphs as in Fig. 16 were produced, indicating not a shortage of reserves, but a shortage of projects needed to come on stream to cover the required supplies. During my time in the German Federal Ministry of Economics such graphs were regularly presented for example by the uranium and electricity industry, which was afraid of not being able to supply the envisaged future reactors with nuclear fuel. Recent examples are the graphs by the IEA for copper, lithium and cobalt, important raw materials for the green energy transition (IEA 2021a, b, p.119). These predicted shortages rarely occurred. The free market mechanism functioned as expected: prices were a reliable signal to reflect demand and supply. Essential is the feedback control cycle of mineral supply (Wellmer and Dalheimer 2012). If a shortage occurs, prices increase which can be painful as long as they last. Or as the Economist wrote: “high prices are the best cure for high prices” (NN 2021). This causes reactions on the supply and demand side.

Fig. 16 Schematic graph for future supply and demand scenarios- a forecast scenario that so far never has come true



Shortages contain the seeds of their own destruction. On the supply side, the usual response to sharply higher prices is to increase both primary production and secondary production. The first is achieved by bringing in new deposits, or lowering the cut-off grade and mining additional lower grade parts of an orebody. The second, by reprocessing lower grade scrap. On the demand side, consumers develop and use alternative materials or substitute technologies that use entirely different materials or simply find ways to get the same output with less material input. After these reactions on the supply and demand side a new price equilibrium is again established.

Such graphs as shown in Fig. 16 can be seen as early warning indicators, too. Resource companies continuously scrutinize the markets to see if there is room for investment for a new mine. If a gap in supply looks likely, most probably mining companies will decide to invest. Therefore, a study that might have appeared a reasonable prediction of a looming shortfall is invalidated by pre-emptive investment decisions. Such forecasts are in a way self-destroying. A self-destroying or debunked prophecy (Honolka 1976) is the opposite of the self-fulfilling prophecy (Merton 1957) based on the theorem of Thomas: If men believe situations as real, they are prone to become real in their consequences (Thomas and Thomas 1929). Everybody knows such situations. If a serious newspaper prints the news that bank XY has problems, this may be all baseless, but can quickly become real, once people start withdrawing their money deposits. Quite the opposite applies to supply gap forecasts. If believed, they will be shown to be unsound by investments.

Conclusion 9: Supply shortages have been forecast frequently in the past. They never actually happened. The self-regulating feedback control cycle of mineral supply

safeguards adequate supply over time. There is no reason to assume that this system of self-correcting forecasts will not work in the future.

Looking into the future

The overriding issues that will determine the future raw material consumption, are policy measures connected with the green energy transition (“Energiewende”). We shall concentrate on this aspect.

The political framework: the green energy transition (“Energiewende”)

The Paris climate agreement, a legally binding international treaty on climate change, was adopted by the Conference of Parties (COP 21) in Paris on December 12, 2015 and entered into force on the 4th of November 2016. Its goal is to limit global warming to well below 2 °C, preferably to 1.5 °C, compared to pre-industrial levels. To achieve this long-term temperature goal, countries aim to reach global peaking of greenhouse gas emissions as soon as possible to achieve a climate-neutral world by mid-century (UN 2021). In the Glasgow Climate Pact of the last COP-Conference in Glasgow (COP 26 in October/November 2021) for the first time explicitly, it was pledged to limit the use of coal (UNCC UK 2021). To take the Federal Republic of Germany as an example: Originally the aim was to be carbon-free by 2050. Now with the new Climate Change Act of 2021, Germany wants to reach climate neutrality already in 2045 (Bundesregierung 2021). By 2030 greenhouse gas emissions are to be reduced

Fig. 17 Metals and minerals used in selected clean energy technologies in comparison to conventional energy technologies (from IEA 2021a, with permission of IEA)

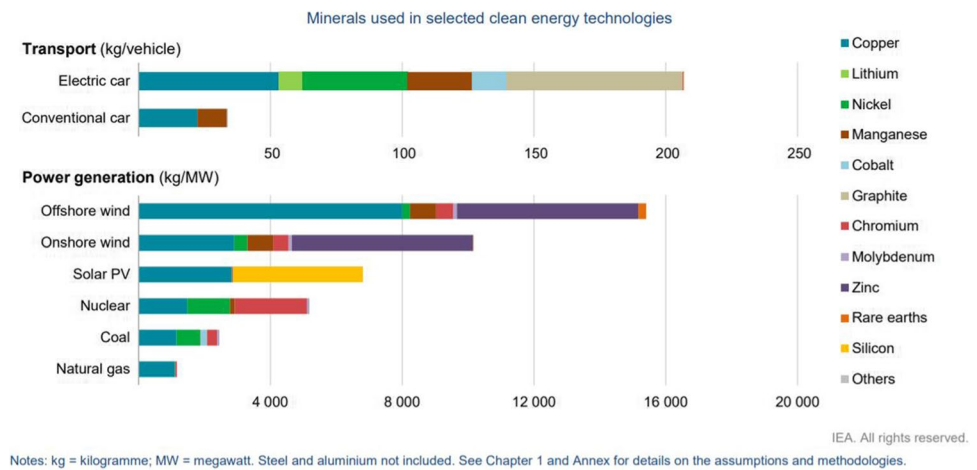


Table 4 Demand for different raw materials for selected emerging technologies in 2030/2035/2040 in comparison with production of 2009/2016/2021 (IZT, Fraunhofer ISI 2009; Fraunhofer ISI/DERA

2016, 2021). SSP1 is the Shared Socioeconomic Pathway 1 of the IPCC climate reports since 2011 (Kriegler et al. 2012)

Raw material 2009	Ratio 2030/2009	Raw material 2016	Ratio 2035/2016	Raw material 2021	SSP1-ratio 2040/2021
Gallium	6.09	Lithium	3.67	Scandium	7.9
Neodym	3.82	Dysprosium/terbium	3.08	Lithium	5.9
Germanium	2.44	Rhenium	2.4	Dysprosium/terbium	5.5
Scandium	2.28	Neodymium/praseodymium	1.7	Iridium	5.0
Platinum	1.56	Tantalum	1.6	Cobalt	3.9
Tantalum	1.01	Scandium	1.3	Ruthenium	2.4
				Neodymium/praseodymium	2.2
				Germanium	1.7
				Tantalum	1.4
				Lanthanum	1.1

by 65% (formerly 55%) and by 2040 by 88% (compared to 1990). The German coal-fired power plants, a main source of CO₂, are to be phased out in 2038 at the latest (BMWi 2021). In the coalition agreement of November 2021, the new German three-party government's endeavour was expressed to try to phase out coal mining and coal power plants already 2030 (SPD, Grüne, FDP 2021). Recently, the International Energy Agency (IEA) in Paris stressed the importance of phasing out coal-fired power plants especially in their study: Net Zero by 2050—A Roadmap for the Global Energy Sector (IEA 2021b).

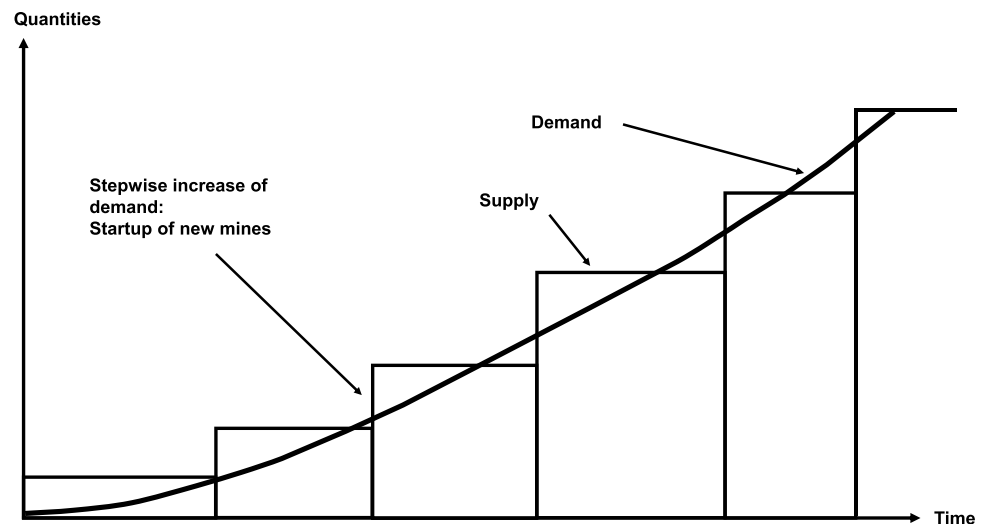
Future raw material requirements

The consequence of the green energy transition (“Energiewende”) is higher material intensity per energy unit, i.e. we will see a growing consumption, disproportionately higher, of certain metals and minerals (Vidal et al. 2013; Hertwich et al. 2015; Watari et al. 2019; IEA 2021a). In Fig. 17, the material requirements in kg/vehicle for an

electric car are compared with a conventional car; and electricity generation in kg/MW by means of offshore and onshore wind and photovoltaics are compared with nuclear, coal and natural gas plants. Considered are only the metals and minerals copper, lithium, nickel, manganese, cobalt, graphite and rare-earth elements. Not considered are the bulk materials steel and concrete. It is obvious how much more material-intensive electric cars and the renewable energy plants are than conventional cars and plants. Electric cars use around six times as much of the considered metals/minerals as conventional vehicles (IEA 2021a, p.89). This comparison, of course, only takes into account the material to construct the vehicles or plants, not the everyday requirements for their running.

The German Mineral Resources Agency, DERA, a special unit within the Federal Institute for Geosciences and Natural Resources, BGR, the Federal German Geological Survey, commissions the Fraunhofer Institute ISI, to undertake roughly every five years an assessment of the expected demand for raw materials arising from prospective high

Fig. 18 Schematic supply and demand curves; the step of the supply curve is caused by the start-up of new production units



technology developments (Table 4). It compares actual production with expected requirements by emerging technologies about 20 years ahead: in 2009 for 2030, in 2016 for 2035 and in 2021 for 2040 (IZT, Fraunhofer ISI 2009, Fraunhofer ISI/ DERA 2016, 2021). In the study for 2021 three scenarios were considered based on the Shared Socio-economic Pathways (SPPs) used in the climate reports of the IPCC (*Intergovernmental Panel on Climate Change (IPCC)* since 2011 (Kriegler et al. 2012). The results for only one, SSP1 (sustainability), are reported in Table 4 and compared with the results for 2009 and 2016.

Due to the rapidly increasing demand for electrically driven passenger cars and the—so far—leading technology of lithium-ion batteries, lithium heads the list of commodities in the study of 2016 on account of the highest increase in consumption, and is second in 2021. There are studies which forecast shortages of supply. However, a critical analysis showed that there are enough projects “in the pipeline” to satisfy an exponential growth of demand (Schmidt 2017).

That does not preclude price peaks. As Fig. 18 shows, demand practically grows steadily, while supply moves in abrupt steps due to the coming on stream of new capacities. This creates alternating periods of over-supply and under-supply, especially in a limited market such as for lithium and other commodities considered critical for the green energy transition (see Table 4). How slight under-supply can create price peaks in commodity markets has been shown exemplarily for sulphur (Kesler 1994). Such price peaks, although painful, are the cure to solve the supply deficit via the above-discussed feedback control cycle of mineral supply (Wellmer and Dalheimer 2012; Tilton et al. 2018).

Future raw material consumption is very much complicated by three variables, namely the process of learning, technological breakthroughs and substitution processes, which makes forecasting over a longer period of time difficult. This can clearly be seen in Table 4, in which the list

of potentially most critical raw materials is changing in 5 to 6 years intervals.

Learning processes and technological breakthroughs are innovation processes. Harhoff et al. (2018a, b) distinguish two principally different innovation processes:

- incremental (stepwise) innovations and
- disruptive or jump innovations.

Incremental innovations build on existing technologies and continuously improve them. They are the basis for learning curves, as illustrated below with the learning curves for wind power. Disruptive innovations are something totally new, for example the replacement of the classic analogue camera by the digital camera or the transistor replacing the vacuum tube; changes that required a whole new range of raw materials.

The effect of learning curves based on incremental innovations

Classical learning or experience curves are sigmoidal curves starting flatly with little learning progress then steepening and finally flattening again, as expressed in the English terms “to be low or high on the learning curves” (Fig. 19 a, e.g. Wagner 1999, p. 56). Frequently start-up problems occur (first it gets worse, before it gets better), resulting in a *J* curve. In project and innovations management this low of the learning curve is also called the “valley of death” (BMW 2015).

The development of wind turbines for electricity generation in Germany is a very good example for such a learning curve with a “valley of death” (Fig. 19b and Fig. 20): In the 1980s, the German government started an experimental project to test the feasibility of generating

Fig. 19 Learning curves. **a** The normal learning curve. **b** Learning curve with start-up-problems and a “valley of death”

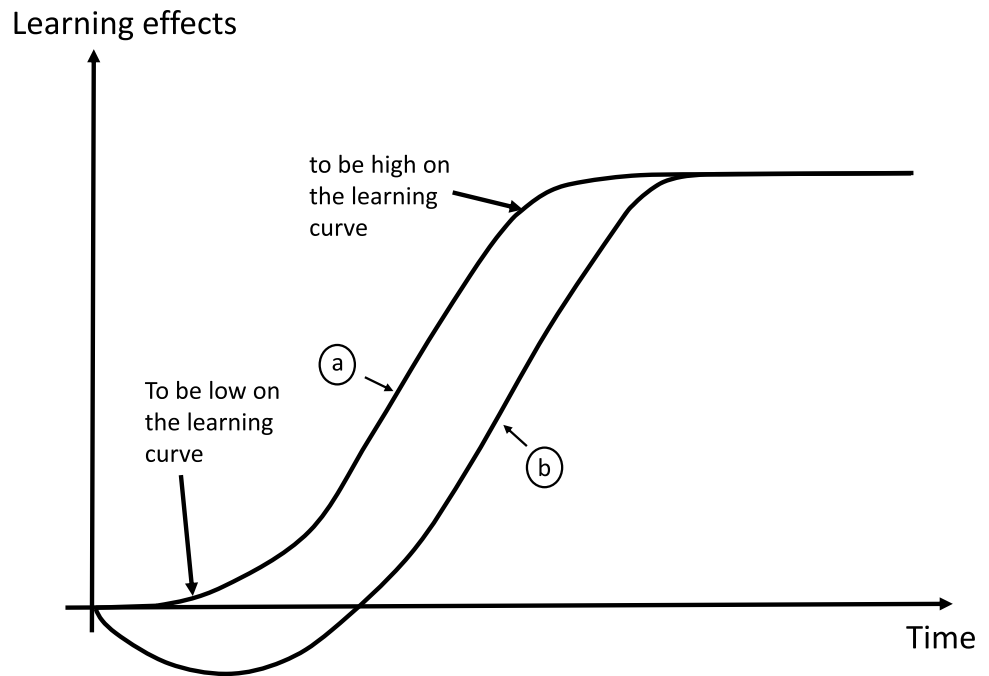
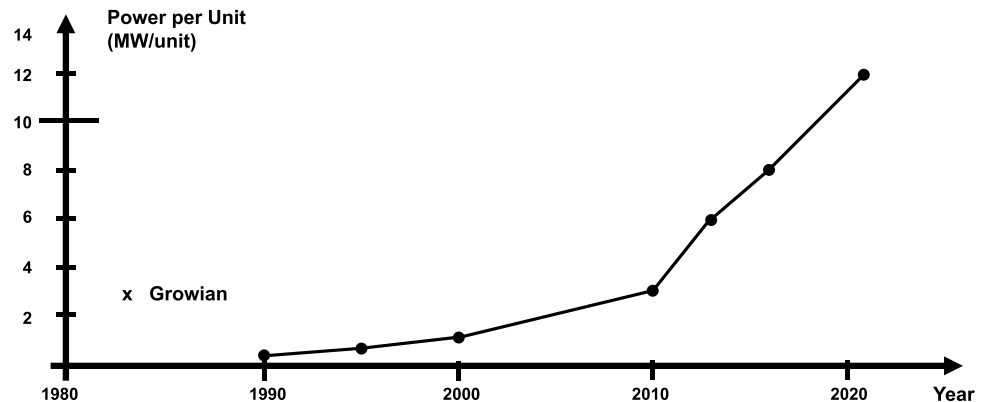


Fig. 20 Power of wind turbines (up to 2000 on shore turbines, since 2000 off shore turbines (data: Deutsches Windenergie Institut (DEWI), IEA 2019, p.20)

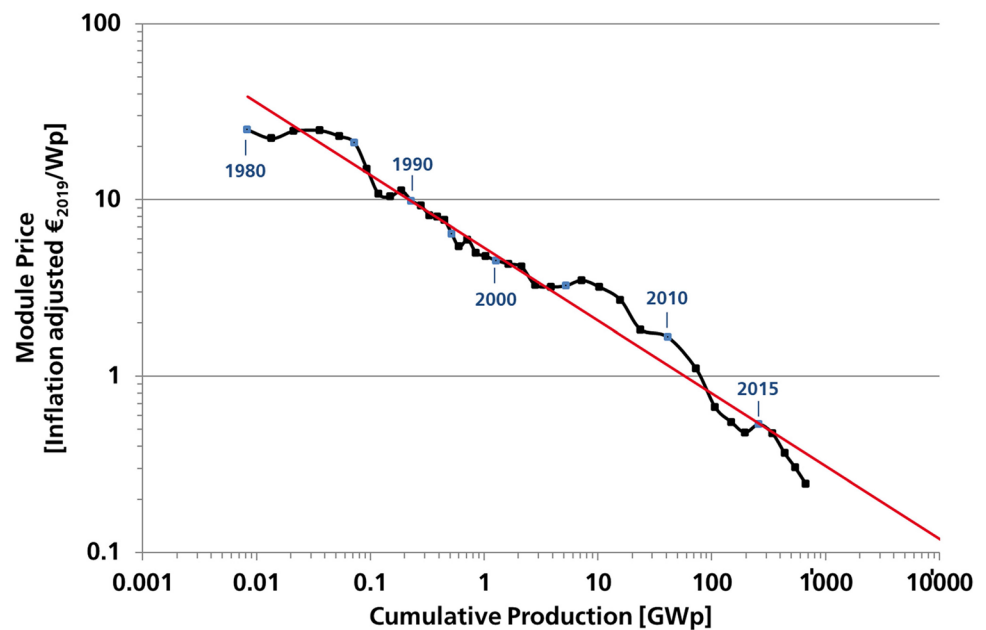


electricity with wind turbines. It pooled the aerodynamic know-how of top German companies to construct a 3 MW windmill, the Growian project. The project failed (Heymann 1995). Then the ball was set rolling and a learning process began when small and medium-sized companies began to build wind turbines with capacities of less than 100 kW to start with, then 100 kW or more, and still growing. With the growth of capacity and the expansion of the market, the size of companies involved grew too: the majors entered the market. Today off-shore wind turbines capacities are larger than 10 MW, with turbines of 20 MW on the horizon (IEA 2021a, p. 64). This again illustrates that learning does not only need money, but also time as illustrated above in “Forecast/actual comparison of the study “Limits to growth—Project on the predicament of mankind” of Meadows et al. (1972)” with

the example of German hydrocarbon exploration during World War II.

Due to economics of scale and other learning effects, costs for generating electricity from wind power decreased significantly. These learning effects can be quantified with a method that goes back to the aircraft industry in the USA. In 1922, the aircraft industry realized that the time to construct an airplane got shorter each time the numbers of completed airplanes doubled (Wright 1936). Such observations can of course be seen with costs and other efficiency parameters and were also observed in other industries. Today they are a standard tool to quantify learning effects. For wind turbines it was observed that from 1985 to 2020 the effect was 7.1%, i.e. each time the installed cumulative capacity doubled, the price went down 7.1% (Goldie-Scot 2020). As a result, the material intensity for wind power could

Fig. 21 Price learning curve for photovoltaic modules (Fraunhofer ISE 2020). (Wp, Watt peak; GWp, Gigawatt peak) (with permission of Fraunhofer ISE)



be reduced. For example, on a kilogramme (kg) per MW basis, a 3.45 MW turbine contains around 15% less concrete, 50% less fibreglass, 50% less copper and 60% less aluminium than a 2 MW turbine (Elia et al. 2020; IEA 2021a, p. 64).

More impressive are the learning effects for photovoltaic modules (Fig. 21): Each time cumulative production doubled, the price went down by 25 % for the last 39 years. Material usage for solar cells has been reduced significantly during the last 13 years from 16g/Wp to less than 4g/Wp (Wp = Watt peak) (Fraunhofer ISE 2020).

Disruptive innovations

To illustrate how radically and abruptly jump innovations can change the raw material requirements, the development of TV screens—although not an example from the energy field—may serve as a good recent example: the transition from the old cathode ray tube TV to flat TV/LCD and plasma screens. The glass of a classical cathode-ray tube contained lead (in the throat and funnel sections) as a protection from X-ray radiation, and barium and strontium in the screen itself. After the introduction of today's LCD flat screens, these elements were no longer required, as the TV glass substrates of the modern displays consist of aluminoborosilicate. This materialized within only 2 years. Strontium production collapsed in the first decade of the new millennium. Within 2 years, production was nearly halved (Renner and Wellmer 2020, Figs. 10 and 11)—a good example of Schumpeter's "creative destruction" (Schumpeter 1912). The technology transition to

modern displays has resulted in a new dependence on indium and tin, required for the transparent ITO (indium tin oxide) layers that function as electrodes in the displays (Wellmer et al. 2019).

Disruptive innovations that would significantly influence raw material requirements of the green energy transition, for example, could be breakthroughs in superconductivity to allow transporting electricity with minimal loss of power, or large batteries for storing excess wind and solar power. Concerning superconductivity, in the German city of Essen in the Ruhr Valley, the first long superconducting cable, cooled by fluid nitrogen, was installed in 2014, a 10 kV line between two electric power transformation substations 1000 m apart (Energieagentur NRW 2020) saving copper or aluminium cables. Ceramics were used instead.

It was estimated that in 2013 8% of global energy consumption was related to mining activities (Harris 2013), which of course encompassed also fossil energies. These, however, must be replaced by renewable energies, i.e. electricity, in the course of the green energy transition. Another game-changing disruptive innovation could be laser-induced nuclear fusion or other advances in fusion technology (Jendrichick 2020; Schwartz 2020).

Such innovations are known unknowns, but one also has to reckon with totally unsuspected innovations, the unknown unknowns of Popper (1988). He claimed that for radically new innovations to occur at all, the future must be unknowable, for otherwise an innovation would, in principle, be already known and would occur in the present and not in the future. Technological breakthroughs will be unexpected "black swans". There is no way to

know when they are going to appear but there is certainty that they will (Taleb 2007).

Substitution

Substitution reminds us that with the exception of the biological nutrient elements nitrogen, phosphorus and potassium, we do not need raw materials as such, but only properties and functions they can fulfil. Therefore, raw materials help us find solutions for functions. Various options are available. This opens the field for substitution. In a market economy competition guarantees cheaper products and greater efficiency; here substitution comes into its own. Which raw materials can deliver the required function best and cheapest?

There can be material substitution (material *x* against material *y*) or technological substitution, switching to an alternative technology which requires different raw materials (Schebek and Becker 2014). The competition between silicon photovoltaic cells against CIGS (copper-indium-gallium-diselenide) or cadmium-tellurium-cells, which at the present has clearly been decided in favour of silicon, would be an example of substitution of the first kind (Fraunhofer ISE 2020). An example of technology substitution would be battery electrical vehicles against fuel cell electrical vehicles (Robinius et al. 2018).

Substitution is an element of the politically much-discussed technology openness, which is a field of tension required by technology flexibility on the one hand, and strategic decisions, necessary in making a long-term investment commitment, and their consequences on the other hand. In this decision process, flexibility is lost to a large degree. A decision of a car manufacturer to go the route of battery electrical vehicles requires a different infrastructure than for fuel cell electrical vehicles. All these decisions have an influence on the future requirements for raw materials. This is also a field of tension for government support programmes. How much better are government experts and scientific advisers from science at choosing the most promising development route than industrial firms honed by competition? The above described development of wind power in Germany in “The effect of learning curves based on incremental innovations” is an example of a government decision taking a wrong turn, leading to misallocation of taxpayers’ money.

When a decision is taken, for instance to build battery electrical vehicles with a certain type of battery, and, therefore, an investment decision for a battery factory is made, there is always the possibility that the chosen route is rendered obsolete by technological advances. For example, at the moment lithium-ion batteries, needing lithium, nickel, cobalt and graphite, is the generally chosen route. It seems that the capacity of the lithium ion batteries is approaching a limit at 250 Watt /kg. With other materials like magnesium,

researchers hope to reach a loading capacity of 400 Watt/kg. Such batteries would also not need cobalt. (Zhao-Karger et al. 2018). Another route being researched is to replace cobalt and nickel as cathode material in lithium-ion-batteries with manganese (Urquart 2018; Lee et al. 2018).

Tentative conclusions for future metal prices

Future price influences

As follows from the “The effect of learning curves based on incremental innovations” to “Substitution”, it is difficult to extrapolate existing technologies too far into the future and make forecasts about possible shortages to come, due especially to learning effects, breakthrough technologies (black swans) and ongoing substitution processes. This applies in particular to the minor and specialty metals and raw materials essential for the green energy transition shown in Table 4, like lithium, cobalt or graphite. Regularly, studies are carried out by the German Mineral Resources Agency (DERA) within the Federal Institute for Geosciences and Natural Resources (BGR), for example, specifically for battery metals (DERA 2021) or for raw material requirements for next generation technologies as described before in “The political framework: the green energy transition (“Energiewende”)” (Fraunhofer ISI/DERA 2016, 2021). It can be expected that the free market system will continue to work in the future to ensure full supply of necessary raw materials. This of course does not mean the end of shortages and price peaks. Recurrent price peaks, while often painful, can in fact be useful. They can function as the necessary cure for overcoming shortages through the application of the feedback control cycle of mineral supply (Wellmer and Dalheimer 2012).

Concerning major metals like copper or zinc and future raw materials supply we will examine another aspect: future price plateaus. Buchholz et al. (2020) could show how since 1918, the end of World War I, real prices developed at a long term constant price level. The authors could define long-term and short-term low-price benchmarks and show that real prices developing in cycles or reacting to shocks normally returned to a certain floor price, the long-term low-price benchmark. In Chapter “The reason for the price break in 1918” it was shown how a new lower price benchmark developed after World War I. The price collapse after the exceptional war production, combined with new technologies, enabled production to settle at a lower but still adequate level than in the period from 1850 to 1914, resp. 1918. The following conclusion was drawn (Conclusion 1): When two effects overlap and amplify, long-term price trends can be broken.

Can this also happen in reverse? Could two effects combine to put long-term pressure on prices and lead to the establishment of a new low-price benchmark for

major metals like copper and zinc at a higher niveau? (see Fig. 3). These two effects could be:

- Pressure on the demand side. First the China boom between 2003 and 2012 drove up demand to levels two to four times higher than before 2003. The steep rise was followed by a period of sideways movements on this elevated plateau, with occasional fluctuations due, for example, to the Corona crisis. The period of stagnation is now succeeded by increased demand for the major metals copper and zinc in the wake of the green energy transition, causing a possible steepening of the price trend since 1918 (see. Fig. 15),
- Pressure on the cost side due the high risk of the social licence to operate which is explained below.

The social licence to operate

Today every responsible mining company has to have a strategy to achieve the goal of societal balance in the framework of the Environmental, Social, and Governance (ESG) criteria for attaining sustainability. An important element of this strategy is the social licence to operate (SLO or in short social licence). It is not a concrete licence that is granted, but a licence which has to be earned by the mining companies (Owen and Kemp 2013; Parsons and Moffat 2014). It is vague and intangible and refers to the ongoing acceptance of a company or industry standard of business practices and conduct by its employees, stakeholders and the general public (Kenton 2021). Mining companies should assume at the beginning of the planning phase of a project that the SLO must be acquired in a dialogue with the various community and stakeholder groups. Thus, SLO is created and maintained slowly over time as a company builds up trust with the community it operates in and with other stakeholders. In the end, the social acceptance of natural resource exploitation can only be guaranteed if the communities can be convinced that their values are being respected, the environmental impacts minimized, the economic advantages shared and reflected in jobs and better infrastructure for the community as a whole, and that the company is a good corporate citizen practicing corporate social responsibility by, for example, adhering to good miner's practices along their supply chains and observing social responsibility principles. This also means that so far external environmental costs have to be internalized.

Each year the consulting company EY conducts a survey in the mining and metals industry about envisaged risks (EY 2021). For years the "social licence to operate" has been in the top group of envisaged risks, in the years 2020 and 2021 it even topped the list. EY (2021) expects that the issue is going to become even more important as stakeholders broaden and develop a stronger voice. As effective

engagement becomes more critical, EY believes miners should consider three tiers of community: (i) local communities will have greater say in how miners should respect indigenous rights and native title, (ii) national communities may push for a return to resource nationalism, with increased debate over who miners sell to and for what purpose, (iii) broader community commitment will come into focus as socioeconomic issues are highlighted post-COVID-19. We may see pressure building to provide ownership of assets to communities (EY 2021).

Two examples of how environmental and social pressure is increasing to impede the start-up of new mining operations (Christmann 2021): in British Columbia/Canada the large-scale Schaft Creek open-pit copper mine with a resource of 3.3 million tonnes of copper content started its mandatory environmental assessment process in 2006, producing over 50 studies so far without obtaining the necessary Environmental Assessment Certificate. The Pebble Mine project in Alaska from which four major mining companies (Cominco/Teck, Mitsubishi, Rio Tinto, Anglo American) walked away, is one of the world's largest undeveloped copper deposit of nearly 26 million tonnes of contained copper. The project has not received the US Environmental Protection Agency permit and may never get it due to high-level political objections to its potential impact on the water quality of Bristol Bay, which is considered one of the world's most valuable salmon fishing grounds.

On the other hand, every tailings dam disaster by blue chip mining companies like the 2019 disaster in Brazil (Córrego do Feijão) or the one in 2015 also in the Brazilian iron mining industry, the Mariana disaster, or the dam burst in Spain in 1998 (Los Frailes), provides sceptics with ammunition against mineral extraction: if these top mining companies cannot operate safely, who can? Therefore, we are strictly against it. This then is combined with the fallacy that we can live from recycling alone, hence we do not need mining at all! The arrogant, couldn't-care-less behaviour of a major mining company in 2020 blasting away 46,000-year-old aboriginal paintings to enable an extension of their iron ore operations in the Pilbara in Australia is only water on the mills of the mining sceptics and is clearly an abrogation of responsible governance (Reuters staff 2020).

Thus, there is a looming threat that not only existing operations are challenged by broader activist stakeholder groups but all mineral extraction becomes socially unacceptable since mining will always be associated with an environmental impact. Thus, a local risk could easily become a systemic supply and cost risk for society (Renn et al. 2020).

Conclusions as to copper and zinc

The energy transition drives demand ever higher. At the same time, the restraining requirements of the social licence

to operate are unlikely to allow cost pressures to lessen. All this might lead to an unprecedented higher level of the lower-price benchmark for copper and zinc. The lower price benchmark for zinc has remained quite constant since 1918 on (see Fig. 3), whereas copper has seen several sudden jolts to upper real price benchmarks (Figs. 3 and 15). Therefore, it seems to be worthwhile to examine previous criticality studies. Generally the parameters examined in such criticality studies are effects of supply shortages/economic vulnerability and supply risk (e.g. Wellmer et al. 2019, p.10 ff). According to Schrijvers et al. (2020) in the period from 2008 to 2019 zinc was examined in 16 studies, of which 2 saw a medium, 14 a low criticality; for copper there were 22 studies, 18 considered copper of low criticality, 2 of medium and 2 of high criticality. For zinc the substitution potential is rated quite high (Graedel et al. 2013, Fig. 5). While possible future shortages of zinc are rarely discussed in the literature, for copper warnings of future shortages appear by highly regarded experts appear regularly (e.g. Gordon et al. 2006 or Ali et al. 2017) and are contradicted just as soon by other equally reputable experts (e.g. Tilton and Lagos 2007; Tilton et al. 2018; Humphreys and Tilton 2018). A working group on resources from acatech, the German National Academy of Science and Engineering, studied the availability of commodities needed for future energy supply and could not envisage a physical shortage of copper (Wellmer et al. 2019). Similarly, the change of the R/P-ratio from 36 in 1970 to 44 in 2020 (see Table 3) cannot be taken as a sign of a looming shortage. The US Geological Survey recently conducted an intensive study of identified and undiscovered copper resources. The results of the study as of 2015 were 2.1 billion tons of copper of identified resources (i.e. 105 times production in 2020) and 3.5 billion tons of undiscovered resources (i.e. 175 times production in 2020) (Hammarstrom et al. 2019; Flanagan 2021). It can be expected that the correction mechanism of the feedback control cycle of mineral supply, with metal prices as the principal driving force (Wellmer and Dalheimer 2012), will continue to do its job in bringing over-pessimistic forecasts down to earth.

However, dismissing a future shortage of physical copper does not mean that prices will not rise due to increased demand and cost pressure as described above. It can still happen that the 10-year price plateau between 2005 and 2015 is repeated and perhaps move even higher, and the low prices prevailing for the last 100 years (Fig. 3) will never be reached again. The steepening of the trend line from 1918 to 2020 in comparison to the one from 1918 to 2003 in Fig. 15 may be an omen.

Discussion

2021/22, with data available for up to 2020, is an appropriate vantage point to look back over the last 50 years. In 1972 Meadows et al. published their famous report to the Club of Rome “Limits to growth—Project on the predicament of mankind”. It started a broad discussion within a wide audience about the future availability of raw materials. Although natural resources scientists, be it geoscientists or economists, soon rejected Meadows et al.’s models as too pessimistic because reserves and resources were not seen as dynamic entities, and, in general, the prevailing mood in this community was with hindsight too pessimistic:

- Raw material prices would go up in nominal as well as in inflation adjusted terms. Real commodity prices would in the long run rise with the real rate of interest. As a matter of fact, commodity prices more or less stayed at a constant level since the end of World War I. There was a boom in the 1970s due to the two oil crises which influenced also other commodities, but in the long run this boom was offset by the lull in the 1980s/1990s.
- Again and again—as now, too—it was predicted that the exploration efficiency would decrease and, therefore, create a pressure on commodity prices. The character of exploration success is cyclic. So far these predictions have not come true.
- The geophysicist Marion King Hubbert (1956) used a peak production model in 1956 to forecast the peak of US oil production (for the lower 48 states) in 1971 with an error margin of only one year. Because of its seeming exactness, the bell-shaped curve, known as the Hubbert curve, became famous, the term “peak oil” was coined and found entrance into daily newspapers. Subsequently, the peak model was applied by other authors to a wide range of other commodities (see e.g. Heinberg 2010; Calvo et al. 2017) and contradicted by other scientists (e.g. Rustad 2012; Tilton 2018). So far we have seen only peaks in demand, not peaks in supply. For asbestos, for example, in the mid-1970s, or lead in 1979 with the phasing-out of lead in petrol (Wellmer and Scholz 2017), and, soon to be expected, new peaks in the wake of electrification of the mobility sector. Taking into account the dynamic nature of reserves, the vast potential of future reserves within the so-far unexplored geopotential field (Fig. 8), the mechanism of the feedback control cycle of mineral supply in a market economy driven by the price signal, and the increasing material from secondary sources, it would be surprising indeed if we ever see a

peak of supply for primary raw materials. What we are likely to see, however, are peaks in demand.

- Above it was stated that since the end of World War I the commodity prices more or less stayed at a constant level. A break occurred at the end of World War I due to the collapse of the high demand of the war economy and about at the same time development of new technologies that enabled a recovery of production to old levels at a lower costs. The question arises, whether two overlapping effects can have the same effect in reverse, establishing a higher price level for a long time to come. Such twin effects could be the increased demand due to the green energy transition requiring continuously higher material input per unit energy generated, and the relentless pressure due to the social licence to operate raw materials ventures—a cost pressure which cannot be compensated in time by technological innovations. The steepening price trend for copper since 1918 (Fig. 15) might be a first omen.

The vantage point of 2020 offers the opportunity also to look back on 50 years of supply strategies. Within these 50 years we experienced in Germany two cycles of raw materials interest each ranging from active involvement to indifference (Wellmer et al. 2019):

- The active phase of the first cycle, which can be considered a supercycle, in the nineteen seventies and eighties saw the German Federal Government supporting exploration programmes. The initiative succeeded in encouraging German companies to acquire strategic stakes in foreign mines and thereby develop a robust backward integration of their business (Barthel et al. 1991). Examples are the stake in the Key Lake uranium mine in Canada, the share in the copper mine Ok Tedi in Papua, the tungsten mine Mittersill in Austria, the lead-zinc-silver mine Song Toh in Thailand, the zinc-copper-lead-silver mine Cayeli in Turkey and a magnesite deposit near Revelstoke in Canada. The German steel industry built up the Bong iron ore mine in Liberia as early as the 1960s and, in addition, possessed two iron ore mines in Brazil already before this backward investment commenced.
- The phase of indifference in the first supercycle resulted from a fundamental reversal of attitude in the 1990s. Following a swing in Germany to reliance on the commodity markets alone, and in the wake of the complete restructuring of Metallgesellschaft AG (from 1993 on)—not only one of the most important German companies in the commodities trading and mining business but a national icon too (Keitel 2010; Wedig 2014)—almost all the German shares in foreign mining operations were sold, often to direct competitors. In 1992, the last German metal mines were closed: the zinc-

lead mine Meggen of Metallgesellschaft AG and the Bad Grund lead-zinc mine of Preussag AG.

- The second cycle, possibly a supercycle, commenced when in 2003 Germany began to rethink its raw materials strategy in the wake of the commodities boom in China. Federal raw materials research programmes started in 2009 (BMBF 2013), the Federal Government formulated its resource strategy in 2010 (BMWi 2010)³. In the same year the German Mineral Resources Agency (DERA) was formed as a special unit within the Federal Institute of Geosciences and Natural Resources (BGR), the German Federal Geological Survey; and in 2011 a new natural resources research institute was founded in Freiberg/Saxony, the Helmholtz Institute Freiberg for Resource Technology. In 2012, German industry acted too by founding the “Alliance for Securing Natural Resources” with the aim of backward integration.
- With the abatement of price pressures in the second decade of the twenty-first century, German industry once again lost interest in striving for raw materials security. In consequence, the exploration support programme of the Federal Government, restarted in 2013, was terminated in 2015 and, also in 2015, the German industry closed the “Alliance for Securing Natural Resources”.

However, the decision to bet on short-term markets for long-term supply of commodities, relying entirely on long-term contracts and diversification of suppliers, might turn out to have been too rash again. The present raw material crisis, especially critical when it comes to shortages of electronic chips, a “raw material” crucial for the high-tech industry and capable of causing lengthy shut-downs in the car industry, seems to have prompted some companies to rethink their strategies, especially with regard to technologies necessary for the green energy transition. For example, it is reported that the chemical company BASF AG is participating in nickel projects in Finland and Indonesia with battery production in mind (Szurlies 2021). It remains to be seen how far the change of heart will go this time round. In 2018, in their strategic Position Paper “Raw materials for the energy transition” (Leopoldina 2018), the German academies, German National Academy of Sciences Leopoldina, acatech, the National Academy of Science and Engineering and the Union of German Academies of Sciences and Humanities, recommended a government initiative to “spark” a renewed effort of backward integration into raw materials by the German industry. Time will show if we are likely to see a third cycle of direct industrial involvement in securing raw materials.

³ This resource strategy was updated in 2020 (BMWi 2020).

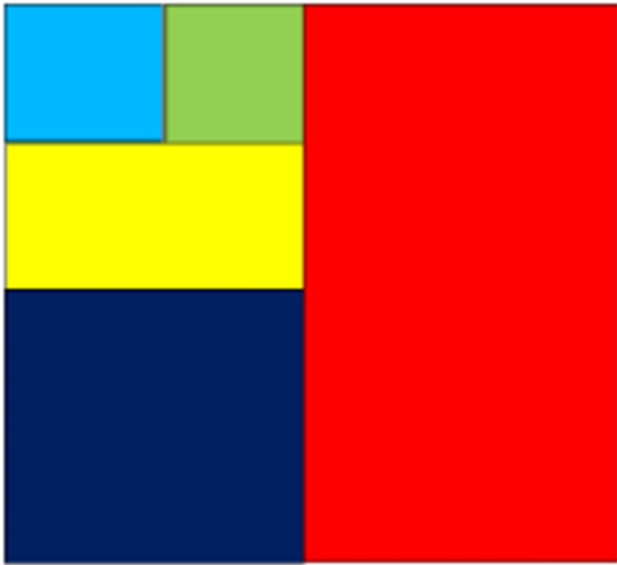


Fig. 22 Deriving a method to calculate times as much metal has been consumed as in the total history of humankind before

Appendix

How to calculate the periods in which accumulated metal consumption is as large as the total metal consumption in all of man's history earlier.

It is best to visualize the approach with folding a sheet of paper as shown in Fig. 22 with the coloured segments. Each time one creates a new square by doubling, the new space is as large as all the previous spaces combined. This method can be utilized by accumulating the metal consumption from the beginning. For the younger metals, resp. ores, like bauxite, nickel and zinc there are data in the databank of the German Federal Geological Survey BGR (BGR 2021): for zinc since 1809, for nickel since 1885, for bauxite since 1888. For copper, the data series starts at 1800. Of course, copper production started much earlier in the Copper Age around 5000 BC, but the amounts were minute. For the total period from the beginning of the Copper Age until 1800 AC a total of 4.7 Mio t were estimated according to Hong et al. 1996, i.e. over the entire history of copper usage by humankind, about 6800 years up to 1800, so much copper was consumed as today in two and a half months.

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