Feasible Futures for the Common Good. Energy Transition Paths in a Period of Increasing Resource Scarcities

Progress Report 1: Assessment of Fossil Fuels Availability (Task 2a) and of Key Metals Availability (Task 2 b)

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1 Introduction

Resource depletion is an aspect which unavoidably restricts possible supply – some day. This fact is beyond uncertainty, yet it is uncertain when resource limitations will occurr. Usually reserve and resource data are compared with the latest annual production in order to get the reserve-to-production-ratio (R/P-ratio). If this is in the order of 30-40 years or even beyond, the situation is seen as uncritical.

However, because of various reasons this simple analysis is too rough to be useful for a serious estimate of possible supply disruptions connected with geological depletion.

First, reserve data are only a very rough measure for the minerals yet to be produced. Erratic reporting or overestimations on the one hand and reserve growth due to the conversion of resources into reserves on the other imply a huge uncertainty with regard to these numbers. For this reason, a very cautious use should be made of them. Historical discovery patterns of fields or reservoirs help to improve our understanding of the real situation.

Second, what counts is not the reserve but the possible extraction rate. That depends on economics, technology and geological restrictions. It is indeed relevant whether high quality reserves are already exhausted or depleted and low quality reserves need to be touched at a rising share. To address these issues seriously needs a good understanding of production dynamics which can only be developed by analysing time series of individual countries and mines as each country is in a different stage of depletion.

Third, technological progress helps to improve the extraction rate or to access lower quality reservoirs with accelerated recovery rate. This progress might influence the speed of extraction as well as the size of possible reserves.

Fourth, the present and future demand rate determines whether a supply peak holds the risk for possible supply disruptions with serious implications on the world economy. An adequate analysis must include possible efficiency gains, substitution and recycling potentials.

It is impossible to perform such an analysis within the present work. It would include long lasting observations of relevant trends for each commodity and for each relevant country based on the corresponding data at individual field or mine level.

Since data availability, data quality and experience in data analysis differ for different commodities, in this study mineral fuels are separated from other ores and minerals.

The first subchapter investigates oil, natural gas, coal and uranium. The possible supply of oil is of highest interest, as it seems that peak production is already reached, with implications of the consequences of declining production for the whole economy and life style.

The second subchapter is dedicated to other minerals, first giving a general discussion followed by a rough survey. Finally, with the example of copper a more detailed analysis is performed.

2 Fossil Fuels and Uranium Availability

The KLIEN-funded project "Save our Surface – Ressourcen-Assessment der Verfügbarkeit fossiler Energieträger (Erdöl, Erdgas, Kohle) sowie von Phosphor und Kalium"[1] discussed the future availability of fossil fuels in detail with many examples of basic trends. The interested reader is directed to that information. Therefore the present discussion focuses on very few aspects, summarizing the most important conclusions.

It must also be emphasized that the views presented in this chapter deviate considerably from conclusions of government or intergovernment authorities such as the US-Energy Information Administration or the International Energy Agency, though both analyses are based on more or less the same empirical data of past developments.

While the Outlook of the International Energy Agency keeps on giving a picture of growing production volumes of fossil and nuclear fuels over the next decades, the present report takes serious the emerging and increasing signs of resource depletion at various levels. This report is guided by the emphasis on possible and, from point of view of the author, even probable developments of resource availability over the next decades.

Even when uncertainty remains it might be wise to plan according to the rule: Hope for the best, but prepare for the rest!

2.1 Mineral Oil

Actually, annual oil discoveries peaked in the period 1960 to 1970 at about 60 Gb/year. Even higher oil prices since 1973 could not invert or stop the tendency of declining discoveries thereafter. Over the latest decade 2000-2010 oil discoveries in average amounted to 10-20 Gb per year (see Fig. 1).

[1] see www.umweltbuero-klagenfurt.at/sos/?page_id=105

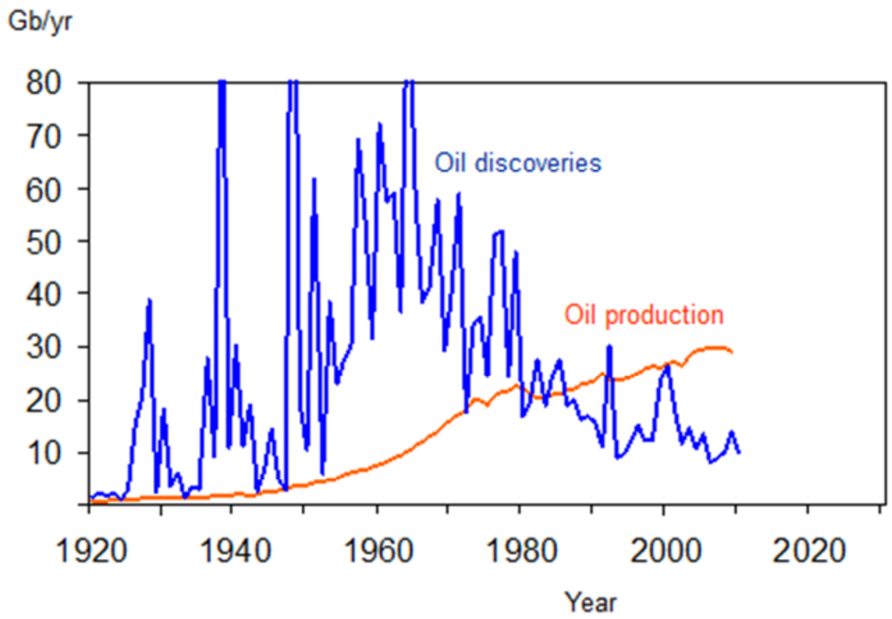


Fig. 1: Annual oil discoveries and oil production (Zittel 2010)

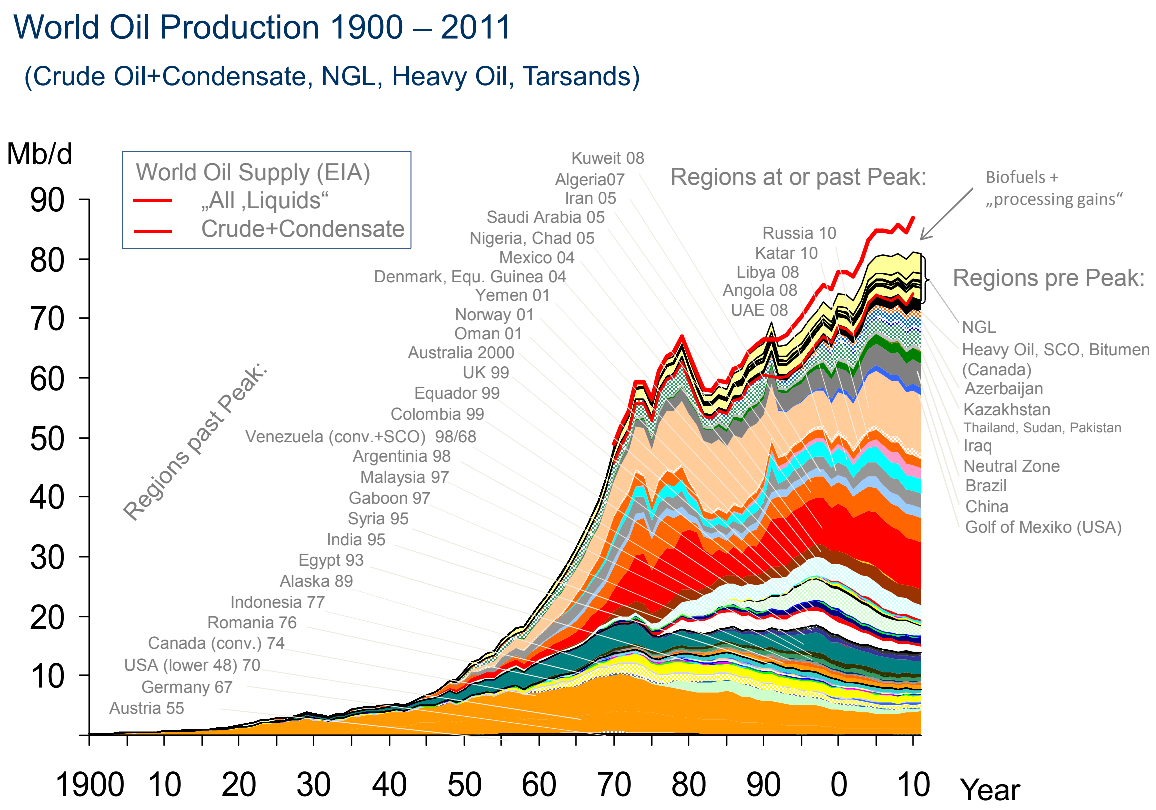
In contrast, world oil production still rose until about 2005 to a level of about 30 Gb per year. This general pattern of discoveries unavoidably must be mirrored by the production pattern. Even today, oil production is based on the contribution of the largest oil fields which are producing since decades and which were discovered more than 50 years ago. For instance the North Sea with about 60 Gb of oil recoverable still today is the largest oil bearing province being found within the last 50 years.

The typical production profile of an oil field rises fast in line with the development of new wells. However, the more wells are developed the faster the pressure declines and the more the oil-to-water ratio rises in favour of water production. For instance, in early years typically pure oil might be pumped while at the end of the operation time of an old oil field about 90 or more percent of the pumped fluid are water, reducing the individual production rate of that pump at least by 90 percent or even more. Therefore at a certain point in time these effects dominate the production profile: the field has passed its maximum and future production rates are declining the more oil is extracted and the more the pressure drops. This typical profile which holds for any individual oil field can for some time be interrupted by technological measures such as artificially increasing pressure by the injection of water or gas or by adding hot steam or chemical additives to reduce the viscosity of the oil. However, the general trend cannot be inverted or stopped for a longer time period. What holds for an individual field, also holds for a region with aggregated individual oil profiles. As soon as the cumulative production of already producing and declining fields no longer can be compensated or overcompensated by the fast development of enough large fields, the whole region passes its peak production. Fig. 2 shows the world oil production by summing up the individual contributions of all countries. These countries are ranked according to the year when they passed peak production. For instance, Austria or Germany passed peak production already in 1955 and 1967. The United States passed peak production in 1970 when Texas oil production passed its peak. Today the lower 48 states of USA produce at a level not having been seen since 1940.

After the jump of oil prices in 1973 and 1979 the development of frontier areas at that time became economic. The contribution predominantly of Alaska (light green area in the figure), North Sea (white areas in the figure), Siberia in Russia and North Africa together with the recovery of OPEC flows helped to increase total production even when production in the lower 48 states and in Canada was already in decline. However the annual growth rate declined from 7-8 percent in the pre-1970ies to 1-2 percent because first the declining production of countries past peak had to be compensated.

By that time the frontiers were pushed further into the deepwater which started around 1980 in Brazil and later on in the Gulf of Mexico. In 1999 UK passed its peak production in 2001 followed by Norway and 2004 by Mexico when the world's largest offshore field, Chantarell started to decline. New field developments first had to compensate for that decline before a net increase in production again became possible. Looking at fig. 2 it becomes obvious that the production extensions in Saudi Arabia (red area) and Russia (light brown area) overcompensated the decline of North America's and Europe's oil production. However in 2005, when Saudi Arabia peaked, even world wide production stagnated irrespective of steeply rising prices. It seems that only a few countries are still able to extend their production, among them Brazil, China and tar sand production in Canada and Venezuela. The figure distinguishes conventional oil and condensate production – which is assigned to individual countries – from natural gas liquids (NGL; yellow areas) production in OPEC and non-OPEC countries and from unconventional heavy oil and oil sands production in Canada (black area). The red line indicates the estimate of the US Energy Information Administration (EIA) including so called processing gains at refineries and biofuels.

Data are predominantly taken from the latest updates of International World Oil Production Data by the EIA which stopped its publication with 2010 data. Where available, more reliable data from national authorities (governments or state companies) are used. Partly – as in Saudi Arabia – these deviate from EIA data by 5 percent or even more. For instance, in 2010 EIA reported a production increase of 700 kb/day in Saudi Arabia whereas Aramco, the state company, reports constant production between 2009 and 2010 in its annual report.



Data Source: Austria, Germany, USA, Canada, Netherlands, UK, Norway, Denmark, Saudi Arabiea Brazli, Mexiko: Statistics of national governments/companies;
Other state: US-EIA, 2011 Data extrapolated from Jan-Sep or estimated for some Staates by LBST
Historical Data until 1970: IHS-Energy or US-EIA (USA); Analysis LBST Nov 2011

Fig. 2: Annual oil production from individual countries sorted by peak year

Between 2000 and 2005 oil price rose by about 50 percent, followed by a threefold rise between 2005 and 2008. The first oil price increase was followed by a production extension. However, even the oil price tripling between 2005 and July 2008 did not result in a similar production increase, instead, production remained almost flat. Even in Saudi Arabia production declined while domestic consumption still rose – a strong indication that Saudi Arabia passed its peak production.

As the analysis of present trends shows, it is very likely that world oil production is at its peak just now. Probably it will start to decline soon at an average rate of between 2 to 3 pecent. If this holds for some time, world oil production might be down by 50% around 2030.

The production profile until 2050 in line with that scenario is given in fig. 3Fig. The figure also includes production volumes for 2030 and 2035 from various IEA scenarios (WEO 2004,… WEO 2011) between 2004 and 2011. Each year the IEA results were downgraded following real developments. WEO 2011 for the first time included a slight decline of conventional oil production until 2035.

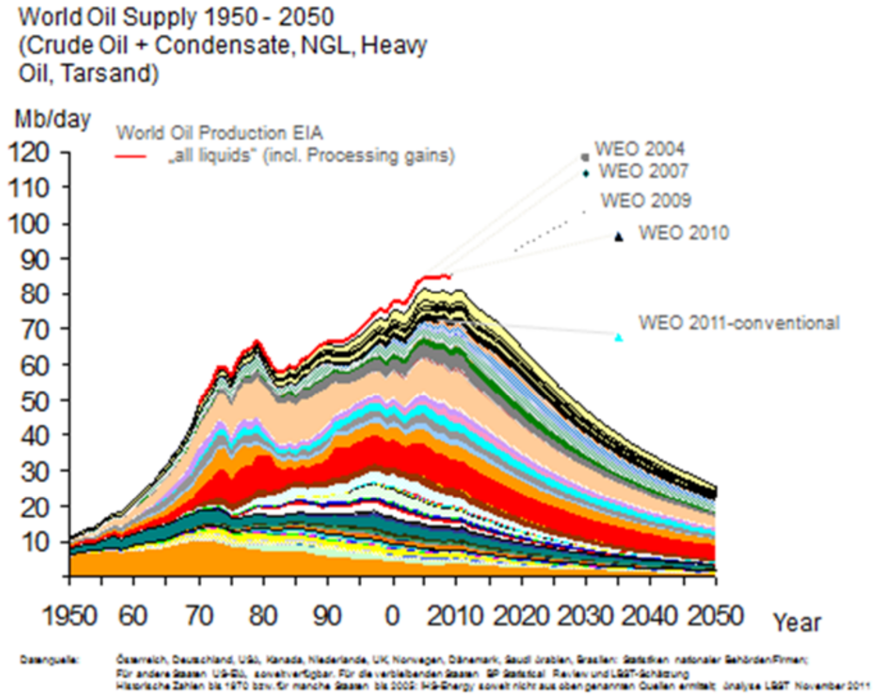


Fig. 3: Annual oil production and scenario 2050 (Zittel 2010); WEO scenario results for 2030 and 2035 are also shown

As already mentioned with regard to Saudi Arabia, at a time of declining world oil production the world will experience different reactions in oil producing countries on the one hand and oil consuming countries on the other: While oil producing countries gain adventages from high export prices they probably still develop domestic consumption by investing into more oil consuming acitivities. However, at the same time this reduces the quantities available for oil exports. Therefore oil will be scarce at world markets much faster than world production declines. It is not unlikely to assume that around 2030, at a world level, oil will vanish or might be traded at extraordinarily high prices. Possibly, besides small domestic quantities, oil consumption in Europe will have ceased or become a luxury product with very limited importance, at that time.

2.2 Natural Gas

The development of natural gas deposits started almost parallel to oil. Due to its close relation to oil – both are hydrocarbons originating from the chemical decomposition of algae and leaves which were deposited in sedimentary rocks hundred of million years ago – the geological understanding of gas and oil deposits is very similar. The history of discoveries also closely follows the history of oil discoveries, though with regional differences and a few years time lag. The history of cumulative discoveries of natural gas is given in figure 4. The steep rise of discoveries in 1971 is due to the discovery of the world's largest gas field, which is located offshore between Qatar and Iran. The part inside the borders of Qatar is called "The North Field". This field is responsible for the present boom of LNG projects in Qatar and provides the base for its huge estimated resources, though reserve data seem to be highly overstated.

The Northern part of the field is developed under the authority of Iran and is crucial for its clout as a gras producer. At present, companies develop this field for LNG production and export markets. Over the last 20 years cumulative discoveries flattened, allowing for a cautious extrapolation of future discoveries until about 2080. The uncertainty of this extrapolation is marked by the broken lines.

The red area in the figure indicates cumulative production. Presently about one third of the discovered gas is already consumed. Further extrapolations by a logistic growth model allow for a sketch of future production. Based on present data, it is very likely that between 2020 and 2030 world gas production passes peak production.

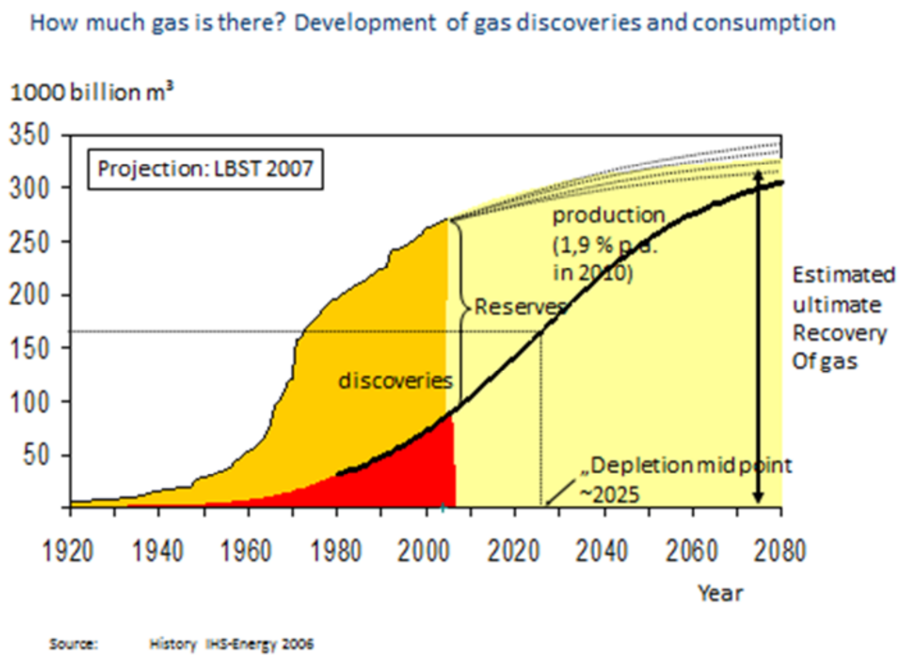


Fig. 4: Cumulative Gas discoveries, gas production and scenario 2080 (Zittel 2010)

The cumulative production profile from figure 4 is shown in more detail in figure 5. The historical production of individual countries is listed individually. Only three regions cover about 60 percent of annual production thus far: Russia with Kasakhstan and Turkmenistan (the lowest yellow area in the left part of the figure), USA (blue layer on top of the former Soviet Union's production) and Canada (dark green area on top of USA). The extrapolation of annual profiles indicates that around 2028 peak production might occur. In total about 220 trillion m³ will be consumed between 2011 and 2100 according to this scenario. The broken red line gives an alternative production scenario which is based on the assumption of a 30 percent increase in reserves. This would require that total discoveries until 2100 have to exceed at least 380 trillion m³. However, the effect would be to push the peak production only by 10 percent in size and about 5 to 10 years into the future.

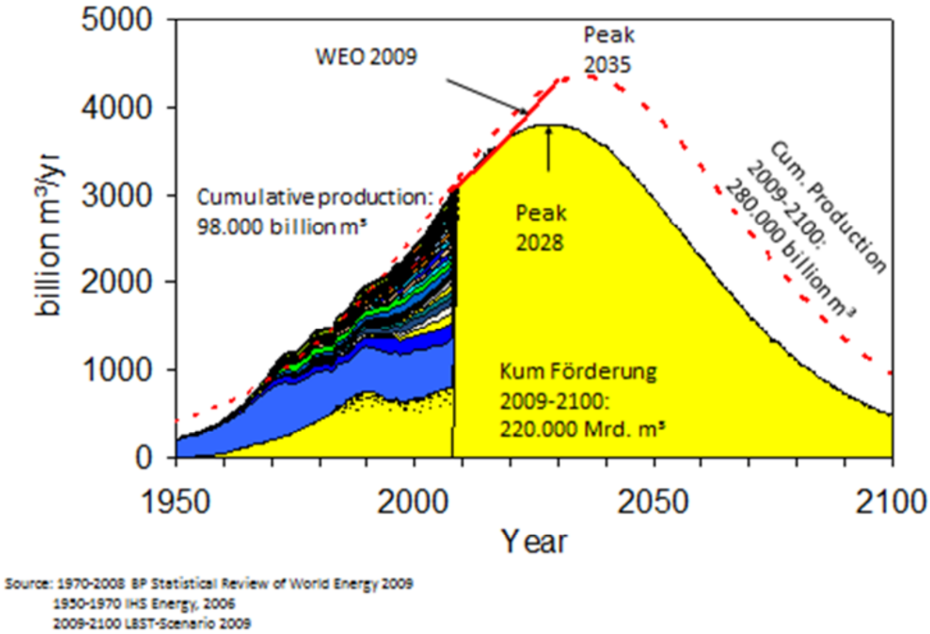


Fig. 5 : Annual gas discoveries and gas production (Zittel 2010)

Different to oil, natural gas is volatile at ambient conditions. Therefore pipelines are required to confine the gas, to store it and transport it to consumers. This needs huge investments with long lead times. In order to reduce financial risk, closed relations between suppliers and consumers developed. As a result, almost isolated regional gas markets evolved: The North American gas market with a pipeline network from Canada to Mexico is, or at least was almost completely separated from the European gas market with supply grids extending from Norway and UK to the North African gas fields and to Siberia or the Caspean Sea in the East.

Liquefaction of natural gas is possible and is used to exchange gas between different gas markets, predominantly from gas supply areas – either in the Caribbean region, in North Africa, Middle East or Indonesia and Australia – to consumers in North America, Europe or Asia. However the huge effort for liquefaction, transport and degasification in the consumer country up to now keeps the contribution of liquefied gas below ten percent of the global gas market.

Therefore independent gas markets developed, with some links between each other. Fig. 6 Fig shows the historical gas supply of OECD-Europe with a scenario extrapolation until 2030. Details of these calculations are discussed in Zittel (2010). Most European countries have already passed peak production, the Netherlands in 1976. Gas production in UK declined, almost parallel to oil production by about 50 percent. Norway still increased production in

2010, however a detailed field-by-field analysis as performed in Zittel (2010) and Soederbergh (2011) demonstrates that based on producing fields, fields under development and already discovered but not yet developed fields, gas production in Norway very likely will peak around 2015. In the figure peak production is assumed in 2017 at 120 billion m³. Therefore we know with great certainty that gas production in Europe already has peaked and probably will decline until 2030 by about 80 percent. This general trend as analysed in Zittel (2010) is also agreed in the scenario calculations by the International Energy Agency (IEA 2011) and the Association of European Gas Producers (Eurogas 2010), though they still differ in their assumptions of the rate of decline.

There is also a general agreement that natural gas imports must tremendously increase until 2020 and even more until 2030 in order to still increase the present European gas supply as calculated by the International Energy Agency (IEA 2008). The scenario calculation in figure 6 assumes that natural gas imports by pipeline from former Soviet Union countries remain constant until 2020 and decline thereafter by 3 percent annually. LNG imports are kept constant (dark green area) or expected to double over the next few years to a new constant supply twice the present amount (see white area marked with broken line).

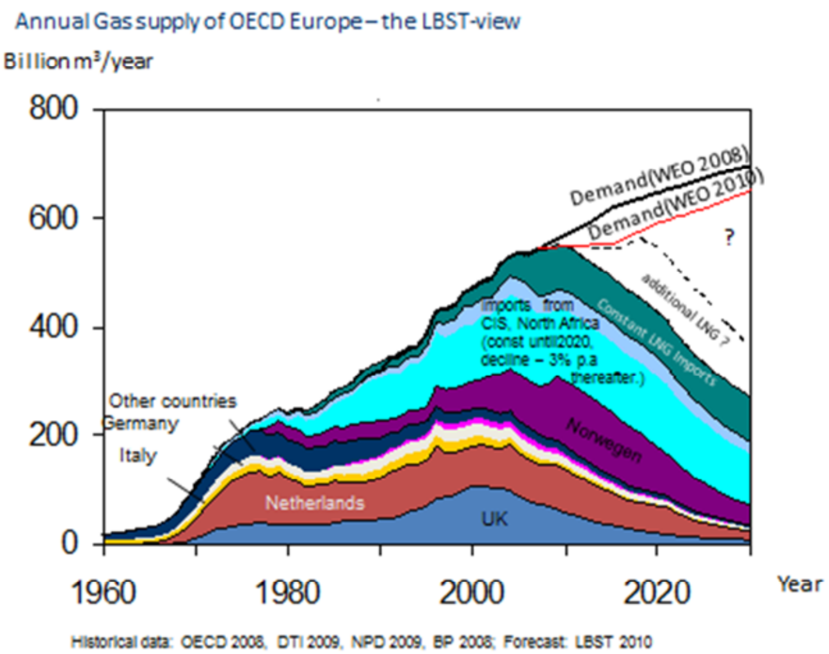


Fig. 6: Annual gas supply of OECD Europe (Zittel 2010)

By far the largest gas imports to Europe come from Russia. Therefore a detailed field-by-field analysis of Russian gas production is provided in figure 7. Production from the largest fields Urengoy, Medvezhye and Yamburg already peaked before 1990 when these fields contributed more than 90 percent to Russian gas supply. Their contribution declined to less than 50 percent in 2010. However the development of new fields, most important among them is Zapolyarnoye East of Urengoy, helped to keep production at an almost constant level with some fluctuations. Fields under control by Gazprom are indicated individually. The contribution from other private companies is only identified according to the total production of each company and a production scenario based on reserves of these companies. Future production of Gazprom is sketched by assuming individual production profiles of known but not yet developed fields according to published data on their planned production start. The scenario traces back to 2009. According to the experience of the last years, new field developments in almost all regions, but even more certain in Siberia and close to the polar circle are delayed by several years. Therefore the sketched production scenario until 2030 eventually might be too optimistic.

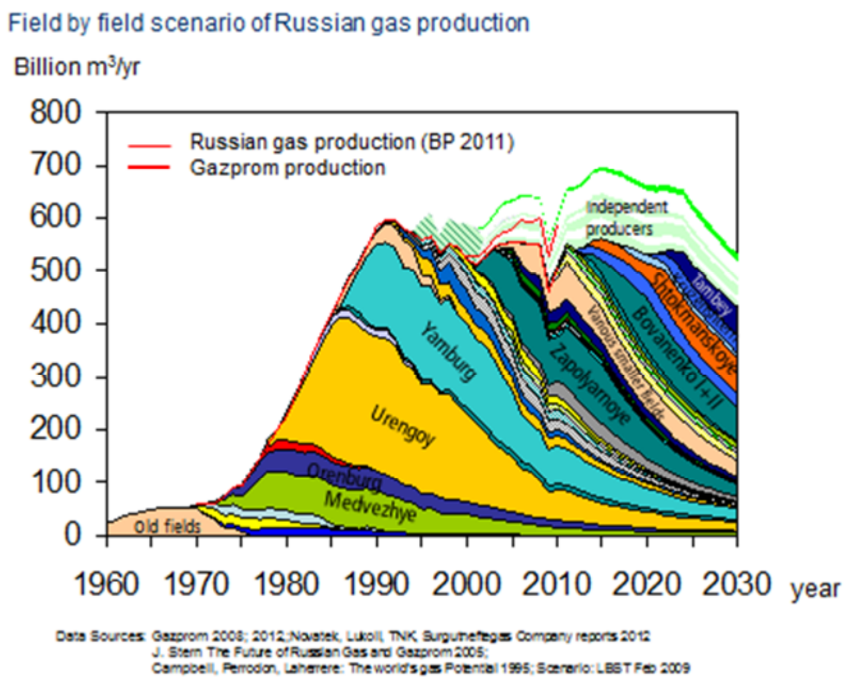


Fig. 7: Annual gas production of Russia (Zittel 2010) . Field by field data since 2009 are estimated; historical data are taken from company reports.

Keeping in mind rising domestic gas demand in Russia and new export lines to neighbouring countries in the Middle and Far East it seems very unlikely that in 2030 gas exports to Europe still can be at the present level. Most probably, gas consumption in Europe has to decline drastically, though partly this gap eventually could be filled by biogas or synthetic gas. However, before 2030 the potential of these alternatives will be very limited. These concerns are expressed in figure 6.

2.3 Coal

Conventional wisdom has it that global coal reserves are ample and supply restrictions due to scarcity must not be expected within the next several decades or even this century at all. This judgement usually is based on the consideration of the ratio of static reserves to production. However, analysing the data in a more differentiated manner reveals that partly this view is based on old data. Another aspect that is often overlooked concerns the dynamics of small but continuous changes. Their analysis allows to focus on specific trends which tend to dominate the dynamic behaviour and to estimate critical time scales on this basis.

Figure 8 shows the development of global proven coal reserves as published by the World Energy Conference (WEC 2010) and reproduced in the BP statistical Review of World Energy (BP 2011). In total, global coal reserves were downgraded by 50 percent over the last 20 years. The static reserve-to-production rate declined from 410 years in 1987 to 118 years in 2010.

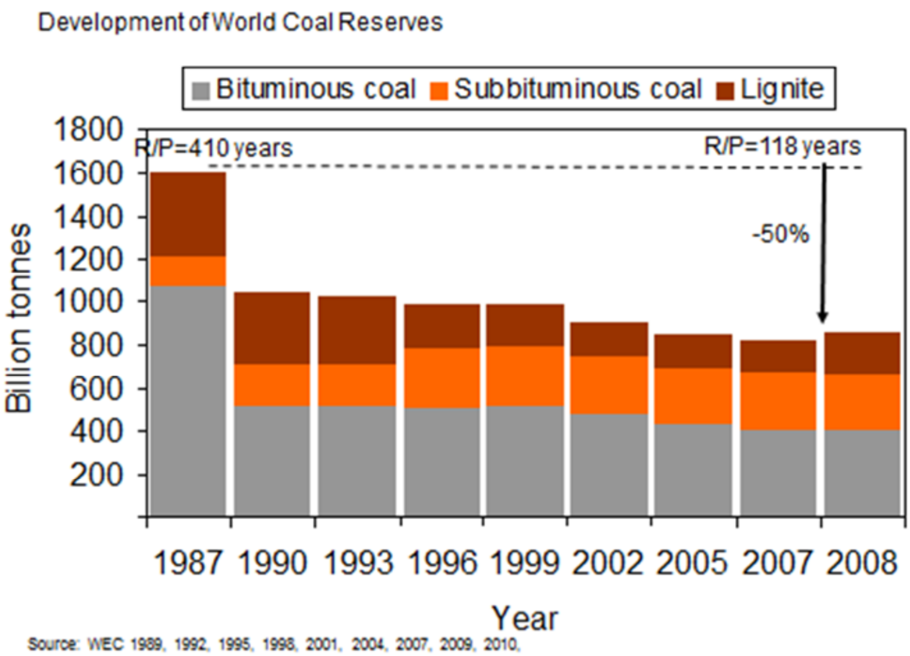


Fig. 8: Proven coal reserves (WEC 2010)

This empirical evidence does not support the often used theoretical argument that with rising prices uneconomic coal resources are transformed to economic coal reserves. At least at a global level over the last two decades this was not the case, though coal prices increased from 30 $ per ton in 1987 to around 120 $ per ton in 2011. At present, Mozambique is developed as a new – maybe the last –untouched huge coal bearing region (Ford 2011). However, development cost are extremely high there. Interestingly, it is Indian coal companies that are above all involved in these developments, which at home actually possess large coal reserves. However, due to their high ash content and poor quality it seems that Indian companies prefer to touch new resources abroad instead of developing proven domestic reserves (Zittel 2011). Neighbouring South Africa, among the 6 countries with largest coal reserves, for a long time was believed to rise exports and production for several decades or even longer. However, recent coal supply problems, export restrictions and reserve downgradings cast doubts on such scenarios. For instance, proven coal reserves are downgraded between 1990 and 2008 from more than 60 billion to about 33 billion tons of coal (WEC 2010). Consequently, the Reserve-to-production ratio declined from 350 years to about 120 years (see fig. 9 Fig).

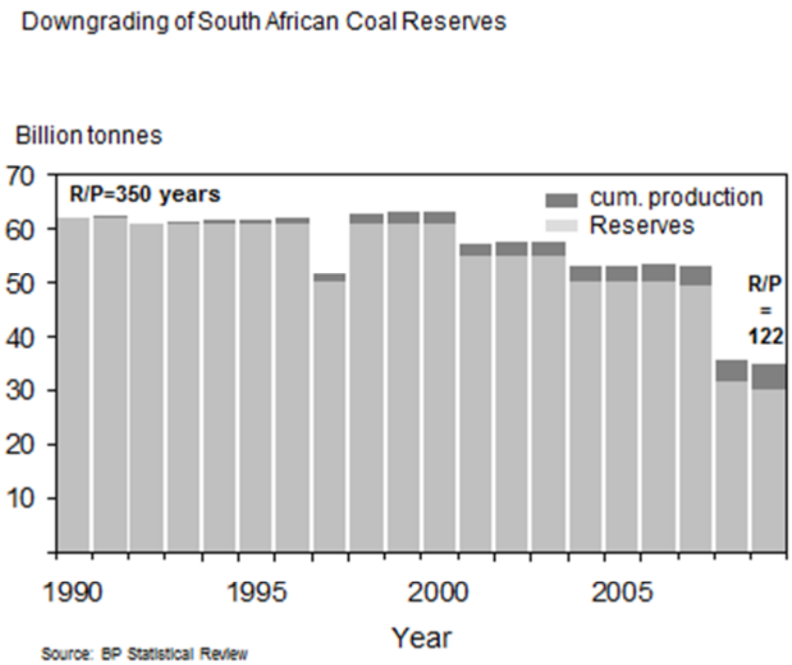


Fig. 9: Proven coal reserves of South Africa (BP 2011)

In addition, the labour productivity of South African coal mines continuously rose from about 1500 tonnes annualy per worker in 1987 to 5000 tonnes in 2003 when it started to decline, falling below 3500 tonnes in 2010 (SSA 2011).

Among the countries with the largest reserves – USA, China, Australia, Russia, India, South Africa contain about 80 percent of them – China and India are also among the largest importers of coal, the USA are a small net exporter and South Africas export rates almost stagnate. The USA, with more than 230 billion tonnes by far the largest reserve holder covering 27% of world reserves, is close to the production peak. At least, high quality coal from Appalachean and Illinois Basins have already passed peak production and are substituted by subbituminous coal which almost completely comes from Wyoming. It is very likely that within the next decade exports will cease, switching the country to a net importer of coal (Hook 2010).

Special attention merits China which is by far the world's largest coal producer, having produced about 3.2 billion tons of coal in 2010 which is 45 percent of world production. But the fast growth of Chinese demand required that the country, in 2003 still one of the largest exporters of coal, switched to a net import position. In 2010 is was the second largest coal importer close to Japan. The trend of Chinese coal imports and exports since 1998 is shown in figure 10.

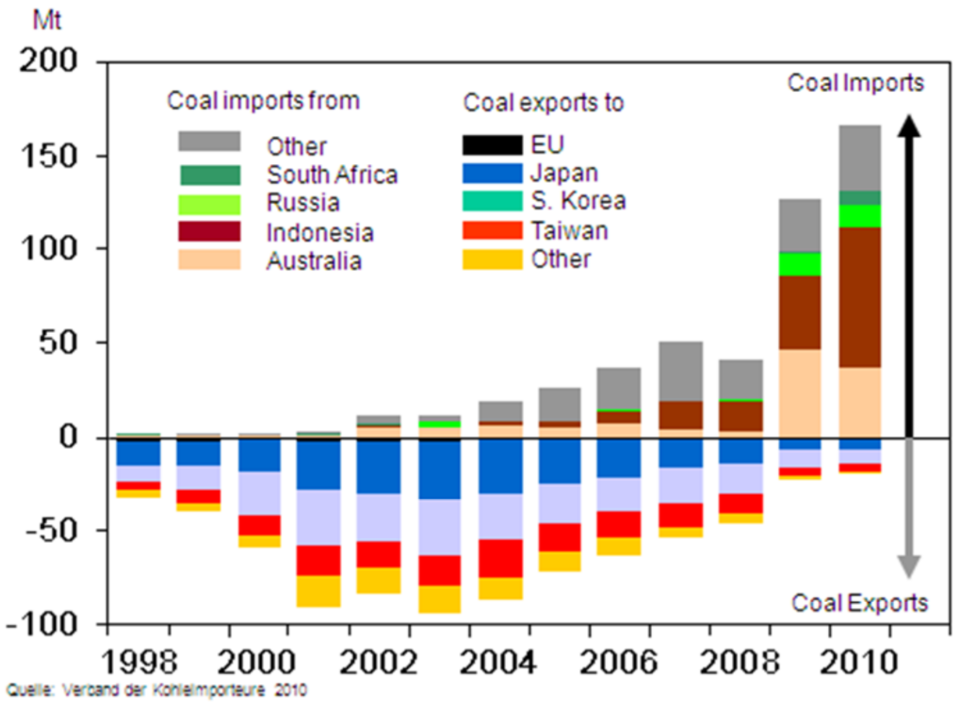


Fig. 10: Annual coal imports and exports of China (Zittel 2011)

The final figure 11 shows the time series of global coal imports and exports since 2001. The exported quantities almost doubled within the last decade. Most alarming is the trend of rising exports to China and India. This rising import demand at world market – still only about 10 percent of world coal production – is predominantly balanced by rising production in Indonesia and Australia. Most prominently, exports from Indonesia grew by a factor of 4 making it the world's largest exporter of thermal coal, in front of Australia, which is the largest exporter of coking coal.

However, Indonesia does not have large coal reserves or resources. It holds less than one percent of world coal reserves. It is very likely that coal production in Indonesia will peak before 2015 and then starts to decline. Combining available statistics, and scenario calculations from individual countries, it seems very likely that coal will get scarce in world markets over the next years – pushing coal prices even further – far before peak production occurs in ten to twenty years from now (Zittel 2010).

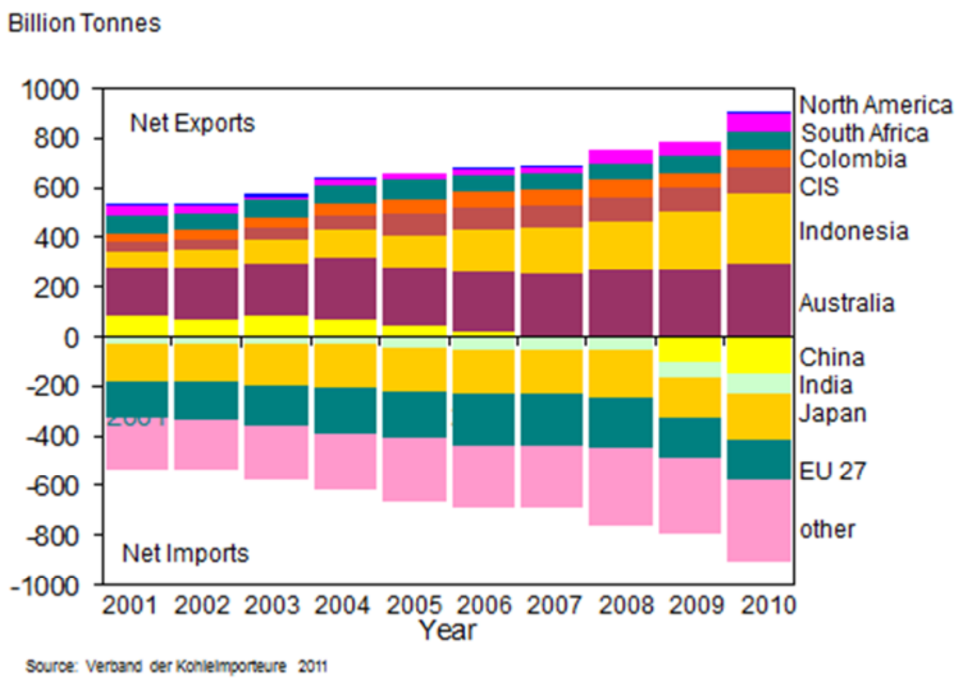


Fig. 11: Annual coal imports and exports at world markets (Zittel 2011)

2.4 Uranium

Many countries count nuclear energy as domestic energy without geopolitical risks though only few of them operate domestic uranium mines. Indeed, in countries like Germany, the USA and even France, domestic uranium mining once played an important role. Current US uranium production declined by about a factor of ten. In Germany as well as in France it ceased or is at a negligible level today. As with fossil fuel resources, most promising mines were developed first. Once these were exhausted, they had to be substituted by mines with less favourable conditions.

Figure 12 compares the development of so called “reasonably assured resources” (RAR) and “inferred resources” (IR) of uranium distinguishing various cost classes. Though these differentiated data suggest that they were created with a high level of accuracy, it must be emphasised that cost classes do not reflect real costs. They should rather be seen as a qualitative measure to distinguish proven reserves with high reliability (RAR of lowest cost class) from less reliable data. Finally, the inferred resources within highest cost class might have the status of a possible reserve which is far from being countable as proven. The left brown bars in the figure indicate cumulative production which is added to RAR in order to get the historical development of discovered resources. The growth of total resources since 1965 is predominantly due to the inclusion of new regions such as the former Soviet Union, which were excluded from earlier reports due to lack of data.

Restricting the analysis to those countries with long time records, it becomes obvious that discovered uranium resources (RAR + IR) declined below its largest figures in 1982.

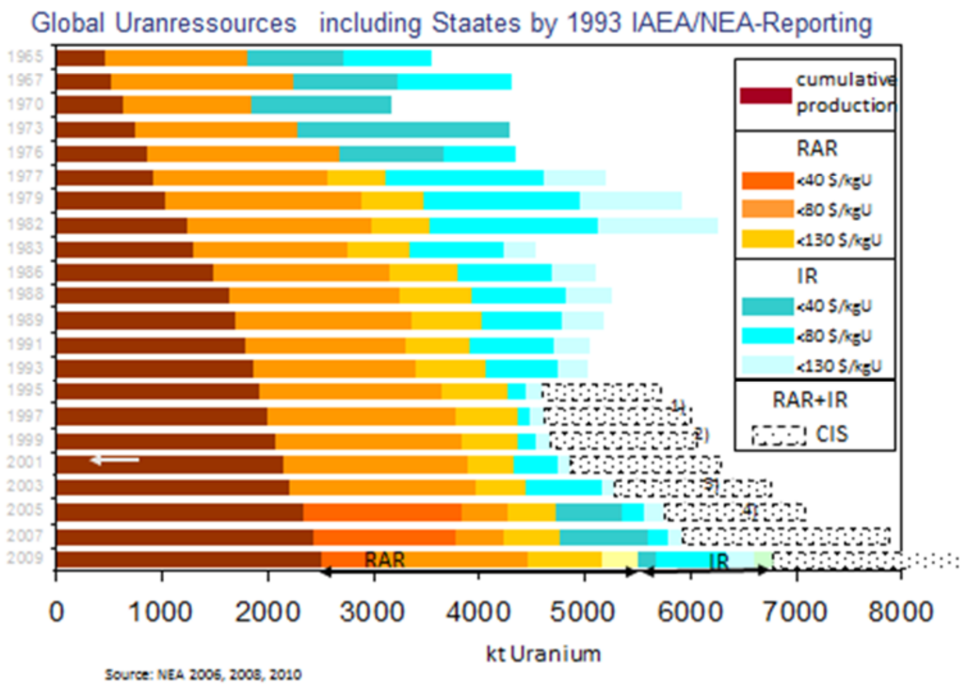


Fig. 12: Development of reasonably assured and inferred uranium resources between 1965 and 2007 (Zittel und Weindorf 2010)

Today, already produced uranium amounts as much as the remaining reasonably assured resources from any cost class, indicating that peak production might be close. A further disaggregation of these data for individual countries is performed in figure 13. Many countries have already exhausted their resources. Promising resources are only identified in Australia, Kazhakhstan and some African countries. However as pointed out in Zittel et Weindorf (2010) or Arnold et Zittel (2011), with the exception of Canada, only mines with very low ore grades are under development as the high grade mines are already developed or exhausted.

In addition, most of the new developments focus on deposits which were discovered several decades ago. After their discovery, they were kept untouched for the future as deposits with better performance were still available for development.

Therefore these new developments of deposits discovered long ago confirm that new discoveries are rare and that mining conditions are worsening.

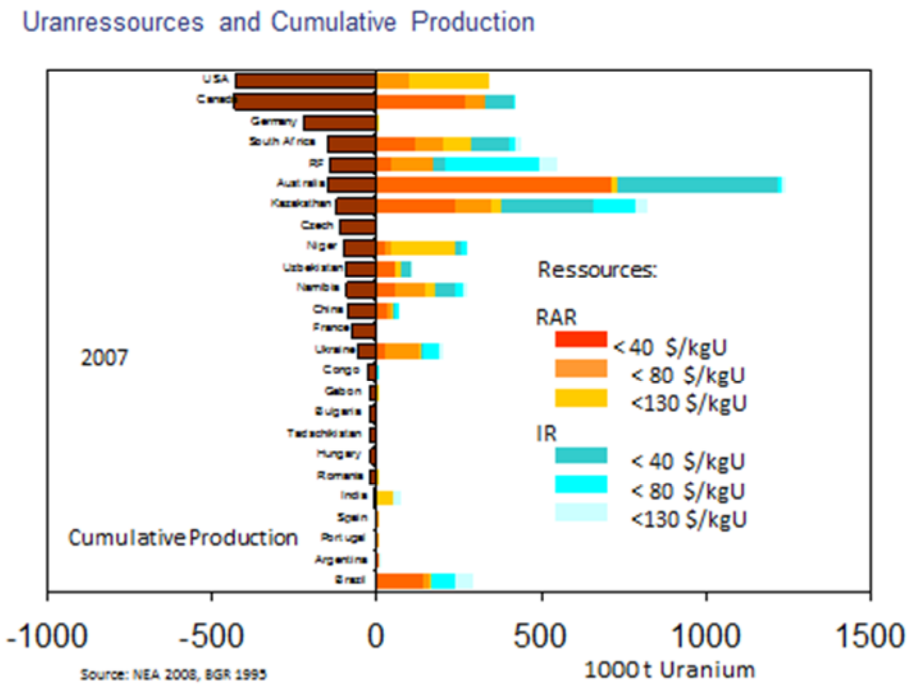


Fig. 13: Development of reasonably assured uranium resources between 1965 and 2007 (Zittel und Weindorf 2010)

A more detailed discussion of these aspects is given in the cited literature. Figure 14 gives a summary of world uranium production since 1950 with a sketch of simple scenarios for future production profiles if the reasonably assured resources of the specified cost class are converted into possible production volumes.

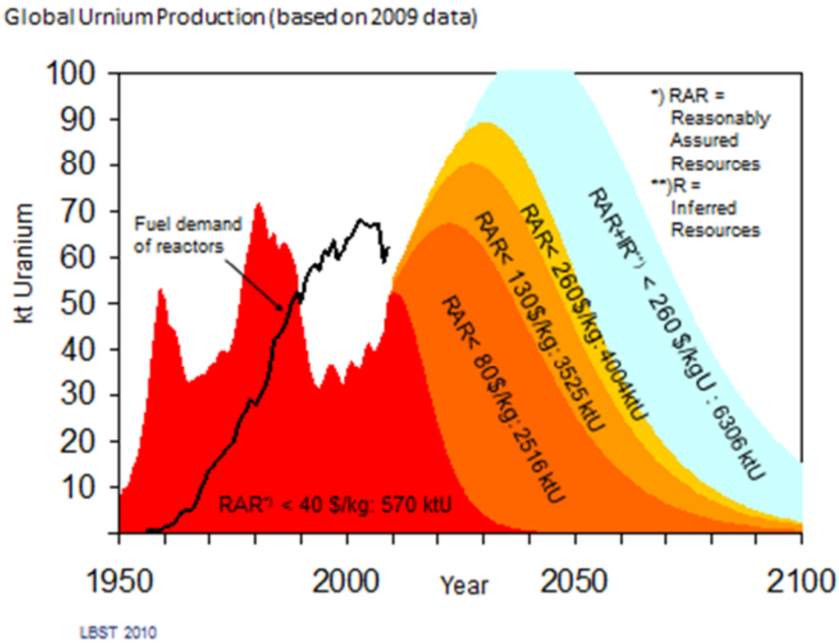


Fig. 14: Development of reasonably assured uranium resources between 1965 and 2007 (Zittel et Weindorf 2010)

Proven reserves – which usually are identified as RAR below 80$/kg – are not enough to feed the present uranium demand for several decades. Most probably production from this source will peak around 2020. Only if resources from higher cost classes can be converted into producible reserves in time, this peak can be shifted upward in volume and postponed. Therefore, existing uranium resources are not adequate to feed a rising uranium demand as foreseen by the IAEA (2009).

So called secondary resources of uranium (see figure 15) come predominantly from tailings, stocks and former nuclear weapons. The depletion of so called highly enriched uranium (HEU) as it is used for weapons is a major source of uranium supply for nuclear fuels, since disarmement agreements between USA and Russia opened these sources to energy markets. However, it is obvious that these resources can only contribute temporally and will be exhausted within a few years. The only remaining secondary resources after 2015 probably will be small amounts from reprocessing plants and plutonium containing mixed oxides (so called MOX fuel).

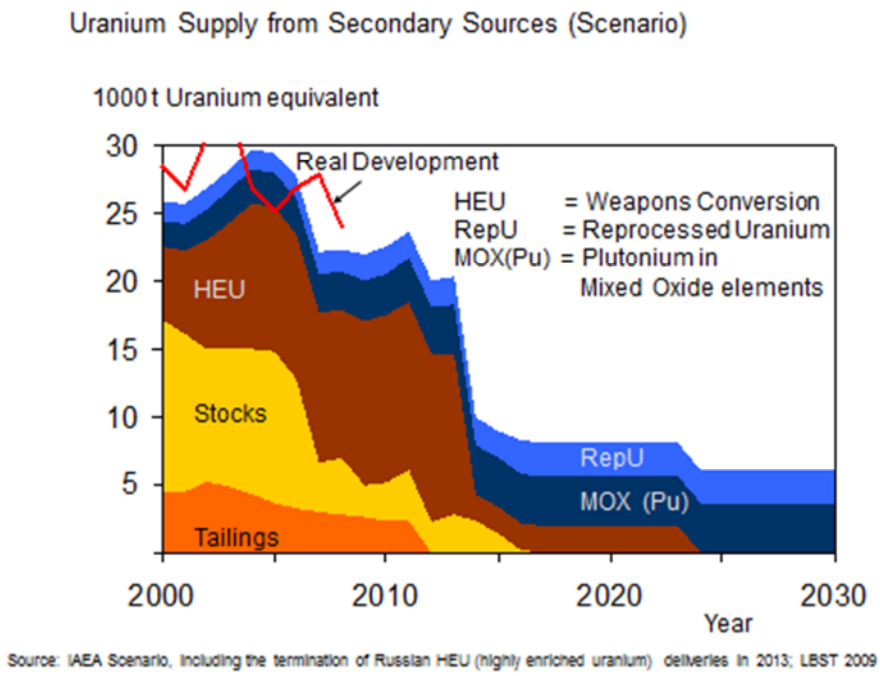


Fig. 15: Development of reasonably assured uranium resources between 1965 and 2007 (Zittel et Weindorf 2010)

3 Minerals and Key Metals Availability

3.1 General Aspects

3.1.1 Political Raw Materials Initiatives

Triggered by the strong economic growth of emerging economies over the last years, predominantly in China and India, the demand for raw materials grew at unprecedented rates, only partly interrupted by the economic crises in 2008 and the following downturn in 2009.

Almost each industry group or government has identified restricted access to key metals as a serious risk which needs to be analysed, monitored and minimized.

The United Nations have implemented an "International Panel for Sustainable Resource Management" addressing these challenges (UNEP 2010) which already published a report on metal stocks in society (UNEP 2010a).

In November 2008 the European Commission launched a new integrated strategy for raw materials (Com 2008), suggesting three pillars for the EU's political response to global resource scarcity:

- Better and undistorted access to raw materials on world markets
- Improving conditions for raw materials extraction within Europe
- Reducing the EU's consumption of raw materials by increasing resource efficiency and recycling.

Since then, an EU expert group has identified 14 raw materials seen as critical for EU high-tech and eco-industries and suggested that the European Unions global diplomacy should be geared up to ensure that companies gain easier access to them in the future.

Milestones of the activities at EU level are:

- November 2008: Presentation of a new integrated stategy for raw materials (Com 2008)
- May 2009: EU industry ministers call for an EU raw materials diplomacy and ask the Commission to draw a list of "critical" raw materials (UEdocs 2009)
- June 2009: EU and US file joint WTO complaint against China for restricting exports of industrial materials (Memo 2009)
- June 2010: Commission tables final report on list of critical raw materials (EC 2010)
- July 2010: EU environment ministers discuss Belgian EU Presidency initiative on Sustainable Materials Management (SMM) (WP 2010).

The next step will be to publish in 2011 a Communication on the implementation of the EU Raw Materials Initiative and strategies to ensure access to raw materials (Euractiv 2010).

One activity of this initiative is the implementation of the EU-Technology Platform on Sustainable Mineral Resources (ETPSMR 2010).

In October 2010 the German Ministry of the Economy published the blueprint of an integrated strategy for the security of sustainable raw materials supply of Germany with non-renewable mineral raw materials (BMWI 2010). Part of this German initiative – which is developed in close cooperation with the German industry – is the implementation of an Agency for Raw Materials at the German Agency for Geosiences and Raw Materials (DERA 2010).

The German Environmental Ministry and the Environmental Agency already started a project aimed to reduce resource dependency (Maress 2010).

In Austria, parliament asked the Ministry of the Economy to present an Austrian Raw Materials Plan (Österreichischer Rohstoffplan) within reasonable time, which should be seen as a master plan for future supply and use of raw materials and which should determine specific plans at regional and communal levels. This initiative is closely linked with the "raw materials initiative" at the European level (BMWFI 2011).

3.1.2 An endless discussion – depletion versus technological progress

The present energy and material fluxes of global society are economically, socially and ecologically unsustainable. This has serious implications for metal availability which are discussed in this chapter. The question of supply has two aspects: First, access to resources and, secondly, demand reduction through substitution with different materials, reduced specific demand and increased recycling rates. Though present developments in industrialised and emerging countries depend on still rising minerals consumption, their finite stocks might restrict and finally end supply growth rates as these minerals by definition are "non-renewable". The question is not if, but when this is like to happen. Indeed, it is not at all obvious, when resource extraction turns from being governed by a "buyers market" into one driven by a "sellers market". Various theories and empirical methods are established to identify and characterise this turning point. Yet none of them works with scientific accuracy.

This discussion is by no means only a scientific one: it is influenced by economic, psychological and lobbyist interests and forces. Besides "hard" facts, "soft" facts also play a role, and not a small one. Soft facts blow up any specific analysis to a combination of facts, scenarios and visions, where "educated guesses" based on empirical observations are important. Under such circumstances, good scientific practice amounts to sketch possible and probable future developments within corridors, the boundaries of which are set by best and worst cases. However, in many studies, scenarios are reduced to just one development that is – correctly or not – deemed probably, or to a bandwidth of possible developments much too small to include all or even the most probable, realistic options. This deplorable "state of the art" hampers seriously any discussion of resource depletion based on science.

Indeed, until today official authorities like USGS, IEA or EIA have huge problems in admitting that future economic growth might be endangered by shrinking future supplies of fossil fuels. Even more, though future metal availability is often addressed, its rising supply until scenarios end is never questioned. The fundamental axiom in the background seems to be that geological resource restrictions will never set limits to economic growth. If supply growth might be endangered, then man-made economic or political decisions, which are not adequate, or limited investments are the reason according to this axiom. This axiom at the same time precludes geological restrictions set by maturing resources to seriously influence access, to limit it or make it increasingly difficult.

The current way of discussing minerals depletion frequently comes down to a polarisation between two views (Tilton 2009):

- The first is known as the "fixed stock paradigm" and relies on physical measures of availability, suggesting that mining in the long run is inherently unsustainable due to its finiteness.
- The second, known as "opportunity cost paradigm", assesses resource availability by what society has to give up to produce another unit of a mineral commodity. While over time depletion tends to drive the opportunity cost of mineral production up, new technology and other forces can offset this upward pressure.

There are empirical and theoretical arguments supporting both views: Obviously, the fixed stock paradigm must be true as within the finite physical world a finite physical resource will be depleted some day. And obviously, also the opportunity cost paradigm must be true, as some time limited resources will be substituted by new materials and technologies and the demand for them will cease.

This distinction would not cause any problem if the consequences wouldn't be different:

- A „voluntary" decline of demand would be driven by opportunity costs of new technologies. Their economic advantages are preferred against rising supply costs of old technologies, depending on sufficient mineral supply. Such a transition would be driven by the phase-in of the new technologies in time, allowing for a smooth transition and rising economic activity.
- An "involuntary" decline of supply driven by geological resource depletion would be dominated by supply restrictions and rapidly rising prices. Due to a lack of adaptation measures, the economy could be disrupted, which in extreme cases could result in an economic crash. The transition to new substitutes – if possible – would not be driven by superior technology, but by scarcity.

Economists often argue with good arguments that the geological limits are far out of reach and therefore not relevant. Known reserves cover only a small part of the ultimate resources. The reserves increase over time by reserve growth and by new discoveries as new technologies and higher prices convert resources formerly either unknown or uneconomic into reserves. Very often this is sketched by a pyramid with most economic resources being small at the top of the pyramid and touched first. Rising prices and new technologies help to access lower parts of this pyramid which are assumed to offer much larger quantities than the easy to extract reservoirs at the top.

For instance, In historical times only copper veins with ore grades of 20, 30 or even more percent were mined. Once these high ore grades were exhausted, mining started to decline. Japan, e.g., faced a production peak in the late 17th Century with far reaching impacts on the Asian and European copper markets (Sakuda 2006). Great Britain faced its peak in the 19th century, when high quality veins were depleted. Also the Chilean copper mines faced a peak in production around 1900 when high ore grade mines were exhausted. However new technologies (flotation) in Chile, first applied there at El Teniente and Chuquicamata at around 1912, allowed to produce ores with 2,5 percent grade at a time when in the USA ore of 0,5 percent copper content already could be processed (Allosso 2007). These new technologies brought a revival. Today, Chile is the largest producer covering about 35 percent of world copper production.

But also the “fixed stock paradigm” may be defended with good reasons. Resources and even reserves differ over a wide range in their physical, technical and economic properties. These aspects are not well described with the usual reserve concept which only distinguishes between reserves and resources. Economic and technical aspects are implicitly covered by the splitting into proved, probable or economic reserves, or, alternatively, into measured, indicated and inferred resources.

Important aspects characterising ore accumulation are (Prior 2010):

- The ore grade of the resource and its size.
- Material (e.g. water use, cyanic or sulphuric acids) and energy requirements per quantity produced. These are strongly influenced by the basic mineral, the ore grade, the state of technology and the distance to infrastructure and markets.
- Labour productivity and multifactor productivity which provide a measure of the effectiveness of the mining process.
- Environmental side effects such as CO_2-emissions per output unit, waste rock removal, distance to villages and inhabitants which might be affected, land and water consumption which might come into conflict with competing uses.

These parameters vary from deposit to deposit and – more importantly – over time also within a given deposit. The ongoing depletion of an active deposit gradually shifts these parameters to the worse. Partly the rising impact of depletion is offset by technological progress. Therefore, in a combined view, a race takes place between technological progress and increasing productivity on the one hand and worsening mining conditions on the other. Rising prices help to shift the economics of mines to allow the development of more complex and smaller mines. But very often this is accompanied by a declining production rate as more complex conditions need larger efforts requiring longer development times.

The balance between mature mines with declining production rates and new mines or new parts of already producing mines with still rising production determines the regional and global production pattern, and whether regional or world production is rising or in decline.

In a very rough sketch the resulting mining pattern can be described by a bell shaped curve, where rising production volumes in the first half of the production history are characterised by low cost, high ore grades, shallow (open pit) mines, simple ores and low mining waste. The second half of production history with declining production volumes is characterised by high cost, low ore grades, deep mines, complex/refractory ores and more mining waste. The production peak occurs some time in between when new technologies systematically cannot compensate declining deposit quality any more. A qualitative sketch of this profile is given in figure 16 below (after Prior 2010).

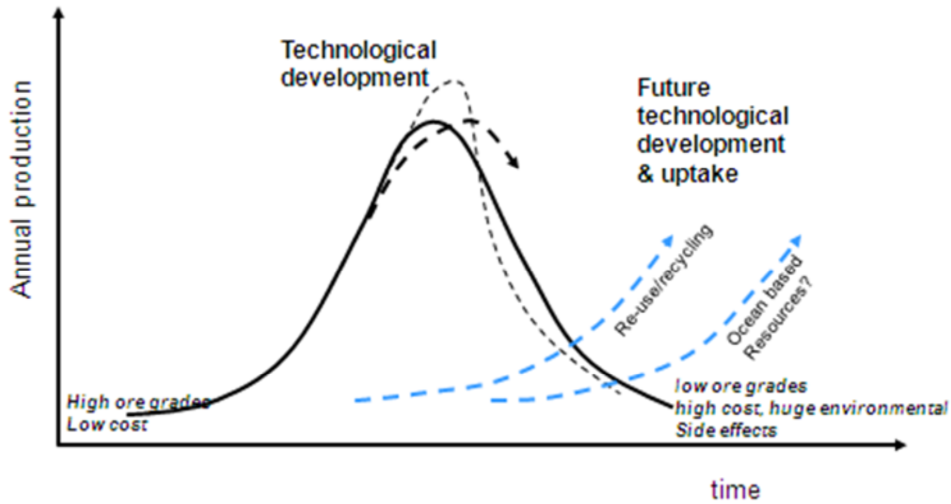


Fig. 16: Schematic profile of finite resource production, after Prior (2010)

Rising economic effort and technological development might shift the peak in height and time or might create a production plateau for some time, depending on details. Also the decline rate beyond peak might be influenced to some extend by prices and technology. But from a broader societal perspective the most important consequence of such efforts is to push the peak a bit higher in volume and further away into the future. Unavoidably this is followed by a steeper decline afterwards, at a time when these volumes would be needed precisely to soften the overall decline pattern.

But a second, even more important effect consists in a growing dependence on the commodity at an increasing cost and at a time when the long-term outlook already shows signals that warn of shrinking supplies. In such a case, necessary investments in adaptation measures – either by a diversification of commodities, an increase in recycling effort, material efficiency or simply by demand destruction – are delayed. Moreover the urgent need to adapt is further hidden to the public for some time: rising supply data are often used by stakeholders to discredit warnings of more cautious researchers. Often, they are driven by a quest for increased earnings, which depend on high demand even at high prices. Generally, these agents do not understand or care for the general challenge posed by such dynamics. Such a behaviour is well known and in the literature called “sunk cost effects” or “Concorde fallacy”. Its basic nature is analysed in a paper with the provocative titel: “Are humans less rational than lower animals?” (Arkes 1999).

Of course, the details of that pattern depend on many, partly not foreseeable parameters, also including economic incentives. However, the more detailed the production patterns are studied and understood, the less important become reserve data and theoretically defined resource data. A major reason for this fact consists in so called “above ground” factors that are influenced by the success story of “below ground” exploration. Fields and mines to be developed must be discovered first. After the early scanning of a region promising areas are explored in more detail. Companies rank their discovered assets according to their economic properties. Those with best properties are developed first. Therefore the discovery pattern of reserves is mirrored by the production pattern which implicitly includes their economic properties in a comprehensive way.

Such a detailed pattern analysis indicates the gradual shift to less optimal mining conditions. The details of this shift in time depend on the details of the specific topics: Are new technologies available in time? How fast is the decline of cheap minerals mining? How fast are environmental side effects increasing? How fast are the ore grades declining? How large are the lower grade resources which can be converted to reserves in time with then established technology? Are new discoveries probable? And what is their quality?

There is no doubt, that this gradual shift takes place almost from the beginning of mining history. Detailed historical trends – where available – tell us, how far we have progressed on this road. Within such an analysis, the geophysical stocks are important, whereas their aggregated number in terms of resource or reserve numbers is of minor interest. It is more the different quality and corresponding quantities of remaining resources with respect to production level and cumulative production that are decisive. These are not counted properly enough. The usual differentiation between reserves, which are economically and technologically recoverable at a given time, and resources is too crude. It is more the quality of these remaining resources that counts, their distance to markets or their individual size – just to mention some of these aspects.

Worldwide, reserve data are collected and published according to different rules, or with different accuracy. Therefore these numbers – which according to theory should reflect the true physical nature – must be used with caution. Sometimes they are exaggerated to suggest optimism on the side of shareholders or consumers, sometimes they are underestimated, so that governments hungry for royalities of a given country are not challenged. For instance, some countries or companies report exactly the same reserve data over many years, though actual production obviously depletes these reserves.

But despite such obvious flaws and mistakes, nevertheless, these data do exist and enter public debates. Huge deviations of reserve reporting between different minerals should be investigated. Though probably superposed by systematic misreporting, they can be used as first guidelines which materials to investigate in more depth. To conclude this discussion, time series and the analysis of developments are superior to data collection of just one year. For instance, figure 17 gives the development of base metal reserves in Canada between 1984 and 2003. These trends clearly indicate that reserves of copper, lead, nickel and zinc are almost depleted in Canada. This is reflected by the fact that the annual production of these metals has passed peak production already: copper in 1973, nickel around 1965, lead around 1980, zink in 1987 and silver in 1990 (NRCAN 2002).

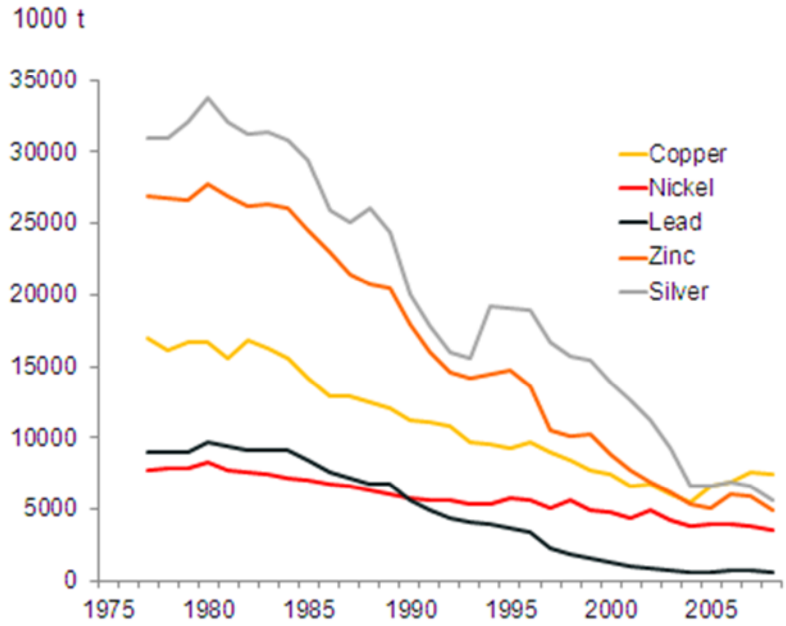


Fig. 17: Development of Canadian reserves of copper, lead, nickel, silver and zinc. Source: NRCAN (2008)

As already mentioned, environmental aspects also play a role. At a world level different environmental standards determine industrial practice and prices and therefore influence the production patterns, prioritising some countries over others. The more the high quality mines are depleted, the more these aspects enter the focus again.

A very dramatic example is the mining of rare earth oxides. Prior to 1995 the USA and Australia dominated the world production of rare earth oxides by far. However, the entrance of China to the world market reversed this situation. Today, China supplies about 97 percent of world demand for rare earth oxides (USGS 2002). This shift is closely linked to the environmental aspects of mining and upgrading of monazite, the most important source material which includes rare earth oxides. Due to its high thorium content it is radioactive and the mining and refining process poses huge challenges with regard to environmental restrictions. The market dominance of China is related to its low production cost. In a certain sense, the USA, Australia and other consumer countries have outsourced these problems to China. Resources and reserves still exist in their own countries. Thus, recent price spikes with the fear of a monopolized market dominated by China triggered the reactivation of projects in USA, Australia and other probable new projects elsewhere (Schüler 2011).

3.1.3 Specific energy demand and end use efficiencies

A systematic analysis of rising specific energy consumption over the depletion process has been given already decades ago by Charles Hall (Hall et al. 1986)

The most economic mining sites usually are those with the highest ore grades. Over time the ore grade declines. The extraction effort at first order is directly proportional to the processed volume throughput. Therefore it rises over time. Most measures to compensate for this effort by increasing productivity shift the work performed by human labour to mechanical or chemical (e.g. leaching processes) work. Therefore the lower the ore grade, the more energy must be spent to mine and refine the minerals. In practice the energy demand per volume of extracted metal increases more than linearly with throughput – apart from technological progresses in energy efficiency. Therefore an ever larger part of energy must be used to extract and refine the minerals. For instance, in Canada the share of energy used for mining in relation to the total final energy consumption increased from 25 percent in 1990 to 36 percent in 2008, or in absolute terms doubled from 14 Mtoe to 27 Mtoe. However the mine production in terms of tons declined for almost all materials, except oil and gas (analysis based on OECD 2010, NRCAN 2010). Oil production increased by 70 percent and gas production by 45percent. Even if rising hydrocarbon production would dominate energy demand, the more than proportional increase of energy consumption in the mining sector must be due to an increase of specific energy demand per production unit.

Figure 18 shows the specific energy demand per mined ton of metal, depending on the ore grade for the metals titanium, aluminium, iron ore, and copper. Though these data are taken from a historical reference (Global 2000, 1980), their general pattern still holds. The higher the ore grade, the less energy is needed for the extraction of the metal. Below one percent, for most ores, energy demand rises in a hyperbolic manner. The lowest amount of energy is needed for iron and copper ores, far below 20 kWh/kg at ore grades higher than 5-10 percent. However, below 1 percent, the energy demand rises easily by a factor of 4-5. By far the highest specific energy is needed for titanium extraction, about 130-150 kWh/kg, depending on the source rock material. At lower ore grades the specific demand also rises. However, the relative increase is smaller than for the ores mentioned before (iron, copper), as the rise starts already from a higher level.

The energy demand, of course, is also influenced by other parameters such as open cast or underground mining, the depth of mining, efforts of ore concentration, melting and milling etc. Later on this aspect is addressed by the example of copper mining.

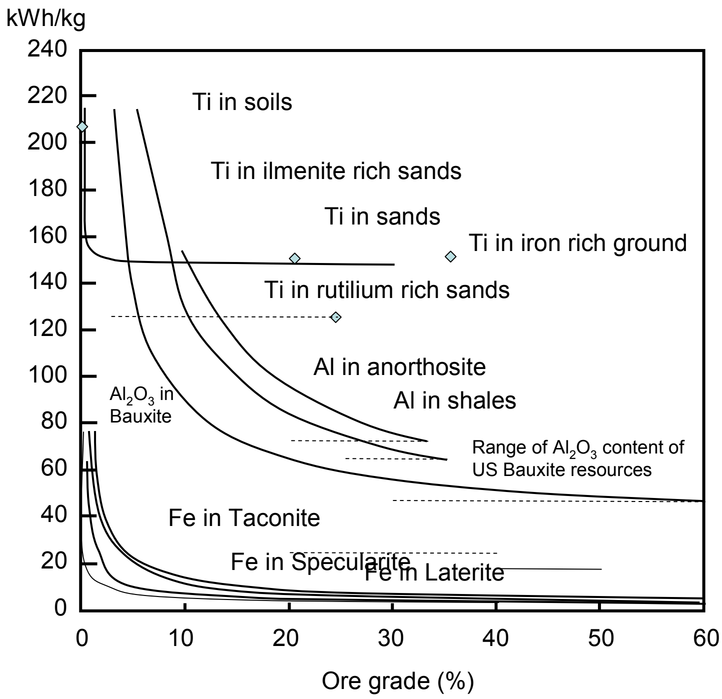


Fig. 18: Specific energy demand for the production metal, depending on the ore grade and the geological deposite type. (Source: Global 2000)

3.1.4 Recycling, efficiency improvements and demand reduction

Other market reactions on rising prices are demand reduction by substitution or demand reduction or destruction. But at the same time, the incentives for recycling waste materials (so called “urban mining”) also play an increasing role. These aspects are discussed in a later chapter.

At this point, a few remarks about efficiency improvement in technical applications is in place. Such improvements help to reduce the specific metal content of the application. However, in the past, efficiency improvements almost always were followed by the creation of new markets which enlarged production volumes and thus resulted in a rising total demand of metals. For instance, as the efficiency of the steam pump and later the steam engine increased, the demand for the base metals needed to construct them also increased. Among other aspects one prerequisite of the market introduction and penetration of low temperature (Proton-Exchange-Membran-) fuel cells was and still is the reduction of the required content of platin group metals (PGM). But once successful, this will result in an increased total demand of PGM metals. Therefore efficiency improvements alone, i.e. without restrictive measures (e.g. rising prices) are ineffective or even counteractive.

Besides many similarities there are basic differences between fossil energy fuels and metals: While energy minerals are degraded to a lower exergy level and completely dissipated into the air via combustion, physical depletion of metal veins does not result in the destruction of the resource that is sought. Metals are not lost at the end of the lifetime of the corresponding products and can be reused in other purposes by recycling them - at least in principle and partially. For instance, it is assumed that about 80% of marketed copper is still in use (Copper institute 2011). But nevertheless losses occur. Moreover, metals which are used in alloys are hard to recover. For instance, recycled iron ore contains a small amount of other composite metals which are not removed during recycling. Thus the level of copper in reprocessed iron increased to about 0.4 percent. It will rise further until no active and expensive counter measures are taken to remove it (Ayres 2003).

The use of exotic metals in mobile phones gives an even more dramatic example of that kind: the more efficient technologies are developed to reduce the specific demand for indium, europium, luthetium or other exotic metals, the more certain the recycling of these metals becomes increasingly difficult due to their low concentration in the disposed products (Kümmerer 2011).

3.1.5 Sociopolitical deficits

Discussing the consequences of mining and its preconditions under current circumstances, it must also be borne in mind that social concerns in the mining sector are always disregarded more or less due to the need of low cost. Generally, mining in countries with low environmental and social standards is cheaper than fulfilling high environmental and social standards during mining and refining as they exist in most developed consumer countries. This is the major reason why mineral resources still available in industrialised countries are mined only to a small amount, while the metal imports from other countries are preferred due to their superior economics.

Almost all political measures target the physical protection of further economic growth based on rising total material consumption. Beyond all measures to reduce specific demand, there is a general agreement that total demand is still expected to grow. This holds especially for new technologies with a rising dependence on rare and exotic metals. For instance, electric drive systems and etc. Current strategies include the increase of domestic mining or its revival.

One general aspect of the European Raw Materials Initiative is the aim to facilitate mining in Europe, to reopen or enhance mineral mining and so to reduce the dependence on imports. For most commodities the effect on import dependence of such strategies probably will be small. Yet from an environmental point of view this initiative can in any case be interpreted as a confirmation that resource depletion has entered a new phase. In this phase, outsourced environmental problems of mining return to the consumer country, grabbing the last domestic resources at home which formerly where excluded due to the economically favourable (but environmentally poor) conditions abroad.

Clearly, this implies further consequences:

- Since domestic high ore grade deposits are already exhausted in Europe, the revival of mining unavoidably results in higher environmental and energetic efforts, reducing the “net” benefit.

- The reopening of domestic mines might be seen as part of the “final resource game”. This game must be played at home and so consumers are directly confronted with the ensuing life-cycle-burden to make their choice: either to keep on with the appetite for resource consumption finally affecting many locations of extraction and refining or to reduce this dependence in favour of reduced environmental damage. Since also inside Europe burden and benefit of mining are not equally shared, unavoidably this will increase conflicts and protests among inhabitants. An early indicator of this challenge is the new “rally” for unconventional gas at home. Theoretically huge deposits of gas are dispersed over large areas. Thus, the development of these resources results in low specific benefits and huge surface impact in order to reach a remarkable contribution to energy supply in the range of a few percent. Finally consumers, who, at the same time, are producers, have to decide to which level they will accept the burden-benefit balance equation.

3.2 Survey of mineral production and selection of key metals

3.2.1 The origin of metals

The history of elements is closely linked to the history of the universe. During the first minutes after the big bang the lightest elements hydrogen and helium were created (Weinberg 1999). Hydrogen and to a small amount also helium directly condensed in the early phase of the universe when the energy density was still very high and the physical density of protons and neutrons large enough to allow for many collisions with corresponding fusion processes. Still about 90 percent of all matter are hydrogen atoms and another 9 percent are helium. More heavy elements and to a smaller amount additional helium are created by fusion processes in stars and red giants. Most heavy elements were created during supernova eruptions. Since the heavier elements are produced by collisions of light elements the abundance of heavy elements declines with the number of atoms in an exponential way since first the precursor elements had to be created. This scheme is further modified by the decay of heavy elements that results in a great number of neutrons and protons. In addition, clusters of very stable elements such as alpha-particles, carbon or silicon atoms alter that pattern further. Also iron creates a stable island. Finally, some of the stable heavy elements like barium and lead also increase. The scale of abundancies in relation to silicon is shown in figure 19.

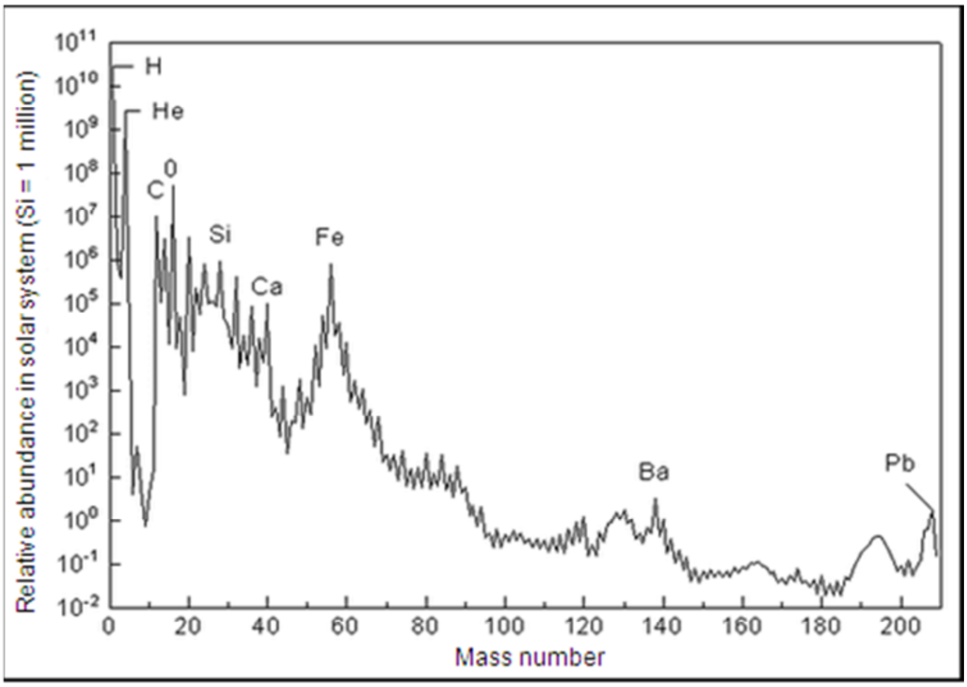


Fig. 19: Relative abundance of isotops in the solar system (Si = 10^6) (Source: http://nuclear-astrophysics.fzk.de/index.php?id=36)

This scheme also explains the origin of the elements on earth. However due to various mechanisms there are certain specificities: The earth is depleted of light elements which tended to escape. Heavy elements are concentrated due to gravity in the inner core of the earth which predominantly contains iron and nickel.

The chemical properties of the elements determine their ability to create complex compounds in the earth's crust. Only very rarely pure metals are deposited, mostly noble metals. Others tend to be confined in oxides, carbon oxides, sulfides or numerous other combinations. These affinities determine the average content of different rocks and geophysical layers. Therefore the typical composition differs in different rock layers.

Table 1 gives a survey of the abundance of metals in the upper continental crust of the earth and in sea water. The data for the concentration are taken from Henderson (2009), supplemented by more recent data from Gao (2010). The total resource is calculated based on the area of the total upper earth crust of 200 million km² size and a depth up to 1500 m. In average the rock density of this layer is 2.7 t/m³. The mass of the oceans is 1.35 * 10^{18}t (Henderson 2009), and reserve data are taken from USGS (2011).

Table 1:*Abundance of elements in the upper earth crust, in sea water and comparison with reported reserves (Tt= Teratonnes = 10^{12} tonnes; ppm = parts per million).*

Metal	**Abundance in upper earth crust ppm**	**Total resource Tt**	**Abundance in sea water ppm**	**Total resource Tt**	**Reserves Tt**
Oxygen	475,000	384,000	859,300	1,160,000	
Silicon	311,368	252,000	2.8	3.780	
Aluminum	81,500	66,000	0.00003	0.000004	0.028
Iron	39,180	31,700	0.00003	0.000004	0.087
Calcium	25,700	20,800	412	556	
Sodium	24,260	19,600	10,800	14,600	
Potassium	23,900	18,800	399	540	0.008
Magnesium	14,900	12,100	1,280	1,730	0.024
Titanium	3,800	3,100	0.0000065	0.000009	0.0007
Manganese	1,300	15,600	0.00002	0.000027	0.00063
Barium	628	508	0.015	0.02	0.00024
Zirkonium	193	156	0.0000015	0.000002	0.000056
Vanadium	97	78	0.002	0.0027	0.000014
Rubidium	82	66	0.12	0.16	
Chromium	73	59	0.0002	0.00027	0.00035
Zinc	67	54	0.00035	0.00047	0.00025
Cerium	63	50	0.0000007	0.0000009	<0.0001
Bor	17	14	4.5	6.1	
Lithium	41	33	0.18	0.24	0.000013

Metal	**Abundance in upper earth crust ppm**	**Total resource Tt**	**Abundance in sea water ppm**	**Total resource Tt**	**Reserves Tt**
Nickel	34	28	0.00048	0.00065	0.000076
Lanthan	31	25	0.0000056	0.0000076	<0.0001
Copper	28	23	0.00015	0.0002	0.00063
Neodymium	27	22	0.0000033	0.0000044	<0.0001
Yttrium	21	17	0.000017	0.000022	<0.0001
Gallium	17.5	14	0.0000012	0.0000016	?
Cobalt	17.3	14	0.0000012	0.0000016	0.000007
Lead	17	14	0.0000027	0.000004	0.00008
Scandium	14	11	0.0000007	0.0000009	
Niobium	12	0.97	0.000005	0.000007	0.000003
Thorium	10.5	0.85	0.00000002	0.000000027	0.000001
Praseodymium	7.1	5.7	0.0000007	0.00000095	<0.0001
Hafnium	5.3	4.3	0.0000034	0.0000046	<0.0001
Cesium	4.9	4	0.000306	0.00041	
Arsen	4.8	3.9	0.0012	0.0016	0.000001
Samarium	4.7	3.8	0.00000057	0.0000008	
Gadolinium	4	3.2	0.0000009	0.0000012	
Dysprosium	3.9	3.1	0.0000011	0.0000015	
Uranium	2.7	2.2	0.0032	0.004	0.000004
Erbium	2.3	1.9	0.0000012	0.0000016	

Metal	Abundance in upper earth crust ppm	Total resource Tt	Abundance in sea water ppm	Total resource Tt	Reserves Tt
Beryllium	2.1	1.7	0.00000021	0.00000028	
Tin	2.1	1.7	0.0000005	0.0000007	0.000005
Germanium	1.4	1.1	0.0000055	0.000007	
Iodine	1.4	1.1	0.058	0.078	0.000015
Wolfram	1.4	1.3	0.00001	0.000013	0.000003
Europium	1	0.8	0.00000017	0.00000023	
Tantalum	0.9	0.73	0.0000025	0.0000034	
Molybdenum	0.6	0.5	0.01	0.013	0.00001
Holmium	0.83	0.67	0.00000036	0.0000005	
Terbium	0.7	0.6	0.00000017	0.0000002	
Thallium	0.73	0.4	0.000013	0.000018	0.0000004
Luthetium	0.31	0.25	0.00000023	0.00000031	
Tamarium	0.3	0.24	0.0000002	0.00000027	
bismuth	0.2	0.19	0.00000003	0.00000004	0.0000003
Selenium	0.09	0.07	0.000155	0.00021	0.00000009
Antimony	0.075	0.06	0.0002	0.00027	0.0000018
Cadmium	0.06	0.05	0.00007	0.000095	0.00000066
Indium	0.056	0.045	0.00000001	0.000000013	
Silver	0.053	0.04	0.000002	0.000003	0.0000005
Mercury	0.05	0.04	0.00000014	0.0000002	0.00000007

Metal	Abundance in upper earth crust ppm	Total resource Tt	Abundance in sea water ppm	Total resource Tt	Reserves Tt
Tellurium	0.027	0.021	0.00000007	0,00000009	
Gold	0.0015	0.001	0.00000002	0.000000027	0.00000005
Palladium	0.00052	0.0004	0.00000006	0.00000008	<0.00000006
Platinum	0.0005	0.0004	0.00000005	0.00000007	<0.00000006
Ruthenium	0.00034	0.00027	0.005	0.0067	<0.00000006
Rhenium	0.000198	0.00016	0.0000078	0.00001	0.000000002
Osmium	0.000031	0.000025	0.000000002	0.0000000027	<0.00000006
Iridium	0.000022	0.000018	0.00000000013	0.0000000002	<0.00000006

For most minerals the concentration in sea water is smaller by at least more than three orders of magnitude than in the continental crust. Therefore the sometimes overly stressed proposal to extract uranium or other metals from sea water once land based reserves are depleted, must be questioned since the technical and financial effort rises with decreasing ore grade.

A different type of resouce might be metals contained in nuggets at the seafloor and in sea sediments which sometimes can contain very high concentrations of specific metals (e.g. black or white smokers at the sea sediments). Their economics might be different.

The comparison of reported reserves from USGS data with the elemental abundance in the earth upper crust also reveals that reserves for most elements cover only the millionth part or even less from the total geological resource. Metals with reported reserves coming closer to the geological limits are silver, gold, tin,copper, zinc and chromium. Their reported reserves in relation to the geological reserve cover the range between 1:10.000 and 1:200.000. These relations might provide a first very crude indicator for the scarcity of these metals.

At the other hand, the most abundant elements on earth besides hydrogen are oxygen, silicon, aluminum, iron, calcium, sodium, potassium and magnesium. Their concentration in the upper continental crust is far above one percent (see table 1).

3.2.2 The origin of metal deposits

Obviously the average ore grade of almost all minerals is far too low to allow commercial mining. This is only possible if the metals are enriched by some mechanism in natural ore deposits. Commercial mining usually is possible for ore grades above a so called cut-off grade which may range from about 0.05 percent ore content (e.g. urnanium) to about 30-50 percent (e.g. aluminium, chromium, manganese and iron). Of course, this limit depends on the economic value of the mineral, on technological progress and on the production of low grade metals as a by-product of high grade metal ores. For instance, commerical iron and bauxite ores contain ores with 50 or even more percent. On the other hand gold or uranium mines with ore grades down to 0.02 percent or even less are already mined.

The chemical nature of elements and their combinations determine their physical and chemical characteristics like affinity to individual minerals, temperature of melting, gasification and condensation. Therefore the geological and hydrothermal history of rocks influences the degradation or enrichment of minerals.

Though open questions still remain, geologists have learned to understand these principles to a large part (Pohl 2005). This in turn is a prerequisite for the understanding of deposit formation. Besides primary deposit formation which is due to volcanic action and movements of hot liquid plutonic rocks, secondary processes have a major influence on deposit formation. Especially hydrothermal processes play an important role. They help to enrich a deposit by circular movements of water, which when heated dissolves specific metals, transporting and accumulating them at locations where the temperature falls below the melting temperature of the specific metal ore. So called black smokers at the bottom of the atlantic ocean in between continental plates are an important example of that type of deposit formation which can be studied still today. Indeed the deposit creation mechanisms of black smokers helped to understand these processes over the last few decades.

But also the opposite mechanism of submerging continental plates is important: For instance, the Eastern riff of the Pacific plate submerges below the American plate and dives into deeper areas where the silicon rich rocks are heated and melted. Once metals were already enriched in the former sediment, the melted fluid flows to other locations and recondenses the specific metals when the temperature falls below the melting point. This process results in creating huge deposits. For instance, it is responsible for the large copper deposits along the Rocky Mountains and the Andes along the West coast of both Americas. More than 50 percent of world copper production comes from these deposits in Chile, Peru, Mexico, USA and Canada.

Though many more mechanisms of deposit creation exist, the resulting general concentration distribution might look as sketched in figures 20 and 21 which are reproduced from a presentation by Andre Diederen. Though the largest amount of minerals at earth is distributed at a very low concentration, only the small amounts which are located and concentrated in deposits with higher ore grade can be mined under commercial conditions and at reasonable production rates. By technological progress, the lower cut-off grade can be shifted somewhat to the lower side, but depending on the general ore distribution pattern (figures 20, 21) the available quantities might rise or diminish at lower concentrations.

Abundant metals follow the distribution pattern of figure 20 , while rare metal deposits have an ore grade distribution pattern similar to figure 21.

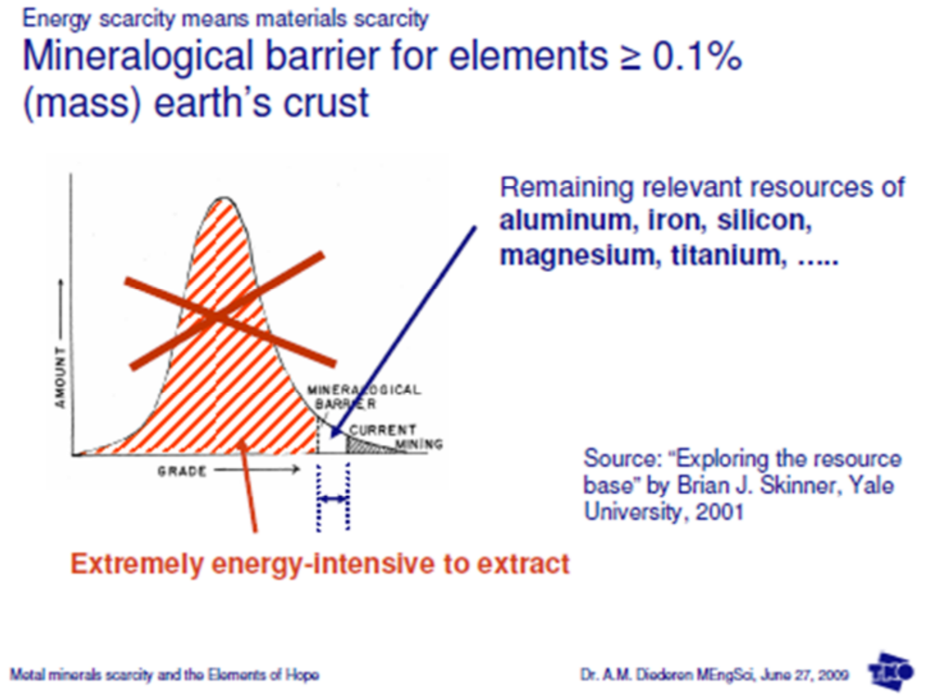


Fig. 20: Ore concentration in rocks and deposits. Only above a so called cut-off grade commercial mining is meaningful (Diederen 2010)

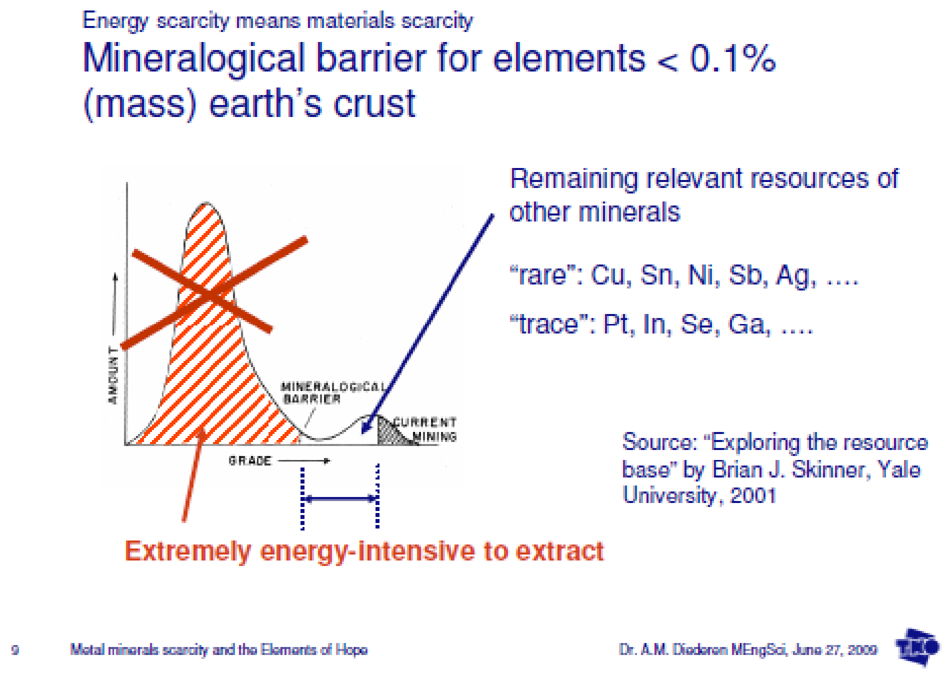
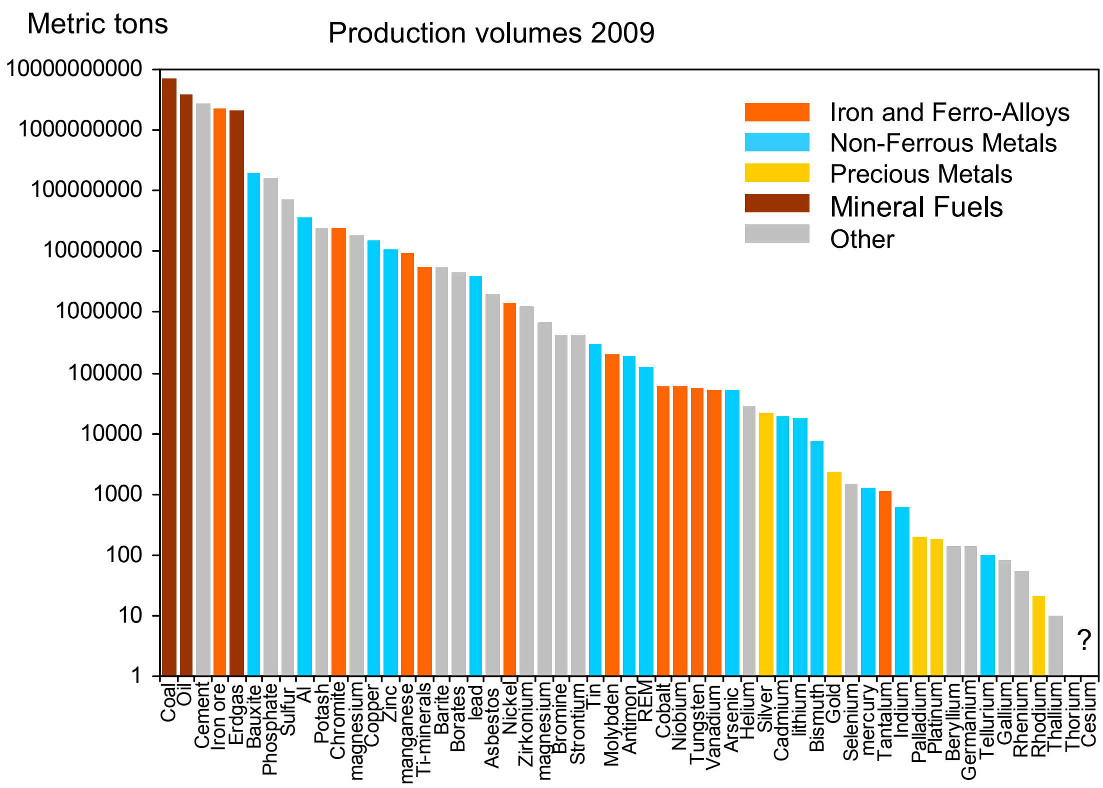


Fig. 21: Elements which are usually in very low concentration must enrich in deposits far above average concentration until mining becomes viable (Diederen 2010)

Depending on the affinity of metals and their chemical properties, some metals are concentrated in ores as a by-product. For instance, usually cadmium is recovered as by-product from zinc ores. In typical ores, zinc atoms are 200 to 400 times more abundant than cadmium atoms. There are many more affinities. Therefore, with high certainty some by-product minerals can be mined together with “leading”-minerals. Actually, reserve numbers of these metals are estimated by assuming that a fixed share of the ore of the leading metal contains the by-product.

3.2.3 Survey of minerals production and reserves

Figure 22 gives a summary of the annual production in 2009 for all energy minerals and for most metal ores. By far the largest quantities with more than 1 billion tons annually each are produced from coal, oil, cement, iron ore and natural gas. At least an order of magnitude smaller are the production rates of bauxite (aluminium), phosphate and sulphur. This scale ends up with precious metals and some other exotic metals which are mined in the range of kilograms per year instead of tons or million of tons.



Source: USGS 2010, BP 2010

Fig. 22: Ranking of production volumes of mined minerals

A first indicator of possible supply restrictions might be the regional concentration of mining. In figure 23 the share of the three largest producing countries of a commodity with respect to all other suppliers is collected. The three largest producers are coloured individually, all others are accumulated in the grey bars. The production of several important minerals like rare earth oxides, tellurium, gallium, niobium, antimony and vanadium is concentrated only in one or two countries. For instance, rare earth oxides are only mined in China (97%) and Australia, antimony is predominantly mined in China, niobium in Brazil and Canada.

A systematic ranking of the market concentration can be performed by using the so called Herfindahl-Hirschfeld-Index (HHI). It gives the ratio of the sum of the square of market share (in percent) of all producers. Therefore, HHI =10.000 is valid when only 1 producer exists while HHI < 1000 indicates that production is almost equally distributed between many producers. Originally it was used to get the market concentration at company level.

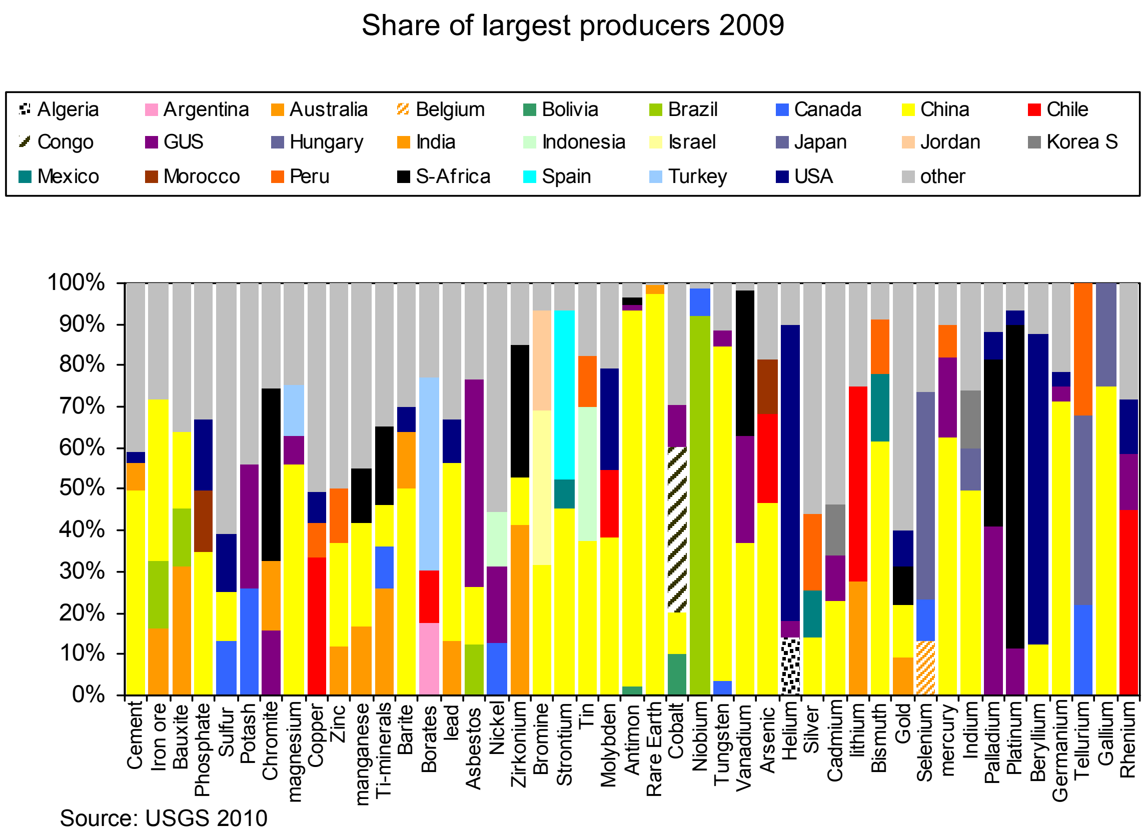


Fig. 23: Share for largest producers in percent of total production volumes in 2009. The grey bar marks the contribution from other producers

Another indicator might be the reserve-to-production ratio (R/P-ratio) which gives the time horizon, when the reported reserve would be exhausted if the production would remain at the constant level of the latest production period. An R/P-ration below 40 means that reserves would last for less than 40 years and vice versa. Figure 24 gives the R/P-ratio for the various metals.

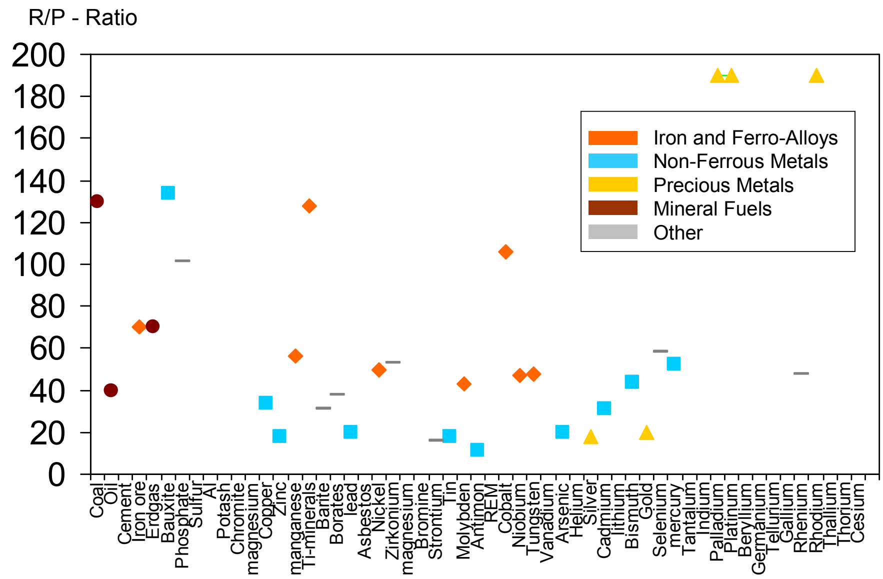


Fig. 24: Reserve-to-production ratio for all investigated minerals

Figure 25 shows the development of the R/P-ratio for bismuth, chromium and cobalt since 1995.

However, this measure needs to be analysed carefully if wrong conclusions are to be avoided. The R/P-ratio might be used as a first indicator to draw attention to an individual metal, which then has to be studied in more detail. For instance, the development of reserves, production and R/P-ratio give an additional insight. A further country-by-country assessment of these parameters very often shows that over time a concentration to few countries emerges, when the reserves easy to touch and close to consumer countries become exhausted.

A declining R/P-ratio only means that reserves are added slower than production rises, or that production declines at a lower rate than reserves. For instance, beyond peak production, the R/P-ratio very often rises with declining production once no new resources are converted into reserves. In that case the rising R/P-ratio hides the more important aspect of a situation where production has passed its peak.

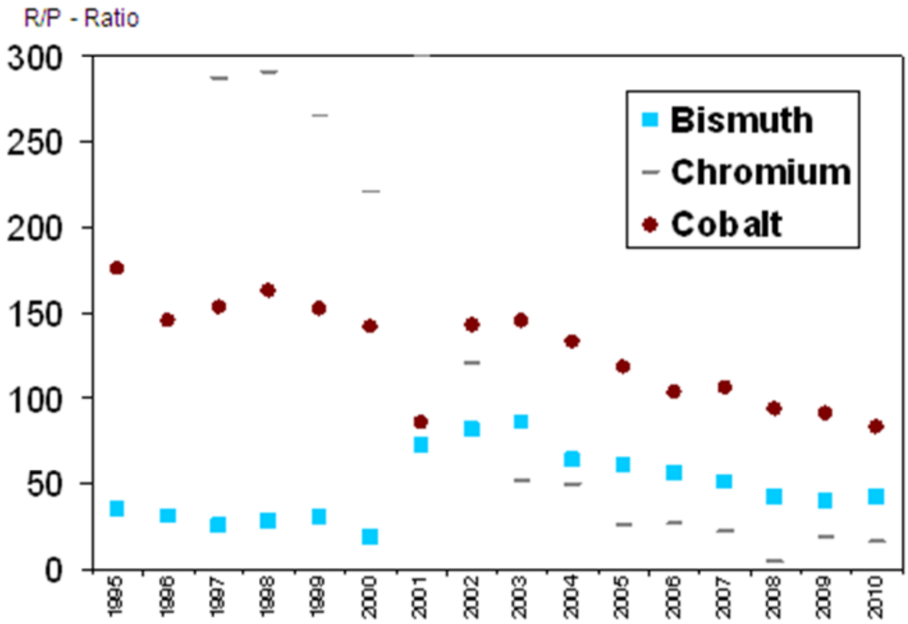


Fig. 25: Development of R/P-ratio for various metals

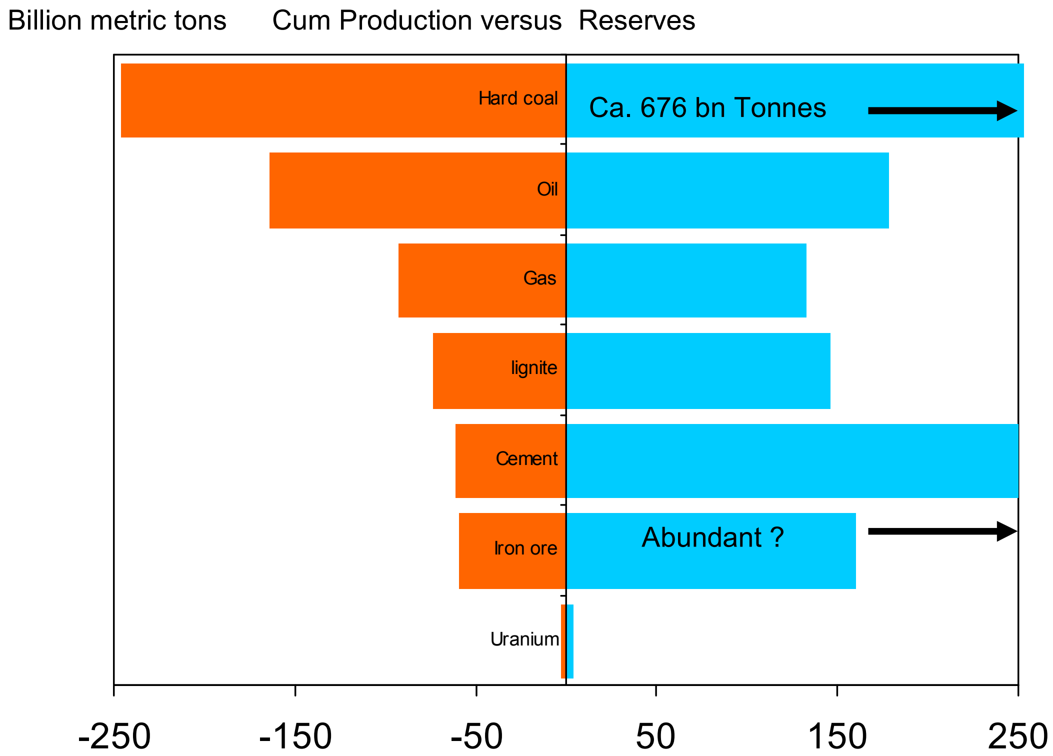
The R/P-ratio of cobalt halved within the last 15 years. A closer look to the data shows that reserves more than doubled over that period, but the demand increased four times. In 2010 the R/P-ratio of Cobalt reserves is still close to 100 years, indicating that reserves are still ample. However, when present trends continue for another two or three decades, this statement wouldn't hold any longer.

The R/P-ratio of bismuth tripled with respect to the year 2000 in line with the reserve data. But this increase is completely due to reserve revisions in 2001 when China's reserves were increased by a factor of ten. Adapting prior data to that rise reveals the general trend of declining R/P-ratio over the whole period.

The third example is chromium. The reported reserves declined by more than a factor of ten, reducing the R/P-ratio almost by the factor twenty. This decline of reported reserves is almost completely due to a downward revision of reserves in South Africa from 3.1 billion tons in 1995 to 130 million tons in 2009.

Further insight in resource restrictions might be gained when besides the reserves or the R/P-ratio also the total production history is included. A rough rule of thumb says, when the cumulative production exceeds the remaining reserves, this might be an indicator of imminent peak production. However, in addition, more aspects of exploitation trends need to be analysed: First the annual production profile and the historical concentration of the production and reserves to specific countries. A full analysis is out of the scope of this report. So the following figures only give a fast comprehensive survey of these data for most metals. The successive chapter presents a more detailed analysis for one metal, copper.

Figures 2 to 30 show cumulative production and reported reserves in total volumes, starting with the largest quantities. The cumulative production is counted with negative values (red bars), reported reserves are shown at the right side (blue bars).



Source: USGS 2010, BP 2010, LBST 2010

Fig. 26: Cumulative (Cum) production and reserves of mined minerals (cumulative production of iron ore is counted since 1900).

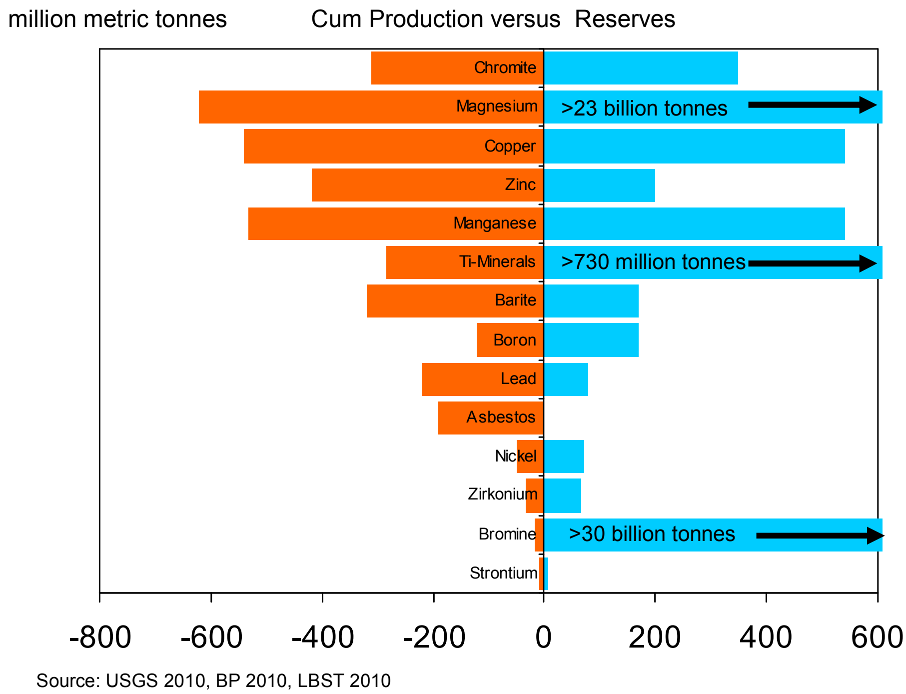


Fig. 27: Cum production since 1900 and reserves of mined minerals

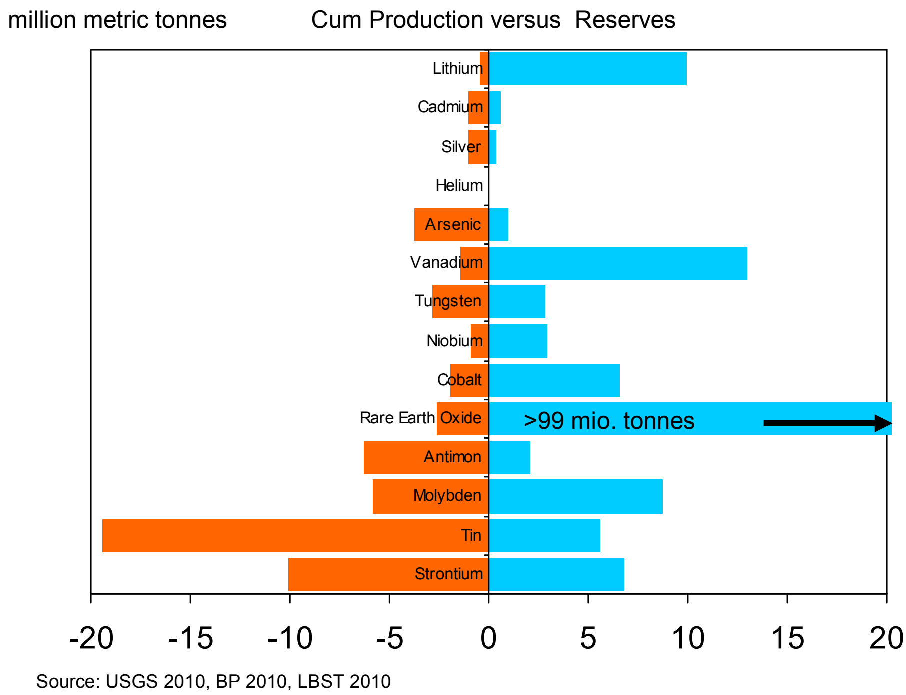


Fig. 28: Cum. Production since 1900 and reserves of mined minerals

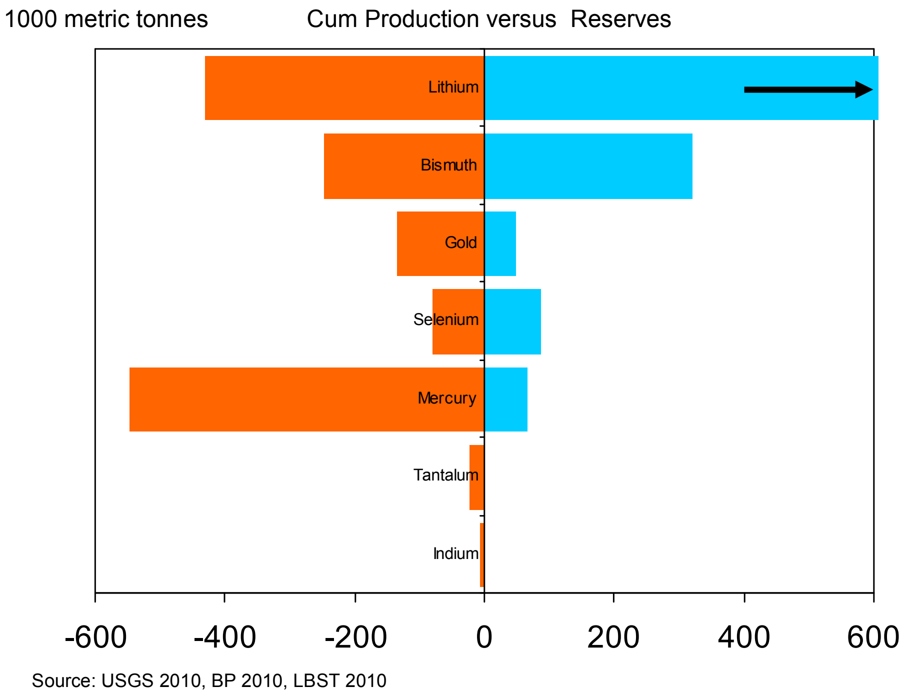


Fig. 29: Cum production since 1900 and reserves of mined minerals

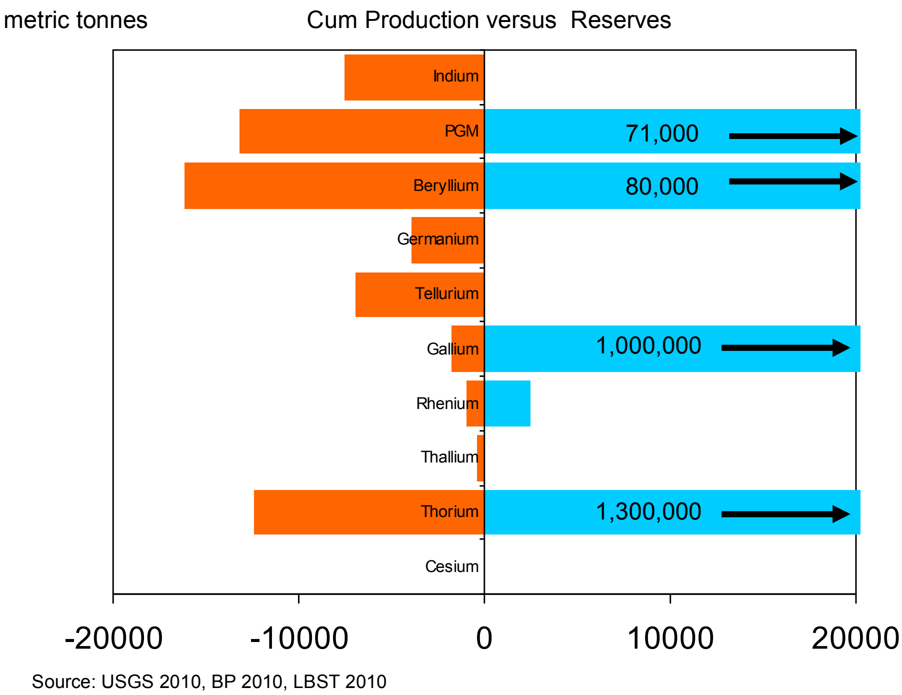


Fig. 30: Cum production since 1900 and reserves of mined minerals

3.2.4 Possible production profiles compatible with reported reserves

Figures 31 to 35 show the historical production of individual metals. These are extrapolated trends with a bell shaped production profile which closely matches the actual production rate and is compatible with the reported reserves until about 2060. Though it is obvious that reserve data are of poor quality and future production rates are not known, these scenarios give a sketch of future developments. At least they can be used to set some warnings in relation to individual metals which should merit higher attention in the frame of further investigations.

For instance, according to these data it seems that antimony, asbestos, arsenic, gold, mercury and strontium already have passed their production peak.

Cadmium, chromium, copper, lead, nickel, silver, tin and zinc seem to be close to or at peak production.

Bismuth, boron, germanium, magnesium, manganese, molybdenum, niobium, tungsten and zirconium might reach peak within the next two decades.

Bauxite, beryllium, cobalt, gallium, iron ore, lithium, platin group metals, rare earth oxides and vanadium might not reach peak production within the next few decades.

These statements give a first ranking. Wrong reserve reporting on the one hand and the effect of economic, technical and environmental restrictions on the other can alter this ranking considerably. But nevertheless, the cautious use of the metals in the first two groups is highly recommended in any case.

With the knowledge from table 1 magnesium should be excluded from this group as its natural abundance far above 1 percent does not indicate a global scarcity. Its distribution frequency is rather of the type of figure 20. However, rising prices as a consequence of the depletion of most promising deposits are possible.

From that analysis is seems that lithium, platin group metals (PGM), rare earth oxides (REO) and Vanadium are abundant at least for the next several decades. But for a detailed assessment further parameters concerning mining structure, infrastructure development etc. must be analysed which are not yet addressed in this survey.

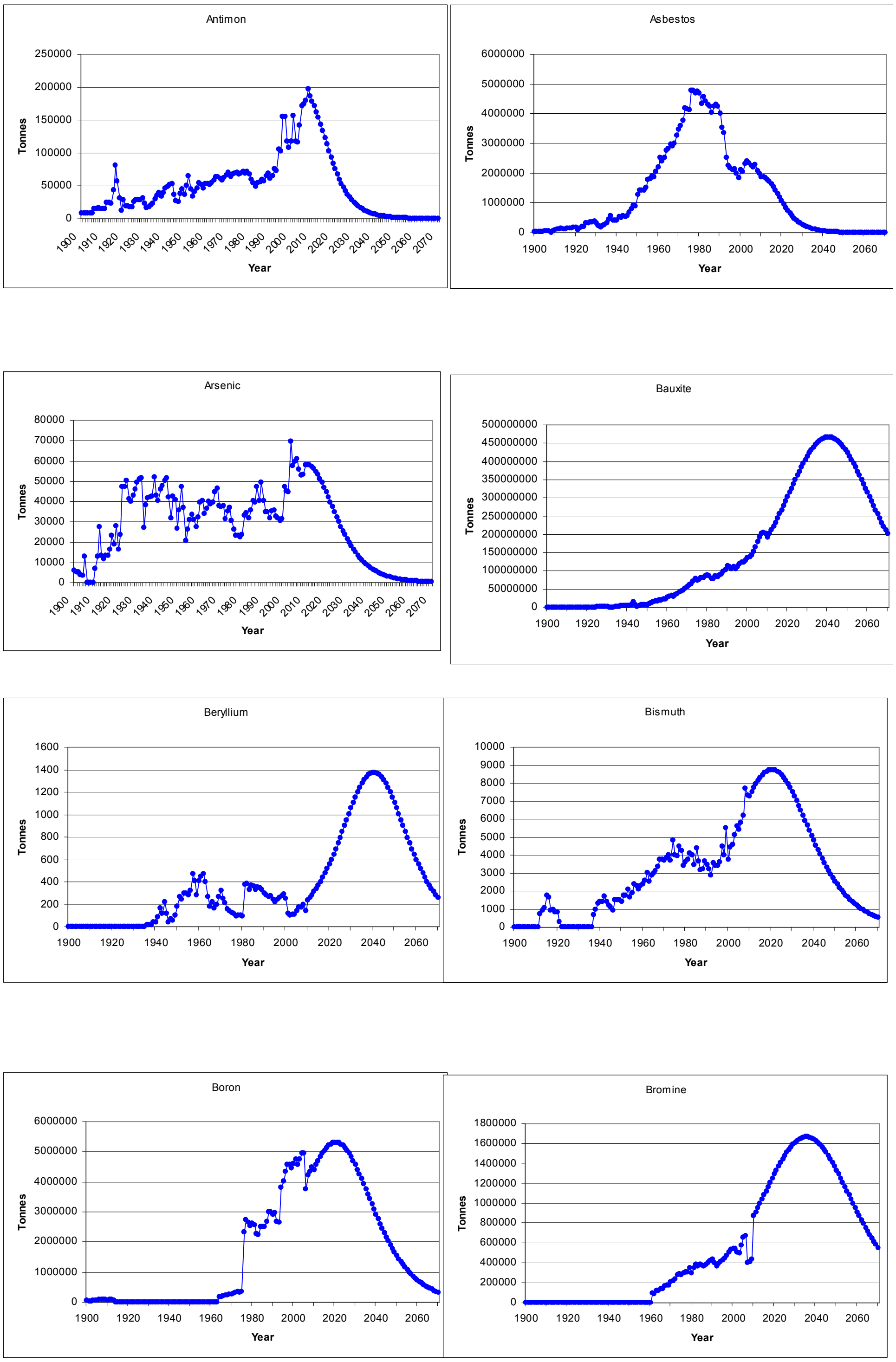


Fig. 31: Possible production profiles based on USGS reserves for antimon, asbestos, arsenic, bauxite, beryllium, bismuth, boron and bromium

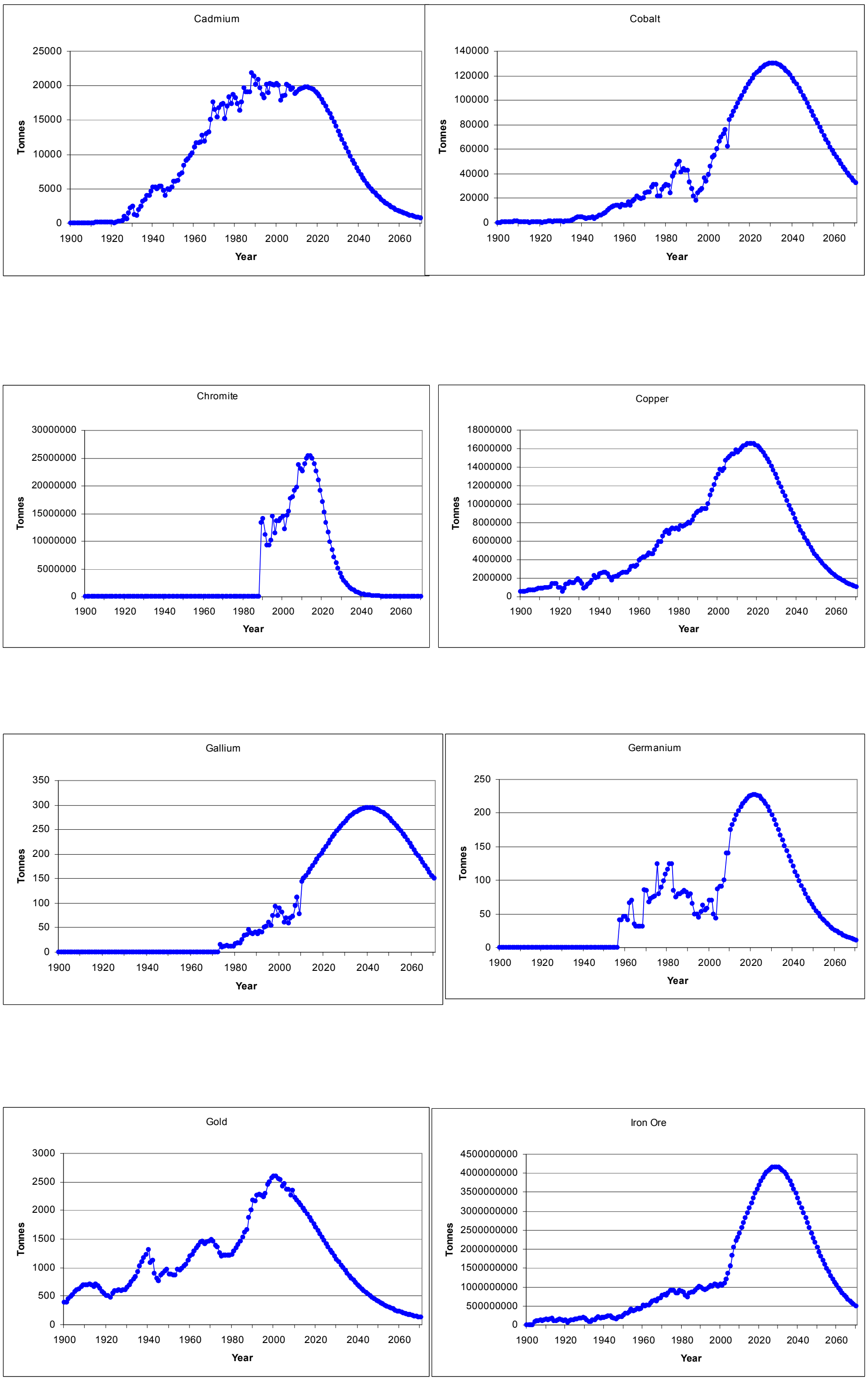


Fig. 32: Possible production profiles based on USGS reserves for cadmium, cobalt, chromium, copper, gallium, germanium, gold and iron ore

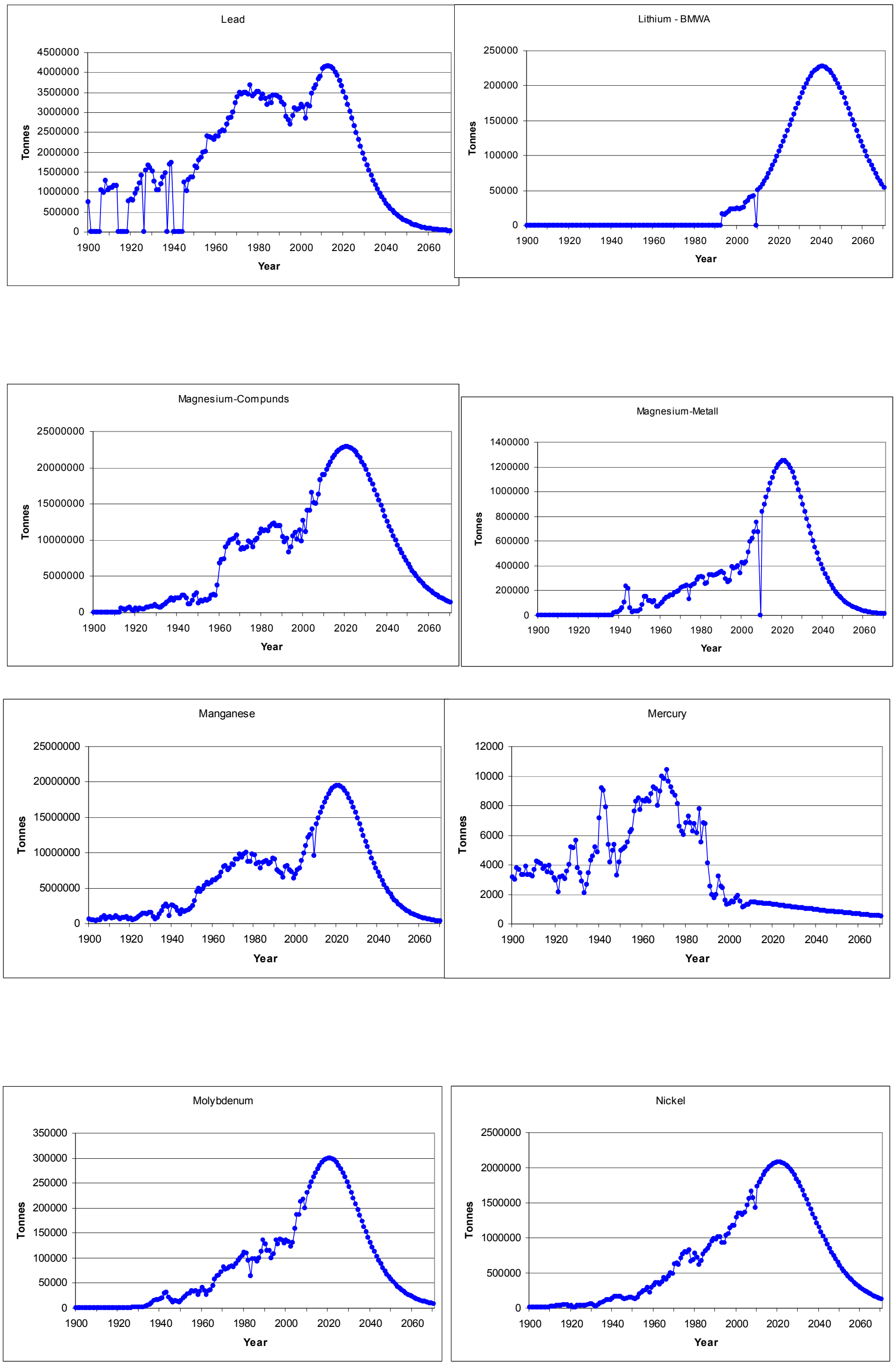


Fig. 33: Possible production profiles based on USGS reserves for lead, lithium, magnesium compounds, magnesium metal, manganese, mercury, molybdenum and nickel

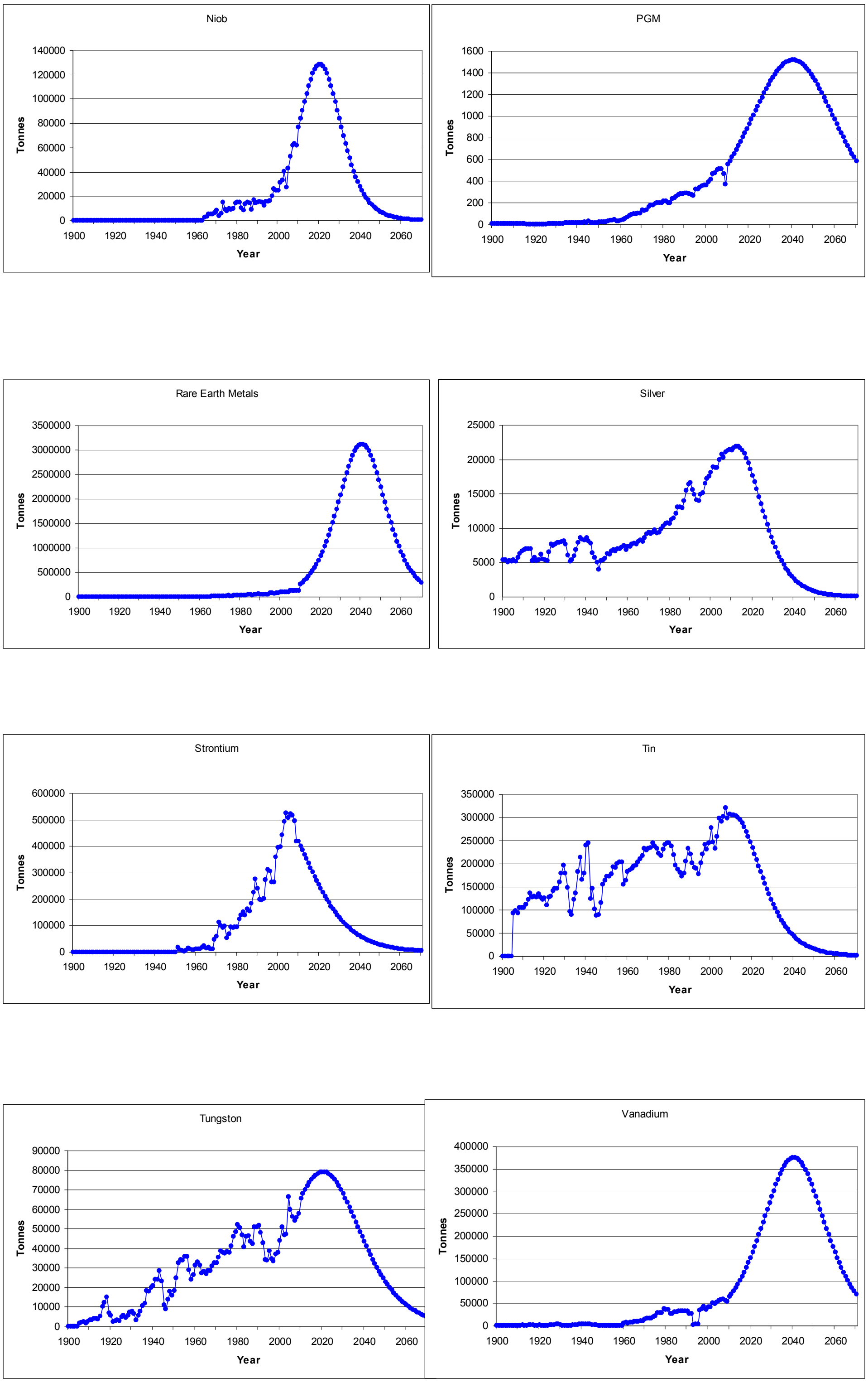


Fig. 34: Possible production profiles based on USGS reserves for niobium, platin group metals, rare earth oxides, silver, strontium, tin, tungsten and vanadium

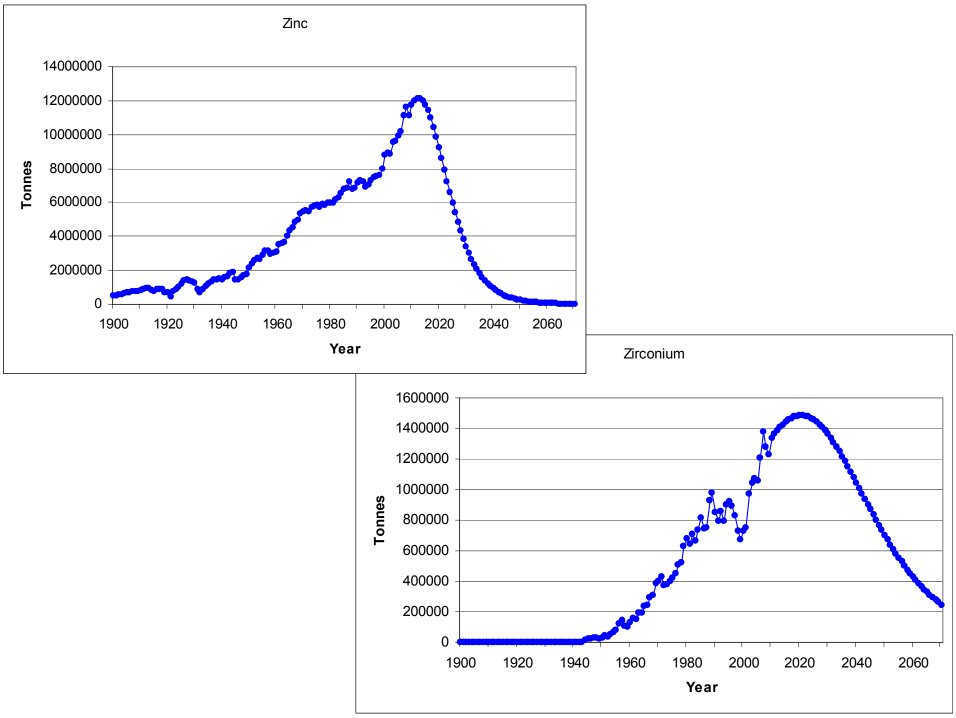


Fig. 35: Possible production profiles based on USGS reserves for zinc and zirconium

3.2.5 Summary of some critical parameters

The parameters "R/P-ratio", "reserve versus cumulative production", "HHI-Index" are summarised in the following table. For that purpose a grouping of the data is introduced.

Reserve to production ratio

<20 years:dark red; shortages in the near term future are very probable

20-35 years: red; shortages in the near term future are probable

35-40 years: orange; shortages in the near term future are possible, and are probable in the mid term future

40-50 years: grey (30%); shortages in the mid term future are probable

50-60 years: light grey (25%) shortages in the mid term future are possible

Reserve to cumulative production:

<0.8: dark red; shortages in the near term future are very probable

0.8-1.2 light red: shortages in the near term future are possible

1.2-1.6 orange; shortages in the mid term future are possible

Herfindahl-Hirschfeld Index (market concentration)

HHI : <1000 no colour

1000-2000: weak grey (10%); low market concentration

2000-3000: grey (15%)

3000-4000: dark grey (20%)

4000-5000: grey (25)

5000 – 6000: orange (30%)

6000-7000: light red (35%)

>8000: red (40%); the word depends on one or two supplying countries

Table 2: Supply risk judged on the criteria „R/P-ratio", reserves and cumulative production (Cum. production). Production and market share of largest producers

Mineral	**R/P-ratio**	**Reserves /Cum. production**	**Herfindahl – Hirschfeld Index (HHI)**
Ferrous metals			
Iron ore	70	2.7	2200
Chromite	15	1.1	2000
manganese	56	1.0	1400
Ti-minerals	128	2.5	1500
Nickel	50	1.4	1000
Molybdenum	44	1.5	2500
Cobalt	106	3.4	2100
Niobium / Tantalum	47	3.3	8500
Tungsten	48	1	6600
Vanadium	240	9	3300
Non-Ferreous metals			

Mineral	R/P-ratio	Reserves /Cum. production	Herfindahl – Hirschfeld Index (HHI)
Bauxite	134	5.3	1800
Copper	34	1.0	1,400
Zinc	18	0.5	1,100
Lead	20	0.36	2,300
Tin	18	0.29	2,700
Antimon	11	0.33	8,300
Rare Earth Oxides	800	38	9,400
Arsenic	19	0.27	2,900
Cadmium	32	0.56	1,100
Lithium			3,400
Bismuth	44	1.3	4,300
Mercury	53	0.12	4,400
Indium			2,800
Tellurium			3,600
Precious metals			
Silver	19	0.38	1,000
Gold	20	0.35	600
Palladium	(190)	(5.4)	3,400
Platinum	(190)	(5.4)	6,300
Other			

Mineral	R/P-ratio	Reserves /Cum. production	Herfindahl – Hirschfeld Index (HHI)
Cement			2,600
Phosphate	102	2.3	1,800
Sulfur			750
Potash	340	6.4	1,400
Mg-compounds	490	>4	3,400
Barite	31	0.53	3,300
Borate	38	1.39	2,800
Asbestos			3,000
Zirkonium	54	1.9	2,900
Bromine	30,000	750	3,000
Strontium	16	0.67	4,200
Helium			5,400
Selenium	59	1.09	2,900
Beryllium	570	4.9	5,800
Germanium			5,100
Gallium	12,800	565	5,900

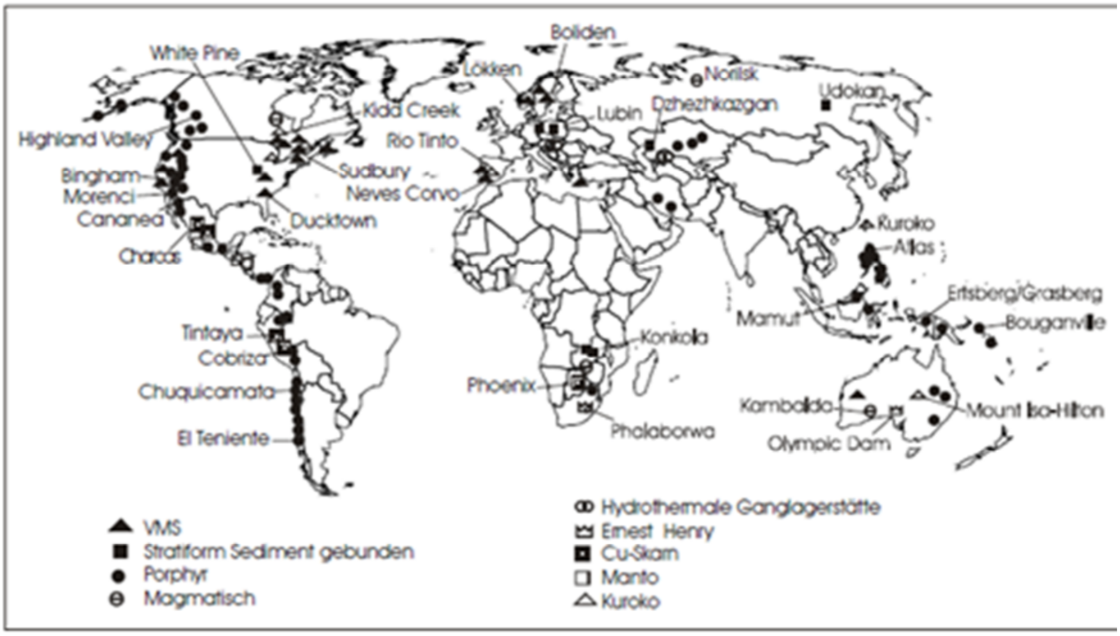
A selection of critical metal supply also must include further parameters such as potential for substitution and recycling, import dependence and relation to important producer countries etc.

This is beyond the scope of the present analysis and partly will be provided in chapter 4.

3.3 Detailed Analysis of Copper production

3.3.1 Deposits

Figure 36 gives a survey of copper ore deposits. The high concentration of porphyry ore deposits along the Rocky Mountains and the Andes is due to the submerging of the Pacific plate below the American plates.



Copper ore deposits

Source: Grassmann 2002 Doctoral Thesis

Fig. 36: Distribution of copper deposits, distinquishing the different geological origins of the ores (Grassmann 2003)

3.3.2 Short selective history of copper mining

The development of human beings was closely related to the discovery and use of metals. In the beginning pure metal deposits looking out of the ground might have attracted first attention. Probably the first metal systematically mined and used was copper. The eldest known discoveries are in Cayönü (Anatolia) where since almost 9000 years copper was in use (von Schnuerbein 2009). In Catal Hüyük the production of copper and lead can be traced back until 6600 BC (ten Horn-van-Nispen 1999). In South-East Europe copper mining was known already 4500 BC. About 500 to 800 years later the use of copper diffused to Central Europe. In the Western Mediterranean area copper mining started from Italy (Apennin) until it found its way to Spain around 3300 BC.

The first indicators of copper refining in the alps can be dated with the discovery of "Ötzi" – the mummy found in the alpine region of Southern Tyrolia – to around 3000 BC. His copper axe and arsenic particles in his hair are strong indicators for copper refining.

Bronze, a -copper alloy with 10-15 percent of tin, was a much more useful metal which, due to its hardness, coud be used much more efficiently for weapons and tools. Probably starting from minor Asia its use expanded to the Middle East from where it found its way to Europe within a few centuries. Around 1600 BC most tools were already produced from bronze. Due to their hardness these tools could be also used for mining. This resulted in a positive feed back loop which increased the speed of their further use. In Middle Europe bronze age mining and refining areas are found in Southern Tyrolia and Austria (Hoeppner et al. 2005).

In the later bronze age Greece and Creta were two of the first cultures in the Mediterranean area which developed states following oriental archetypes. Predominantly slaves were forced to work at antique mining sites. In the most important mine of the Greek Empire, Laurion close to Athens, about 20,000 slaves had to work. The rise of Athenes around 560 BC coincides with the beginning of silver mining in Laurion which at its peak produced about 20 tons of silver annualy. However, mining stopped suddenly in 413 BC when the slaves flew to Sparta during the Peloponnesian war. Later, mining at Laurion started again but disrupted once more when the silver price collapsed while Alexander the great overflooded Athens with lots of captured silver coins. Finally, mining at Laurion ceased in 86 BC (Cech 2010).

In Greece the state leased mining rights for taxes. The lease owner operated the mines with rented slaves. Maybe the first public energy project – as it might be called cynically – was proposed by Xenophon around 300 BC. He proposed that all inhabitants of Athens should pay to the government for buying slaves who then could be rent to miners. The rental rate should be distributed to the inhabitants as kind of basic income (Fellmeth 2008). The project failed due to the huge investments and long lead times before the return of invest would have started. Probably the upper class which had to pay the largest share of the project cost resisted it. This crude example is used here to remind to the origin of the phrase "energy slaves" as it is employed in today's sustainability debate to visualize the use value of energy, and as even today miners in many areas of the world work under conditions similar to slavery – they build the backbone of modern society's energy supply. In a rough guess each 100 Watt of average power is similar to the work of one energy slave.

The Roman Empire also used slaves for mining, predominantly in Spain. The first Spanish mines were already developed by Phoenicians. Even today the name of one of the largest mining companies reminds of one of the eldest mines: Rio Tinto in Spain which already was operated in Phoenician times. An often used Roman mining practice was the technique of "ruina montium": Slaves had to undermine a mountain until it lost its stability and started to collapse. Then the ore was collected from the ruins. Impressive monuments of that mining technique still can be seen in Medulas (Spain) (Cech 2010).

During the Roman empire copper mining reached a first peak at about 15,000 tonnes annualy. With the collapse of the Roman empire also copper mining collapsed, surviving in Europe only at a small scale. In the early Medivial times silver had to be produced in order to pay for the luxurious goods which were imported from China by the European gentry. Copper mining for coins became important. In the 14th and 15th century mining in Europe experienced a revival, cities with mining sites entered economic prosperity. In the 16th century many of the easy to produce mines were already exhausted. Already in the 11th century during the Chinese Sung dynasty in China copper (or generally metal) mining had seen a renaissance with a second production peak of around 10,000 tons per year (figure 37).

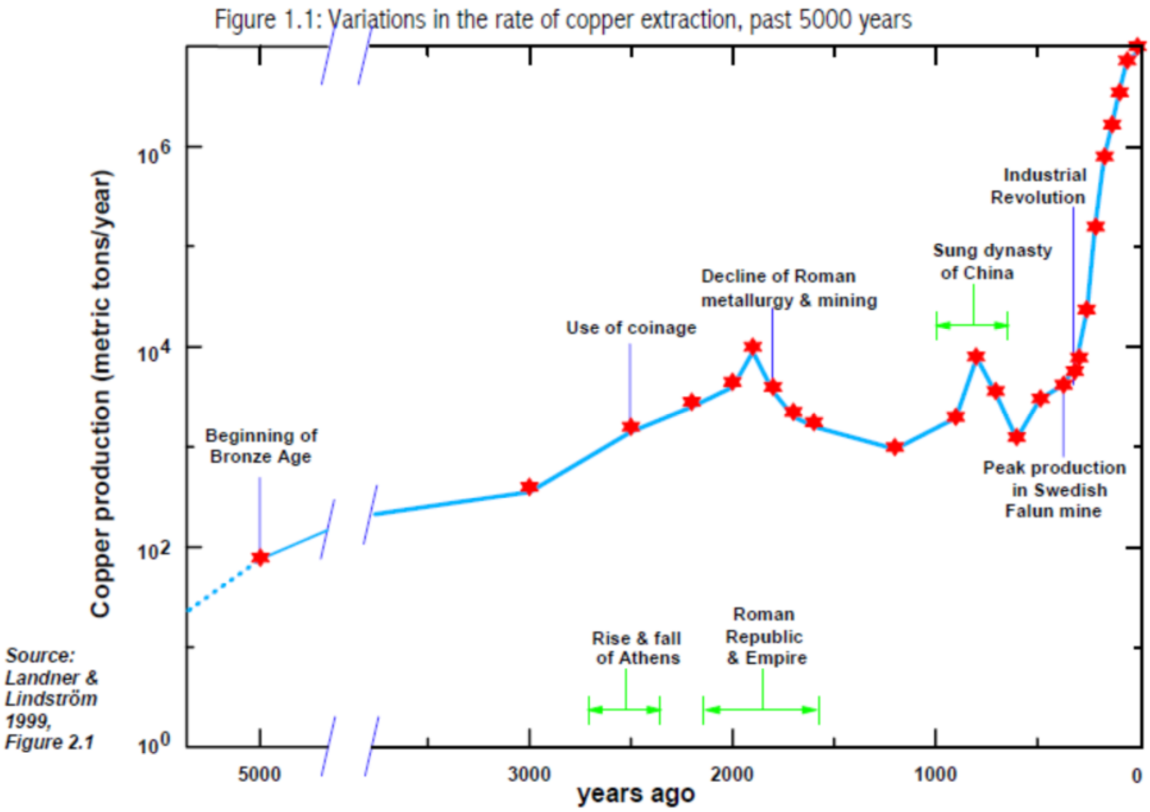


Fig. 37: Historical record of copper mining from archeological sites and air samples from Greenland ice cores (Ayres 2002)

The Swedish copper mine Stora Kopparberg in Falun became a famous mining site, when due to the huge capital needs probably the world's first corporation was founded in 1284 (Welt 2011). In the 17 th century it was by far the largest mine in Europe producing about half of European copper output. However its output peaked already around 1650 at about 3,000 tonnes (figure 38).

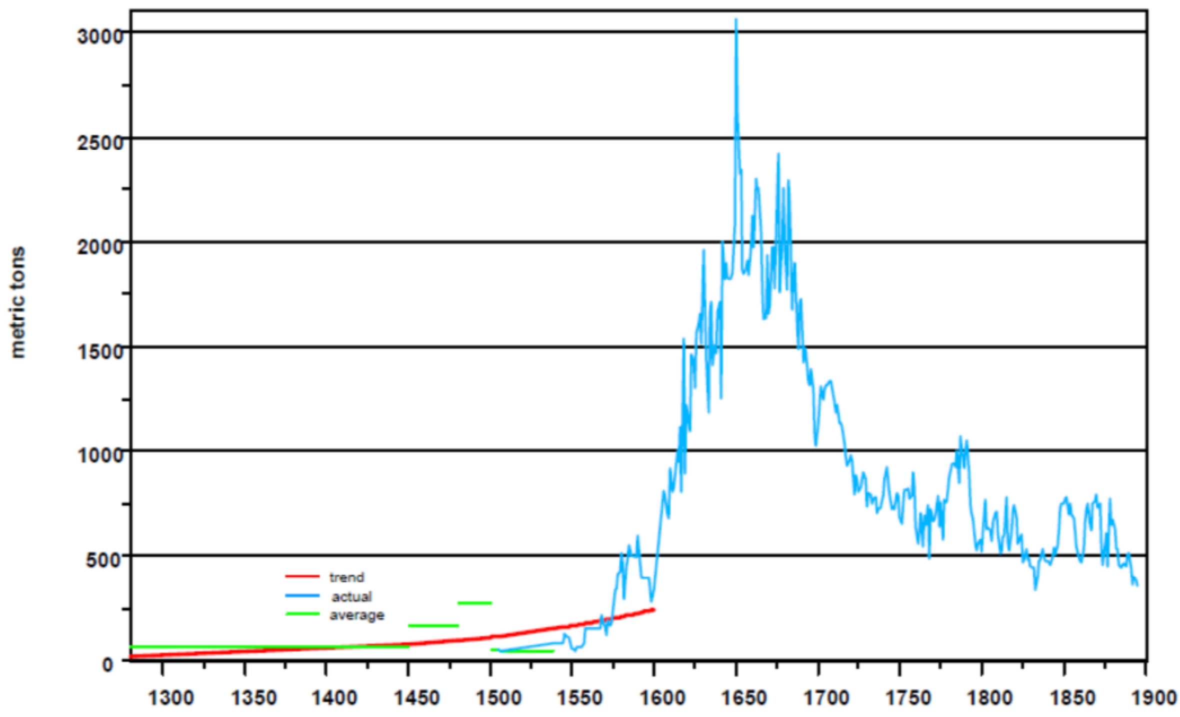


Fig. 38: Historical production of Falun copper mine in Sweden (Ayres 2002)

Later on, European copper exports played an important role during the colonialisation of India. The Dutch East India Company (VOC) opened in Japan the only European commercial settlement exporting - among other goods - Japanese copper to other Asian markets. During the return voyages the ships imported silver to Japan as Japanese silver production already had passed peak production before 1700. As a consequence of the Japanese silver peak, copper production in Japan was pushed upwards until it also reached peak production in 1701 at about 5400 tons which was followed by a decline to below 3000 tons per year around 1750 (Shimada 2006). Copper exports were restricted at that time by the Japanese authorities. The rising Asean demand, primarily for coinage, was continuously satisfied by European exports. However, due to the decline of Falun in Sweden and in other regions, Dutch merchants lost the access to these markets.

This was on the advantage of the British East India Company which had easy access to the rising production of copper mines in Cornwall and Wales. These rising exports of British copper to India seemed to be a major adventage of Britain in the hegemonial dispute on India with the Netherlands (Shimada 2006) which finally resulted in the colonialisation of India by England. On the other hand the rising demand from abroad triggered the fast production increase in Britain which reached its production peak in the middle of the 19^{th} century. In the course of the following steep decline copper production in Cornwall and Wales almost stopped until 1900 except minor quantities. Finally, in 1938 copper production ceased there. Figure 39 gives an estimate of British copper and copper ore production.Based on available data the typical ore grade is calculated. Before 1750 the copper ore grade was in the double digit percentage range. It gradually declined to below 10 percent around 1800 and to below 5 percent around 1900.

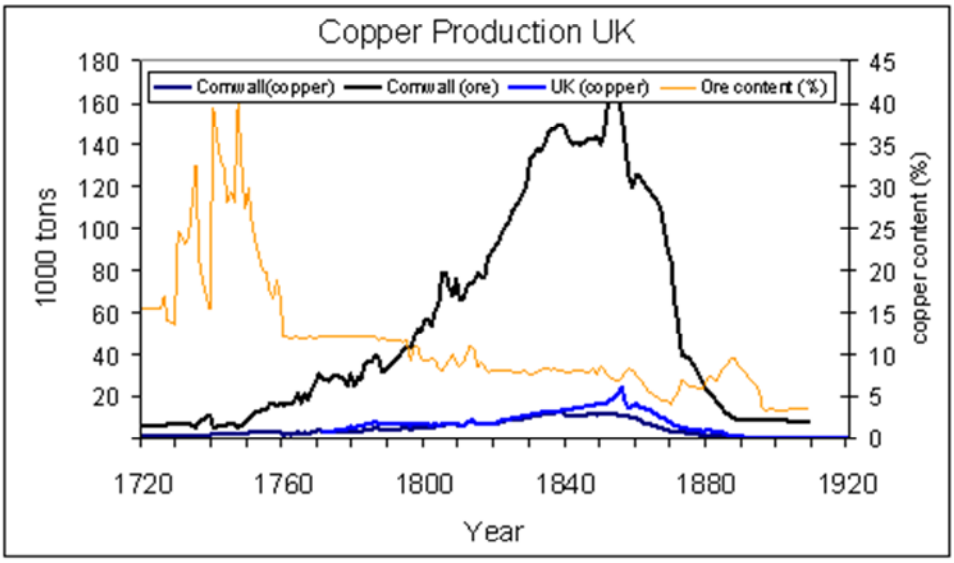


Fig. 39: Historical copper production in the UK. Besides Cornwall, the most important mining area, only Wales contributed to copper mining for some time (Stat UK 2011, Sekuda 2006, Mitchell 1988).

3.3.3 Signs of depletion

The above described depletion trends in the UK are typical for almost any producing region. Figure 40 shows corresponding data for the historical copper mining in Australia between 1842 and 2007. Also in Australia the ore grade before 1880 amounted to about 15-25 percent and rapidly declined to about 5 percent until 1900. In the last two decades the typical ore grade amounted only to a few percent. As a consequence, with declining ore grade, the specific water and energy consumption per tonne of mined copper rose rapidly (Mudd 2007).

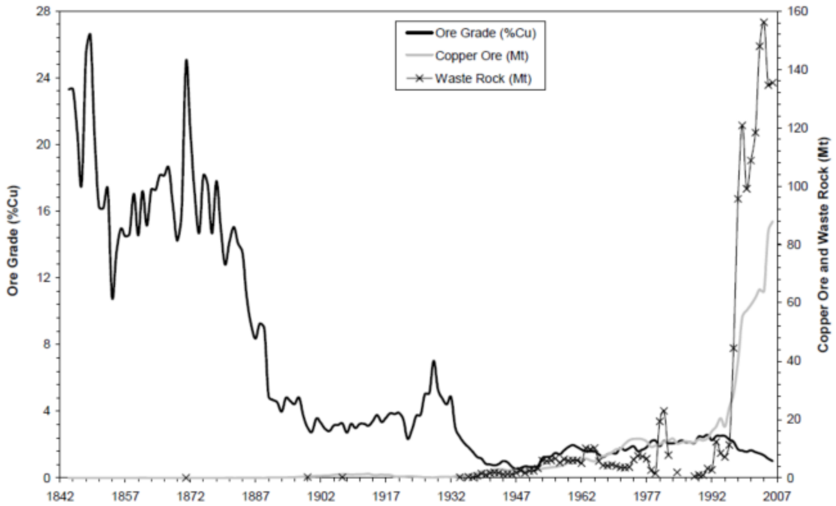


Figure 43 – Copper Ore Grades, Ore Milled and Waste Rock (minimum reported)

Mudd: The sustainability of mining in Australia 2007

Fig. 40: Declining ore grade and rising waste production of copper mining in Australia (Mudd 2007)

Also Canada, which in 1975 still was among the top five copper producing countries, already passed peak production several decades ago. Figure 41 shows the historical copper discoveries. These peaked around 1965 (Cranstone 2002).

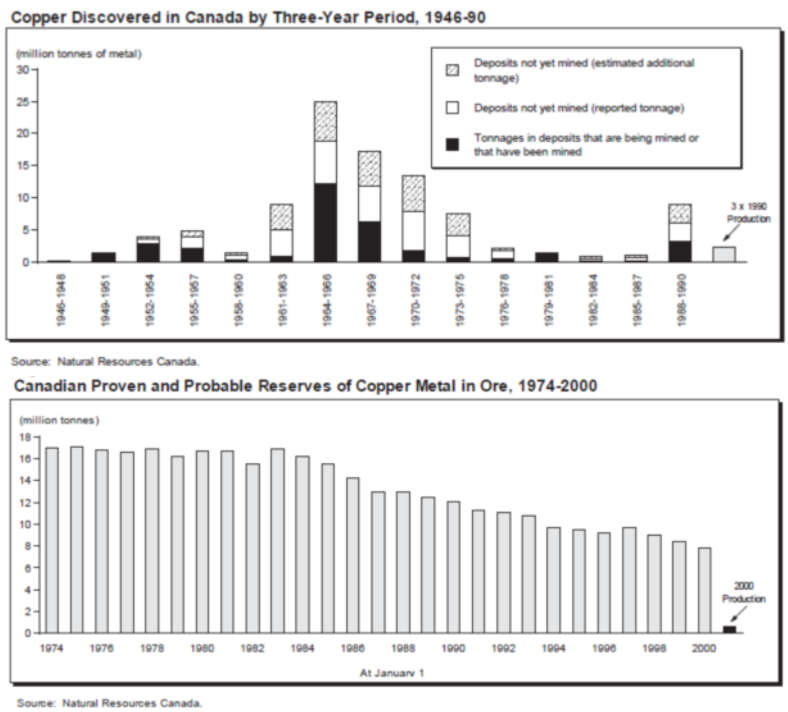


Fig. 41:Historical copper discoveries in Canada and development of reserves 1974-2000 (Cranestone 2002)

The lower part of the figure shows the development of reserves. Due to declining discoveries the reserves declined also. Thus, from year to year, reserves were diminished by the annual production. A comprehensive overview is given in figure 42. Declining reserves are superposed by cumulative production. The slight rise of the sum of both time series reflects the fact that copper discoveries are still made, but at a low level. The reserve data which are based on Natural Resources Canada (NRCAN), the relevant public authority in Canada, are also compared with reported reserves by US Geological Survey (USGS). Both time series of reserves coincide quite closely. However it becomes apparent that USGS does not update its data annually. Between 1996 and 2002 reported reserves remained constant while Canadian data include the decline of reserves due to ongoing production.

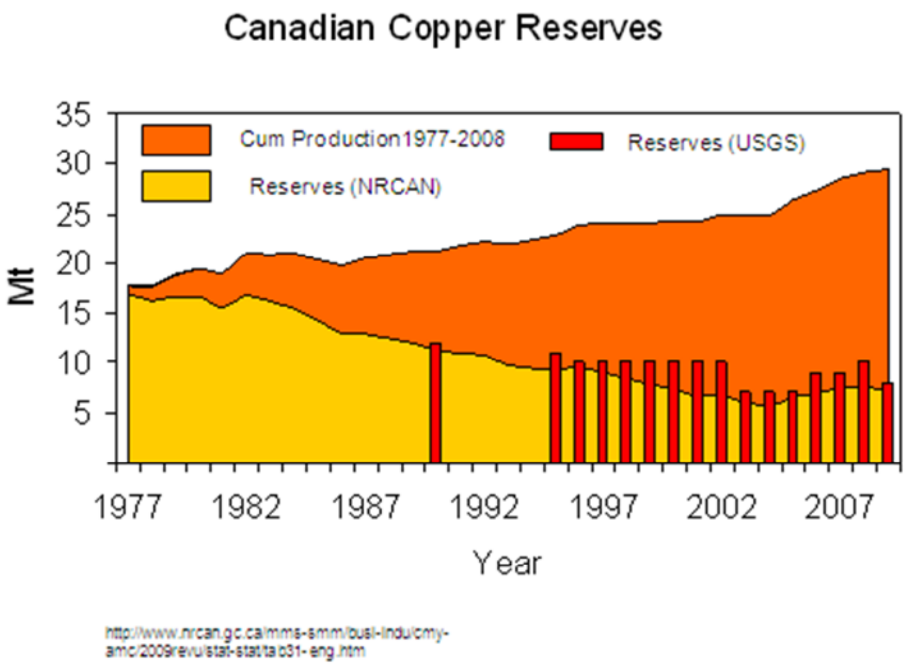


Fig. 42: Development of copper reserves and cumulative production in Canada. The reserve statistics of Natural Resources Canada (NRCAN) are compared to reported reserves of US Geological Survey (USGS) of the corresponding years.

Canada is an example of a country with a long mining tradition. Minerals mining at commercial level started almost 150 years ago. Today many metal deposits are already depleted in Canada. For instance, figure 43 shows similar trends for nickel. Nickel discoveries since 1980 are almost negligible. This results in a plateau of the sum of reserves and cumulative production. USGS reported reserves are included in this figure for the sake of comparison.

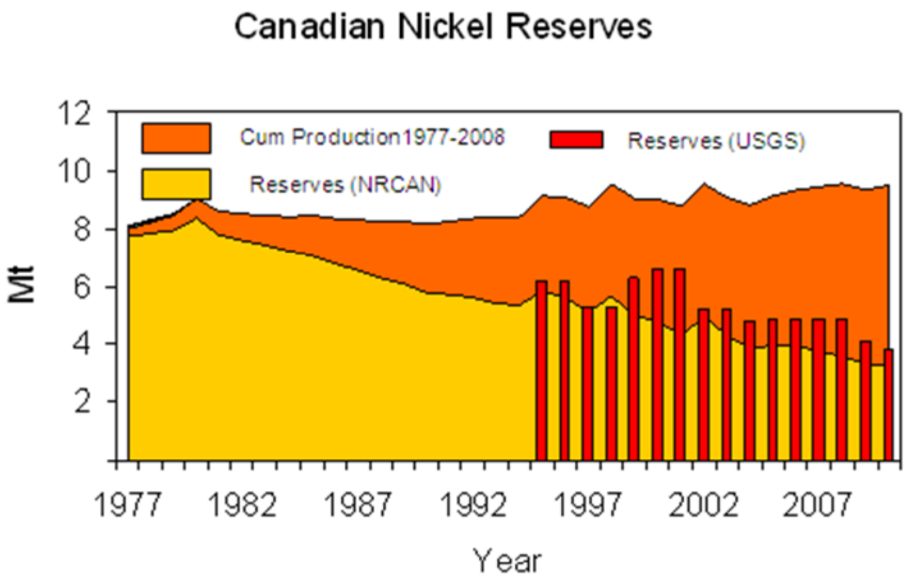


Fig. 43: Development of nickel reserves and cumulative production in Canada. The reserve statistcs of Natural Resources Canada (NRCAN) are compared to reported reserves of US Geological Survey (USGS) of the corresponding years.

For silver the historical data sets show a similar trend (figure 44): reserves rapidly declined while new discoveries are missing. This results in a flat graph of the sum of reserves and cumulative production. However, USGS reported reserves clearly overstated the silver reserves by about 100 percent. Only in 2002, the data were updated, downgrading reserves by more than 50 percent. For the following seven years again, each year the same reserves as in the previous year are reported. Finally, in 2010 reserves again had to be revised downward by more than 50 percent in order to adapt them to the data as reported by NRCAN.

Also reserves and historical production volumes for zinc fit into that scheme, again exhibiting missing discoveries since about 30 years (figure 45). As a final example for the Canadian mining history figure 46 shows the historical data for gold. It is the only example in Canada where discovieres increased almost ten times over the last 30 years. Obviously, Canada already has depleted most of its mineral resources.

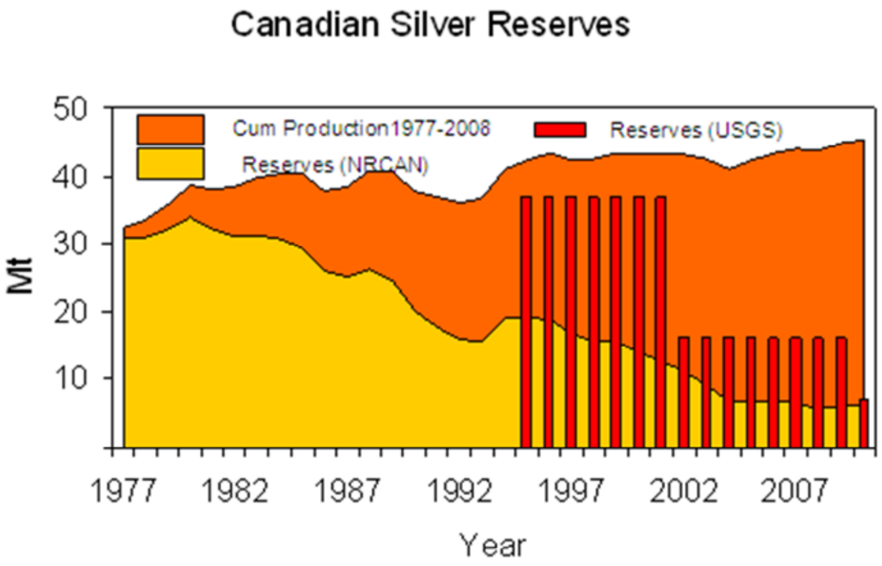


Fig. 44: Development of silver reserves and cumulative production in Canada. The reserve statistics of Natural Resources Canada (NRCAN) are compared to reported reserves of US Geological Survey (USGS) of the corresponding years.

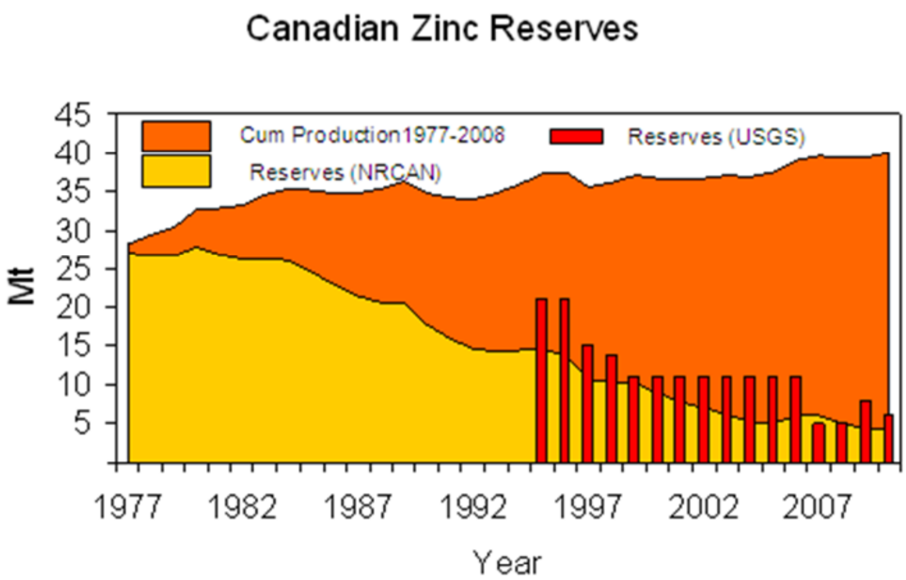


Fig. 45: Development of zinc reserves and cumulative production in Canada. The reserve statistics of Natural Resources Canada (NRCAN) are compared to reported reserves of US Geological Survey (USGS) of the corresponding years.

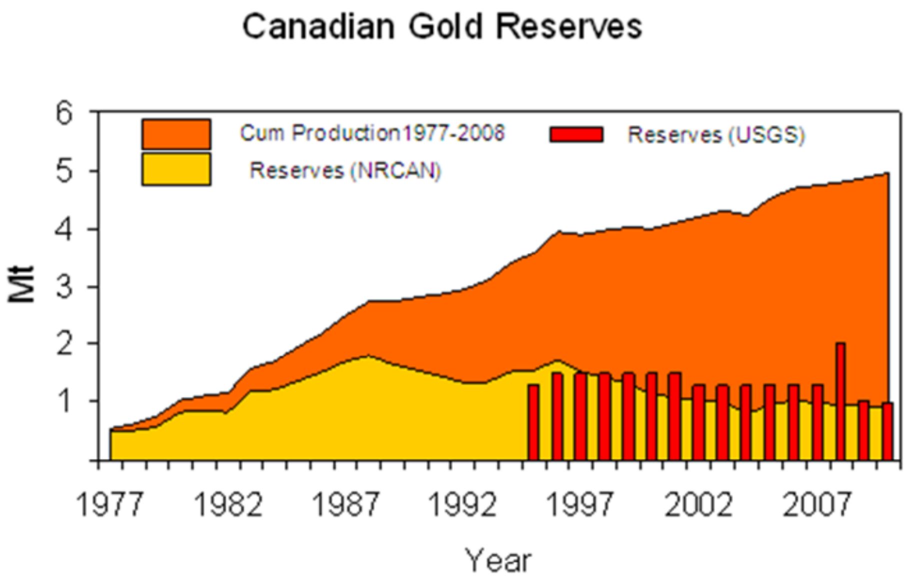


Fig. 46: Development of gold reserves and cumulative production in Canada. The reserve statistics of Natural Resources Canada (NRCAN) are compared to reported reserves of US Geological Survey (USGS) of the corresponding years.

Figure 47 shows the cumulative production of copper for each country compared to its reserves and its reserve base. Actually, USA, Canada, Zambia, Zaire and most of the small producers have already exhausted their discoveries by far more than 50 percent. This is a strong indication that peak production already occurred in these countries. Other countries like the former Soviet Union (GUS) are close to peak production as reserves and cumulative production are almost in balance. Chile, Peru, Australia, China, Poland, Indonesia and Mexico seem to be far before peak production. These countries probably still can increase production considerably – despite the quality of reserves as already discussed in figure 37.

The inlet of figure 47 demonstrates the ranking of top producers in 2009. Over the last years, Chile became the largest producer with almost 40 percent share on world production exceeding the second producer by a factor of four. Figure 48 shows the production pattern since 1932, ranking the countries with respect to the date when they passed peak production. Around 1973 the steep production increase of previous years slowed down in line with the oil price shock In 1973. At that time USA, Chile and Canada were the largest producers with almost equal production share. The production in the USA still rose slowly for some years before it reached peak production in 1997. Since that time Chile is the only country which rapidly increased its share making it to the world's top producing country.

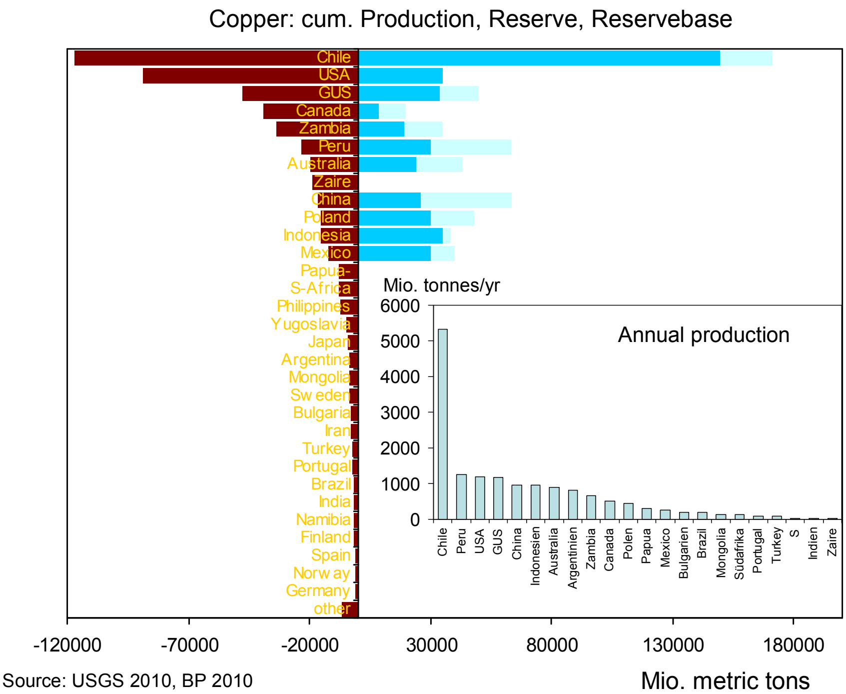


Fig. 47: Country assessment of cumulative copper production (brown bar, neg. value), reserves (blue bar)and reserve base (light blue bars; reserve data for the small countries are not reported).

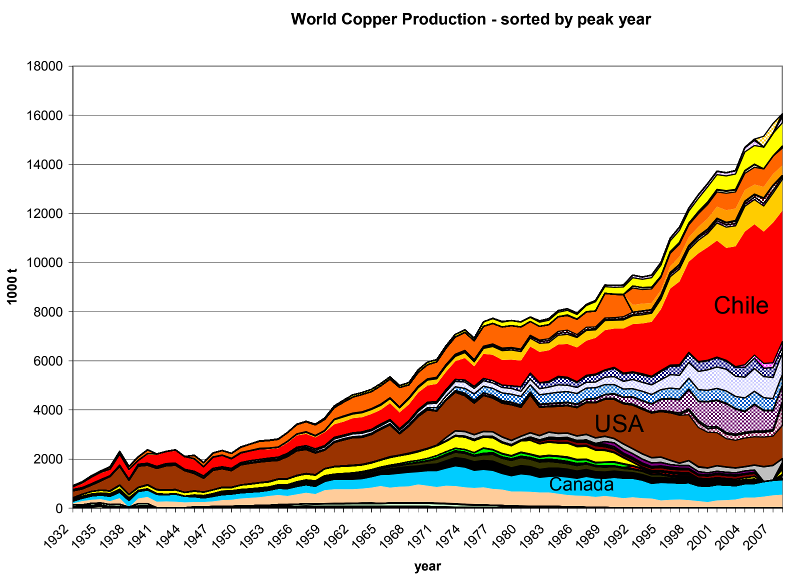


Fig. 48: World copper production 1932-2009

A more detailed analysis of copper production in the USA exhibits that also here the ore grade was steadily declining, from about 10-20 percent around 1850 to 3-4 percent in 1900. In 2000 the average ore grade was already far below 1 percent. This trend still continues as can be seen in figure 49.

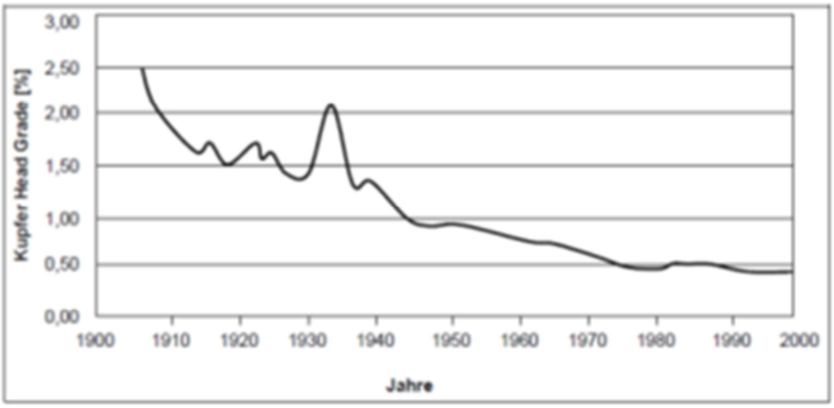


Abb. 4-6: Entwicklung des durchschnittlichen Cu-Head Grade der Erze des US- amerikanischen Bergbaus als Zeitreihe nach WILBURN ET AL. (2001).

Fig. 49: Development of copper ore grade in the USA during the last century (source: Grassmann 2003)

However, the declining ore grade was more than compensated by an increase of efficiency as can be seen in figure 50. Labour productivity continuously increased between 1915 and 2000. Higher output per mine worker hour is an indicator of more efficient technological processes. The progress of technological efficiency very often is accompanied by rising energy demand. However, the rising labour productivity stagnated around 2000 and already started to decline.

Despite rising productivity, total US copper production peaked in 1997. Figure 51 shows the contribution of the ten largest producing US mines over the last 20 years. These contribute almost 99% of total US copper production. Peak production of the largest mine, Morenci in Arizona, could not be compensated by the extension of other already producing mines or the development of new mines. The opposite happened, production of two other mines in Arizona, San Manuel and Pirty Valley, ceased in 1999 and 2000 steepening the decline after peak production. Total production in 2010 was already down by 40 percent against 1997 while productivity increased by 20-30 percent. Obviously, the USA have passed peak production. These data fit to the crude analysis above, indicating that reserves are by far smaller than cumulative production (figure 47).

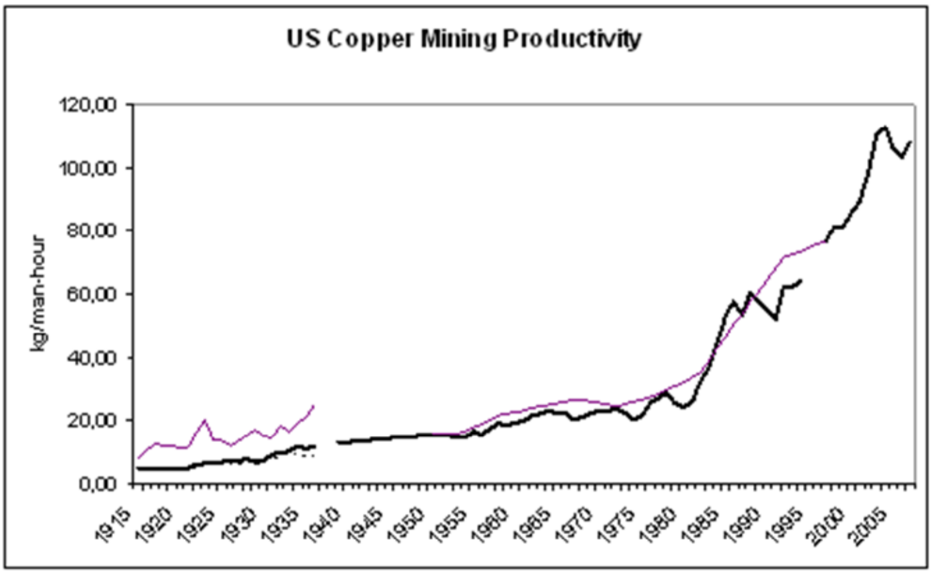


Fig. 50: Labour productivity in the copper mining industry in the USA between 1915 and 2007 (Barger 1944, Tilton 1997, 2001, LPC 2011)

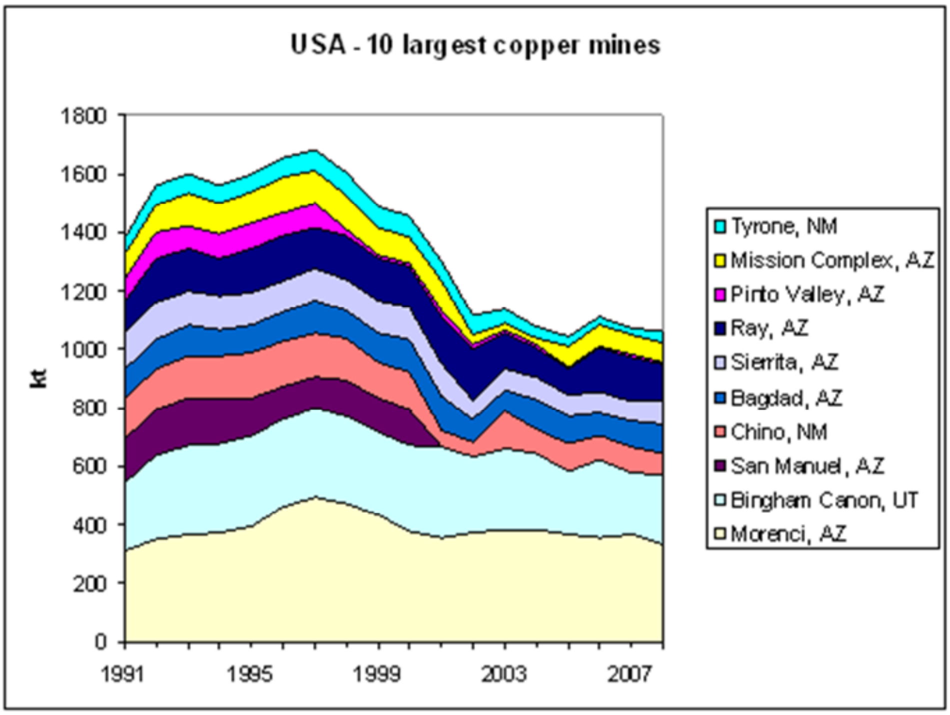


Fig. 51: Copper production of the 10 largest U.S. mines, which contribute 99 percent of total US production (Tilton 2001, USGS 2009).

As a final example serves the analysis of copper mining in Chile, by far the world's largest copper producer which contributes about 35 percent to world production. Figure 52 shows the copper production over the last four decades with the contribution of each mine. Until 1990 two mines, Escondida and Chucicamata, contributed almost 90 percent of the total output. Rising copper prices triggered the fast development of new mines, El Teniente being by far the largest among them. As Chucicamata, El Teniente is an old mine producing since more than 80 years. At first glance it seems that the fast extension of El Teniente brought the mine already to its peak production since its production declines since a few years. This decline is hidden by the development of further smaller mines. The total output of Chile ist still rising or at least flat. However, this pattern reflects that the race against decline has already started also in Chile by keeping high production levels only with the faster development of new mines.

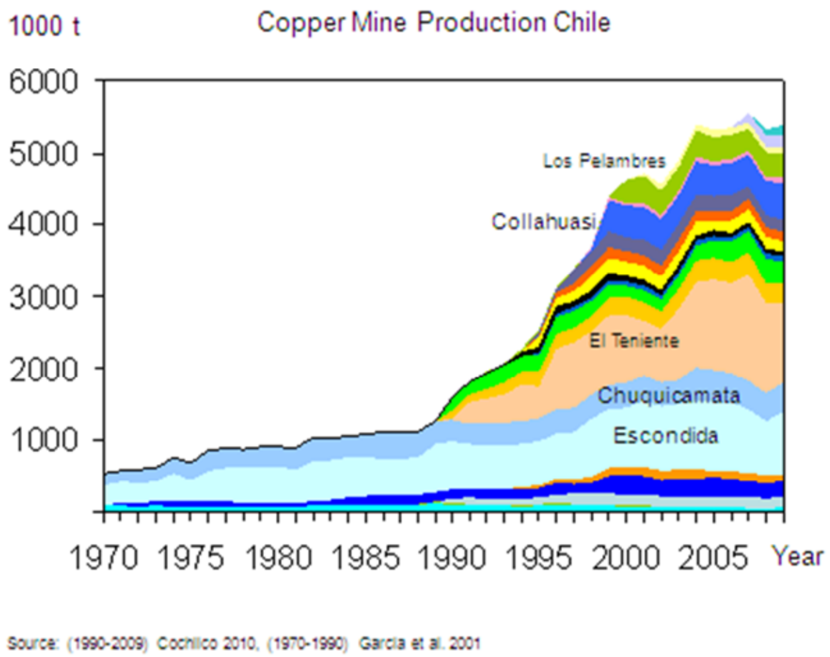


Fig. 52: Mine-by-mine contribution to total copper production in Chile since 1970 (Cochilco 2010, Garcia 2001).

This hypothesis is further confirmed by the declining ore grade as sketched in figure 53. In former times, Chiles copper production already peaked more than 100 years ago when high grade ores above 10 percent were exhausted. However, new mining technologies (flotation) which already were common practice in UK and USA, allowed to successfully develop low grade ores (Alosso 2007). At that time in the USA ores below 1 percent were already commercially producing. The introduction of flotation techniques in Chile allowed to develop ore grades of 2-3 percent. The last years since 1990 again saw a steep rise of Chilean copper production which was spurred by high copper prices. However, at the same time the ore grade of Escondida declined rapidly from almost 3 percent in 1990 to 1.3 percent in 2009. Even the average of most other mines which are controlled by Codelco and which also include El Teniente and Chucicamata, declined already to below 0.8 percent ore grade. Though Chile still has vast copper reserves, their ore grade continuously declines making mining more challenging due to higher energy demand and rising waste production.

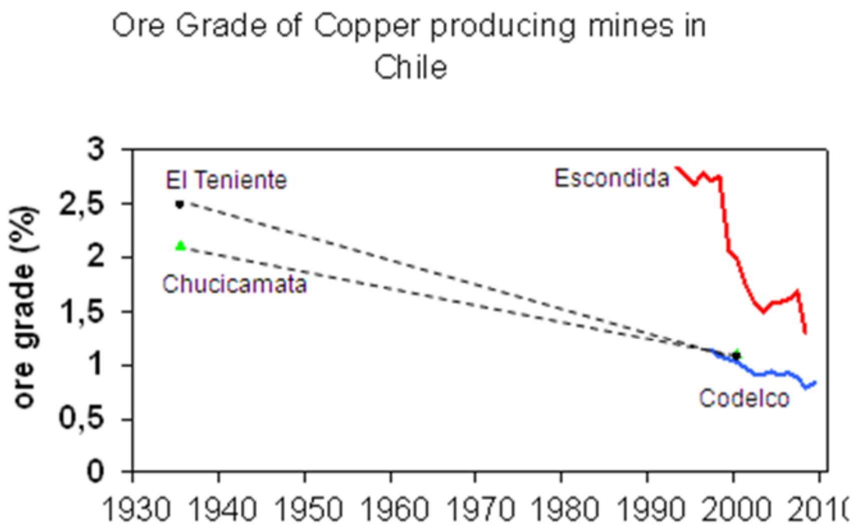


Fig. 53: Declining ore concentration between 1930 and 2009. Escondida is the world's largest copper mine. The production of Escondita, Chucicamata and El Teniente covers more than half of Chile's copper production (Alosso 2007, Cochilco 2010).

This declining trend of copper ore quality is a common phenomenon. For instance, the average ore grade of the producing mines of one of the largest mining companies, XTRATA, declined since 1980 for almost all metals by 40 to 60 percent. Figure 54 gives these facts for copper, lead and nickel, mined by Xtrata.

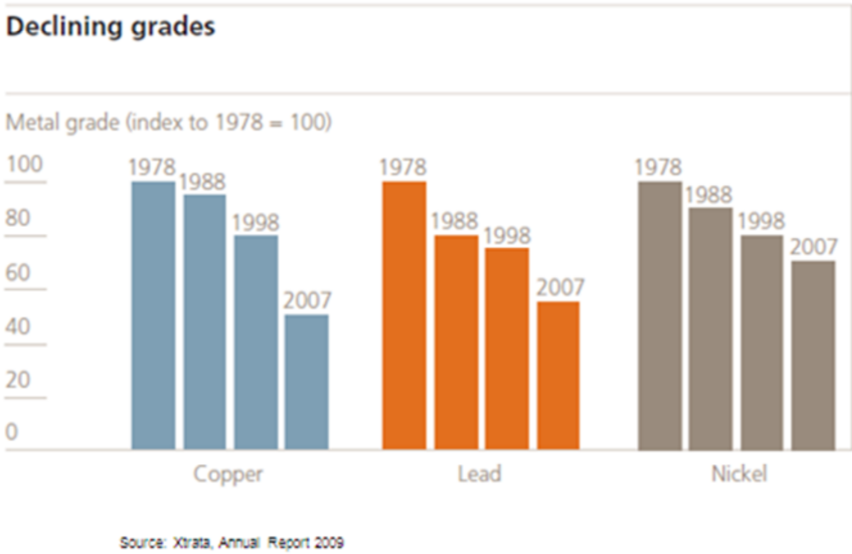


Fig. 54: Declining ore grade of mined metals of mining company Xtrata (Xtrata 2009)

A detailed analysis of the ore grade of world copper reserves is given in figure 55. Less than ten percent of world copper reserves have an ore grade larger than 1.5 percent – a figure which 30 years ago would have been seen as a very low ore quality, probably below the cut-off grade and not worth to be commercially mined. The average ore grade is about 0.6 percent or in other words: half of world reserves have an ore grade of less than 0.6 percent.

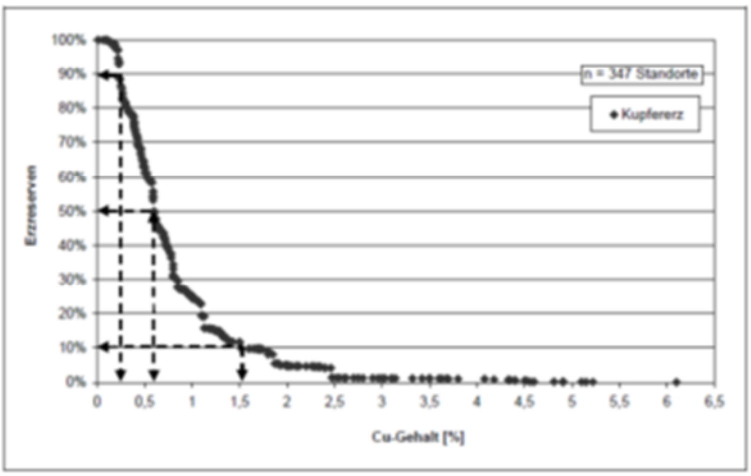


Abb. 5-8: Kummilierte Häufigkeitsverteilung der Kupfererzreserven gegen den Cu-Gehalt, (Datenquelle: siehe Kap. 2.2.5).

Fig. 55: Cumulative distribution of world copper reserves with respect to ore grade (Grassmann 2003).

Declining ore grades require rising energy inputs to extract and refine copper. Figure 56 gives the specific energy demand of copper mining and melting with respect to ore grade for various mines and for different situations within the same mine. The trend is obvious though an exact relation seems to miss.

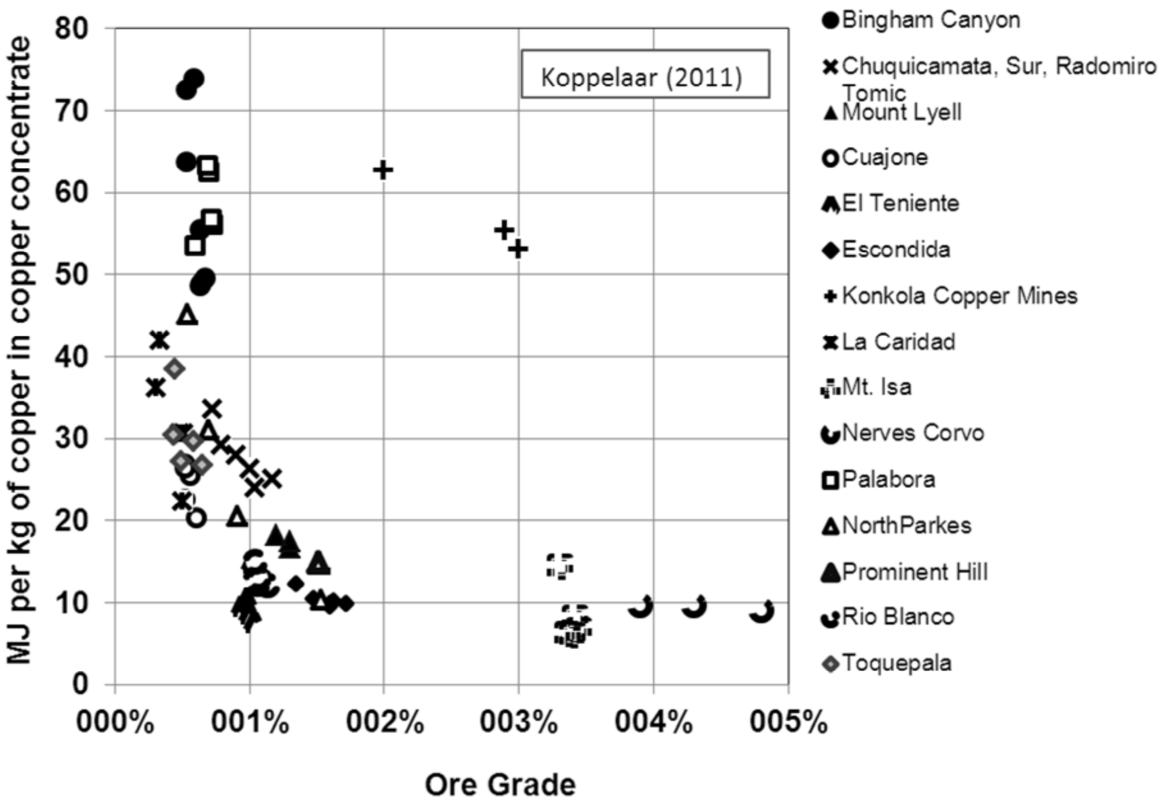


Fig. 56: Specific energy demand of copper mining with respect to ore grade (Koppelaar 2011, 2012)

Obviously other parameters also influence the energy demand for mining. One important aspect, of course, is the mining depth – the deeper a mine, the more energy is required to move the ore containing rocks to the surface. The inclusion of the depth considerably improves the relationship. Figure 57 shows the same data as figure 56, but this time not in relation to the ore grade, but to the mining depth divided by the ore grade. This scaling results in an excellent fit. Since easy to extract copper ores are both high grade as well as close to surface or even found in open pit mines, future mining more and more will be restricted to underground mining – thus getting deeper and deeper – and to lower ore grades. Both aspects will result in rising energy demand per unit.

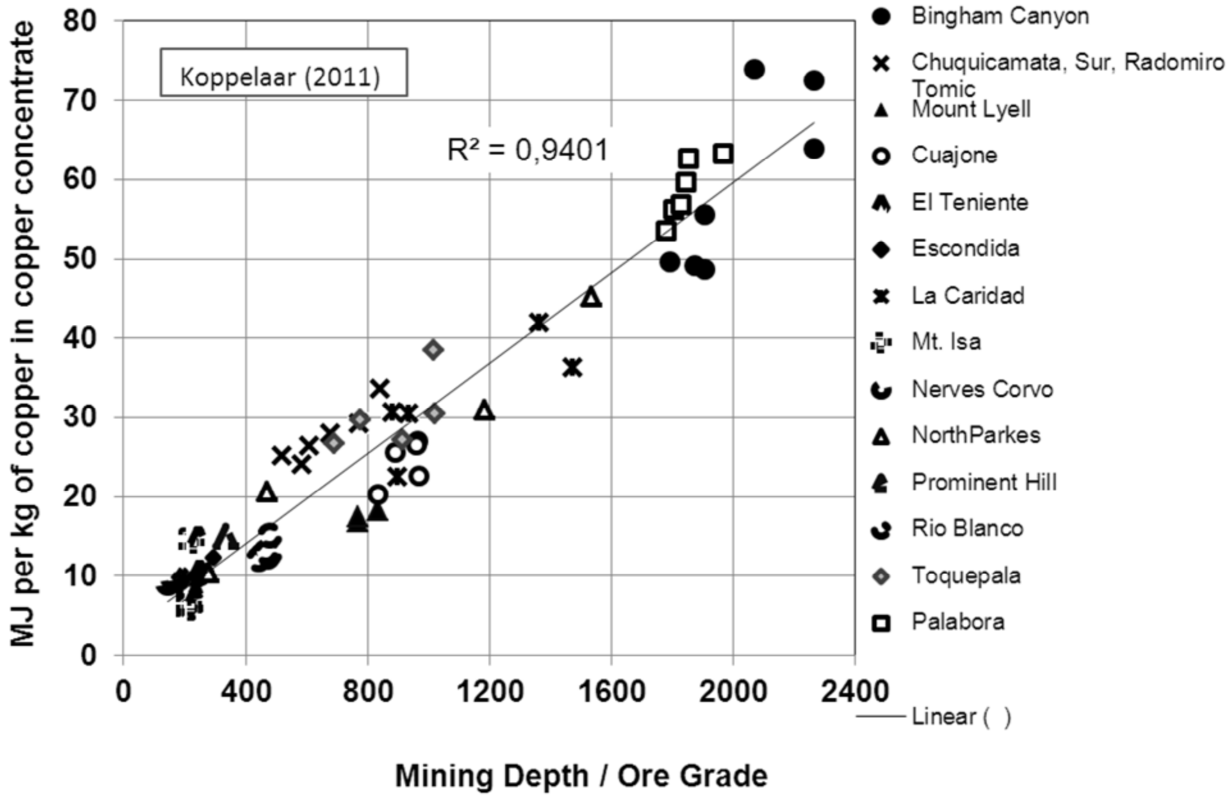


Fig. 57: Specific energy consumption of copper mining with respect to (ore grade /mining depth) (Koppelaar 2011, 2012)

Finally, figure 59 provides a scenario calculation which partly is based on reported reserve data, but also on depletion analysis of individual countries. A linear Hubbert regression analysis is used to extrapolate the depletion pattern of historical mining to future mining at country level. If the historical record pointed towards a linear relationship (Hubbert-linearisation), the historical trend was extrapolated to estimate the future production profile and the future reserves. If these data were not convincing, the reported reserves were preferred for the extrapolation.

The resulting world production profile suggests that world copper production could peak already before 2020. Taking care of the many uncertainties with reserve data this conclusion should be seen more as a cautious warning. However available data do not support a scenario where copper production might still rise for the next two to three decades. Against the backdrop of present knowledge this might be possible, but it seems a far less probable scenario.

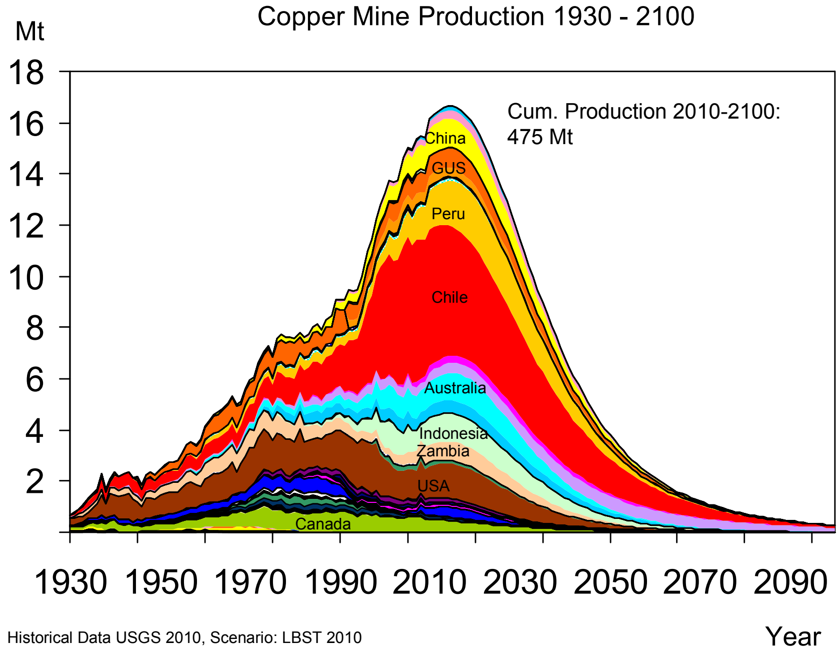


Fig. 59: Scenario of future copper production based on individual production profiles for each country.

Table 3: Reported reserves of copper according to USGS

Country	**Production 2009 (t)**	**Reserves (t)**	**R/P**
Australia[1)]	900,000	24,000,000	27
Canada	520,000	8,000,000	15
Chile	5,320,000	160,000,000	30
China[2)]	970,000	29,510,000	32
Indonesia	950,000	31,000,000	34
Kazakhstan	410,000	18,000,000	44
Mexico	250,000	38,000,000	152
Peru	1,260,000	63,000,000	50
Poland	440,000	26,000,000	59
Russia	750,000	20,000,000	27

Country	Production 2009 (t)	Reserves (t)	R/P
USA	1,190,000	35,000,000	29
Zambia	655,000	19,000,000	29
Other	2180000	70000000	32
World	15800000	540000000	34

The joint ore resource committee of Australia published proven and probable reserves of 19.8 Mt copper at Janaury 2009 while economic demonstrated copper resources are 77.8 Mt copper (Geoscience Australia 2009)

Based on China Statistical Yearbook 2010:
copper reserves 2002: 29.669.000; 2006: 30.699.000; 2009: 29.510.000

3.3.4 Dominant use

According to USGS Commodity News, the most important copper use is for building construction. About half of US consumption is used in that sector (50%). Further important markets are: Electric and electronic products (21%), transportation equipment (11%), consumer and general products (10%) and industrial machinery and equipment (8%). Ayres (2002) has collected a data base from which he could calculate the change of copper in stocks and possible recycling rates by assuming typical operation times for the individual copper applications.

The typcial specific copper consumption of various technologies and products is summarised in table 4.

Table 4: Specific copper consumption of various applications

Application	demand	Source
Conventional car	25 kg (up to 40 kg in future)	1, 2
Conventional truck	67 kg	2
Motor cycle	7 kg	2
Hybrid car	Additional copper coils with 12 kg per car	2
Permanent magnet engine (3 kW)	1.7 kg Cu, 0.3 kg Nd-Fe-B for Magnet	2

Application	demand	Source
Fuel cell car drive train (50 kW)	30 kg	2
Transformator (550 MVA)	~ 40 t	1
House	200 kg	3
Generator (500 MW)	14 t	1
Computer	5-7 %wt	4
Monitor	8%wt	4
Laptop	<16%wt	4
Mobile Phone	9-16 g	5,6
Electric Voltage line of train (per 100 km)	2500 t, of which 25 tons are Cadmium	1
Electric railway net	600.000 t Cu (Swiss) ~ 77 kg/inhabitant	4, 7
Telekommunication	116.000 t Cu (Swiss) ~16 kg/inhabitant	4
Ships	2-3 %wt	7
Ship screw	20-25 tons of messing	7
Accelerator (Brookhavn magnet)	4000 t Fe and 400 t Cu	
Agriculture (copper sulfate)	200.000 tons copper sulfate are produced annualy	

1) European Copper Institute 2011
2) ISI 2010, Rohstoffe für Zukunftstechnologien
3) Th. Graedel Metal Stocks, Flows and Sustainability by Thomas E. Graedel Yale University; Center for industrial Ecology 2010
4) Wuppertal Institute 2011
5) Hagelüken 2005
6) Sullivan 2006
7) Copper in electrical engineering, see www.copper.org

Possible substitutions of copper in various applications are (according to USGS Commodity News):

- Aluminum substitutes in power cables, electric equipment, automobile radiators and cooling and refrigeration tubes
- Titanium and steel are used in heat exchangers
- Optical fibre substitutes in telecommunications applications
- Plastics substitute for copper in water pipes, drain pipes and plumbing fistures

3.3.5 Possible recycling rates

According to the Copper Institute, about 80% of all mined copper is still in use. Based on the present demand the recycling rate is about 35% of US supply. (USGS 2010) and 30-50 % in Germany (BGR 2004).

3.4 Summary and conclusions

In this chapter general trends and aspects of depletion are addressed. The example of copper was analysed in more detail. The basic nature of these trends can be traced back to the obvious fact that resources usually are ranked according to the economics of their exploitation, which follows the rule that most promising deposits are developed first, leaving behind more complex deposits for later development stages, when easy to touch deposits are almost depleted and prices higher. Most of the conclusions given below can be found in the excellent book by (Diederen 2010a).

There are two basic types of mineral distribution patterns which roughly can be characterised from the average ore concentration as sketched in figures 20 and 21.

- Scarce minerals have a very low average concentration in the upper continental crust in the ppm-range and far below the cut-off limit where any commercial activity sets in. Part of the ore needs to be enriched in specific deposits by geological processes until mining becomes economically possible. Therefore the total mineral distribution is the sum of two Gaussian-type distribution patterns. The primary distribution has its maximum of availability at the average concentration of the mineral in the upper crust in the ppm-range. At very high concentrations a second Gaussian-type distribution is superposed with its maximum at higher ore concentration. Very often this second maximum falls in the range where commercial mining is possible. However due to the rare number of deposits this maximum is much lower than the first maximum at average concentration. Economics determine the lower cut-off grade until which the deposit development of the highly enriched resources is meaningful. But rising prices or technological advances shift the cut-off grade to lower concentrations. However, the extractable amounts decline at lower concentration once the second, smaller distribution peak is passed. There is a huge barrier of several orders of magnitude of ore concentration between the cut-off grade of commercial mining and the distribution maximum of resources in the ppm-range. Therefore, once the highly enriched deposits are exhausted, the mineral becomes scarce, even when rising prises allow to reduce the cut-off grade further. Actually most metals belong to that group which are rare. Their extraction rate might exhibit a peak within the next several decades.

Based on the analysis of their historical production profile, probably cadmium, chromium, copper,gold, lead, nickel, silver, tin and zinc are close to or at peak production already. Others like bismuth, boron, germanium, manganese, molybdenum, niobium, tungsten, and zirconium might experience peak production probably within the next two decades.

- Minerals which are abundant in the earth crust tend to show a different Gaussian type distribution pattern with the maximum characterised at the average ore concentration, usually above one percent. The higher the ore is concentrated above the average, the smaller becomes the amount. Economic development activity starts only above a specific cut-off grade of the ore which, again, is determined by development cost with respect to prices. Increasing prices and/or rising technological efficiency reduce the lower cut-off grade and consequently increase the available reserves. Minerals which follow that concentration distribution profile are abundant and their extraction is not limited in the foreseeable future by geology.

  The elements of that group were first identified by Andre Diederen. He introduced the phrase “elements of hope” (Diederen 2010a). These are predominantly those minerals with average concentration in the upper earth crust above 1 percent, namely oxygen, silicon, aluminium, iron, calcium, sodium, potassium and magnesium. This classification does not exclude that their future development might be much more energy and cost intensive than in the past and that due to pure economic reasons their development might be much slower than in the past. But there is no such a limiting barrier for their development than for the elements from the first group.

A resilient and cautious strategy would be to use elements from the first group very rarely and substitute their use as far as possible, either by other elements, by enhanced recycling or by more efficient use in specific applications. But it must be emphasised that recycling of these metals becomes increasingly problematic as their more efficient use also reduces their metal content in the disposed products. Recycled iron scrap is increasingly polluted with the blended ingredients. For instance, the average level of copper contamination of recycled iron has already increased to about 0.4 percent (Ayres 2002). This is one of the reasons of the huge price increases for high quality steel.

A wise strategy would also try to base future technological development on those materials which are abundant. It is a challenging task to find substituts for these elements without reducing the material properties. For instance, indiumoxide is used in touch screens because of its transparency and its electrical conductivity. A possible substitute might become graphene which consists of a monolayer of carbon atoms. But this vision is still far from being realised (Bol 2011).

Where substitution is not possible or known, it might be wise to end the use of this application. For instance, neodymium and some other rare earth elements improve the efficiency of magnets and electric generators and motors due to their magnetic properties. There are no other elements available with similar magnetic properties. Therefore it must be questioned whether the improvement of technical efficiencies of these applications is justified by implementing more of these exotic materials. Probably, a resilient strategy is to use less complex magnets at the cost of slightly lower efficiencies. Some car companies, for instance, claim to follow that strategy with the development of their electric cars.

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