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REVIEW ARTICLE

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Sustainable development and the exploitation of mineral and energy resources: a review

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Abstract Natural resources, e.g., metals, industrial minerals, water, and soil, are the essential basis for our economy and well-being. We have to know where these raw materials come from and how they are mined. Sustainable development requires the maintenance, rational use and enhancement of natural resources, as well as a balanced consideration of ecology, economy and social justice. Four general rules concerning the implementation of sustainable development for renewable and non-renewable resources are discussed. Examples of the consumption of selected materials from historical times to the present day are presented, as well as of regional distribution, usage (in contrast to consumption), lifetimes of resources, the supply-and-demand cycle, recycling and substitution in modern times. To fulfill the requirement of sustainable development, the efficiency with which resources are utilized has to be improved. The learning process, often driven by financial rewards, leads from one technology to a better one, thus increasing the efficiency of the use of a resource or commodity. Examples of learning curves are discussed. Industrial countries have to transfer their advanced technologies to developing countries in order to avoid undesirable development in the mining industry and use of natural resources in those regions. The use of the best available technology by the mining industry, taking into account economic considerations, and the necessity to establish environmental guidelines are essential if environmental impact of the production of non-renewable resources is to be minimized. Far more critical than the production of non-renewable resources under the aspect of sustainable development and the capacity of the pollutant sinks of the Earth is the element of natural attenuation with regard to the resources soil and water.

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Introduction

In industrialized countries, normally, everything functions. Because the majority of the population usually lives in cities far from any mine or quarry, nobody thinks about the origin of natural resources – they are just “there”; they can be bought at any time and anywhere. Our life is accompanied by natural resources at every step. The water we shower with in the morning comes from water stored behind dams or from aquifers beneath our feet. The porcelain we eat our breakfast from is made of kaolin, from mines probably in Germany. The nickel in the steel alloy of the knife we use for breakfast is – statistically – produced out of 20% recycled nickel. The larger remaining portion originates, according to our import statistics, mainly from five countries: with 58% of total imported nickel metal from Russia, 8% from Norway, 7% from Great Britain, 7% from Australia, and 6% from Finland (BGR 2000). Knowledgeable people, however, know that the nickel from Great Britain and Norway originally comes from Canada, because the Canadian nickel companies, INCO and Falconbridge, own nickel refineries in these countries, which are supplied with Canadian nickel concentrates or matte, respectively. Even the symbol of our information society, the personal computer, contains 31 metals, taken as ore from our Earth and then beneficiated, smelted, refined, and processed (Jeffery 1998).

As a consequence, a responsible society has to consider, now and in the future, where its raw materials come from and how they are mined. Of the 80% of raw materials that are needed in Germany, the bulk of it as construction materials, are still mined in Germany – a figure more or less the same for any industrial country in Europe (Table 1). The remaining 20%, energy resources such as most of the crude oil and natural gas, and all the

Table 1 Effective per-capita consumption of mineral commodities per 70-year life span in Germany; those raw materials that are produced partly or totally in Germany are marked with an asterisk (BGR 1998)

Sand and gravel*	316 t	Gypsum*	7.0 t
Crude oil	109 t	Kaolin*	2.0 t
Aggregates*	143 t	Dimension stone*	1.8 t
Lignite*	133 t	Aluminum	1.5 t
Limestone, dolomite*	94 t	Peat*	1.3 t
Hard coal*	66 t	Phosphate	1.2 t
Steel	33 t	Steel alloying metals	1.0 t
Cement*	33 t	Copper	1.0 t
Clays*	22 t	Potash*	0.6 t
Industrial sand*	11 t	Sulfur*	0.5 t
Rock salt*	11 t		

metals with the exception of the recycled secondary part, to be discussed later, have to be imported from all over the world. We are the customers of the world (Fig. 1). Thus, we should have a vital interest to work out concepts for a sustainable development of natural resources within and outside Germany.

Sustainable development

The concept of sustainable development

Sustainable development is a normative term – according to the philosopher Immanuel Kant – like liberty and equality. In the UN Report "Our Common Future", commonly called the Brundtland Report, sustainable development is defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland 1987). This has become the internationally most accepted definition, defining intergeneration fairness. This definition has been expanded by the United Nations Environment Programme, which has added that this concept also requires the maintenance, rational use, and enhancement of the natural resource base that underpins ecological resilience and economic growth, and that it implies progress towards international equity (UNEP 1989).

The next step was the Rio Declaration at the UN Conference on Environment and Development in Rio de Janeiro in 1992 and Agenda 21, which stresses the three elements of sustainable development – ecology, economy, and social justice: To conserve the basic needs of life, to enable all people to achieve economic prosperity, and to strive towards social justice. All three objectives should initially be considered to have the same priority. Whereas the Brundtland definition above stresses intergeneration fairness, Agenda 21 stresses intrageneration fairness.

Guidelines for sustainable development

The first practical guidelines for sustainable development came from the German forestry administration. The man credited with "inventing" sustainable development was a miner, Oberberghauptmann Johann-Karl von Carlowitz, who published his book "Sylvicultura oeconomica" (1713; Fig. 2). Von Carlowitz was the head of the mining administration of the famous silver-mining district in Freiberg, Saxony. He was not only responsible for the mining and smelting operations in his district, but also for forestry, because timber was needed in the underground mining operations, and the smelting of the sil-

Fig. 1 The origin of metallic resources imported into Germany

Fig. 2 Oberberghauptmann von Carlowitz and his famous book Sylvicultura oeconomica (courtesy of Mr. Rudolph, newspaper "Freie Presse", Chemnitz)

ver ores required vast amounts of wood for charcoal. He realized that uncontrolled deforestation for these purposes would lead to the collapse of timber production. He was the first one to spell out what sustainable development meant in forestry, i.e., that the amount of wood cut should not exceed the growth rate.

It was the "Age of the Enlightenment", a time when the philosopher Kant stated (1784) "Take the courage to make use of your own intelligence". The idea that one had to balance regrowth with the harvest probably developed in several places and it was only von Carlowitz who got it into print first. For example, the forestry administration of the southern Black Forest in Germany at that time, belonging to the Hapsburg Empire, is also credited with developing this concept. The consequences of not obeying this rule were all too apparent all over Europe. For example, the medieval German town of Nuremberg had for its time a significant copper smelting industry based on ores and concentrates from areas in today's Czech and Slovak Republics. The whole smelting industry had to close down between 1456 and 1461 because of a lack of wood and had to move to the Thuringian Forest, about 200 km further north.

Although von Carlowitz' rule for non-renewable resources seems quite logical, it was probably as difficult at the beginning of the 18th century to become broadly accepted as it is today to avoid over fishing and to get fishing quotas internationally accepted – to cite another example of a renewable resource. The reason why theoretical logical arguments against the overuse of natural resources are difficult to accept in practice has always been that drastic structural changes in the economy and society have to occur, and the people and interest groups that are directly affected resist the necessary changes and are, therefore, not willing to take the long-term view necessary for intergeneration fairness.

In contrast to the logical development of guidelines for the use of renewable resources, guidelines for non-renewable resources are more difficult to develop. The Enquete Commission (1993) on the "Protection of Man and the Environment", set up by the German Parliament (Bundestag), formulated four general rules concerning resources for implementing sustainable development – rules that can be applied worldwide:

- Rule 1: use of renewable resources. The rate of consumption of renewable resources should not exceed the rate at which they can be regenerated. This rule is, in essence, the same as already formulated by von Carlowitz in 1713.
- Rule 2: use of non-renewable resources. The consumption of non-renewable resources should not exceed the amount that can be replaced by functionally equivalent renewable resources or by attaining a higher efficiency in the use of renewable or non-renewable resources.

Rules 3 and 4 concern the resilience of the environment and the carrying capacity of our Earth's systems.

- Rule 3: material and energy input into the environment should not exceed the capacity of the environment to absorb them with minimal detrimental effects.
- Rule 4: the rate of anthropogenic input and environmental interference should be measured against the time required for natural processes to react to and cope with environmental damage.

Later, a fifth rule was added concerning health risk by the German Expert Commission for Environmental Problems (Sachverständigenrat für Umweltfragen, SRU).

- Rule 5: hazards and unacceptable risks to human health caused by human activities are to be avoided (SRU 1994).

If we consider why we need natural resources (with a few exceptions like potassium and phosphate, used as fertilizers in agriculture –to be discussed later), it is not

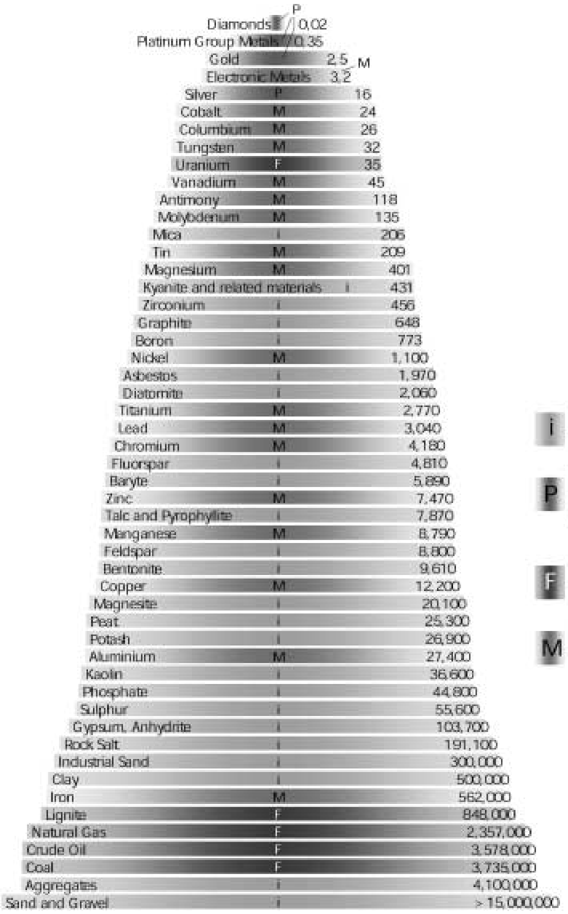


Fig. 3 World production of mineral resources in 1998 by quantity; in 1,000 tonnes (ores given as metal equivalent, natural gas in million m^3) (left)

i Industrial Minerals

P Precious metals and Gemstones

F Fuels

M Metals

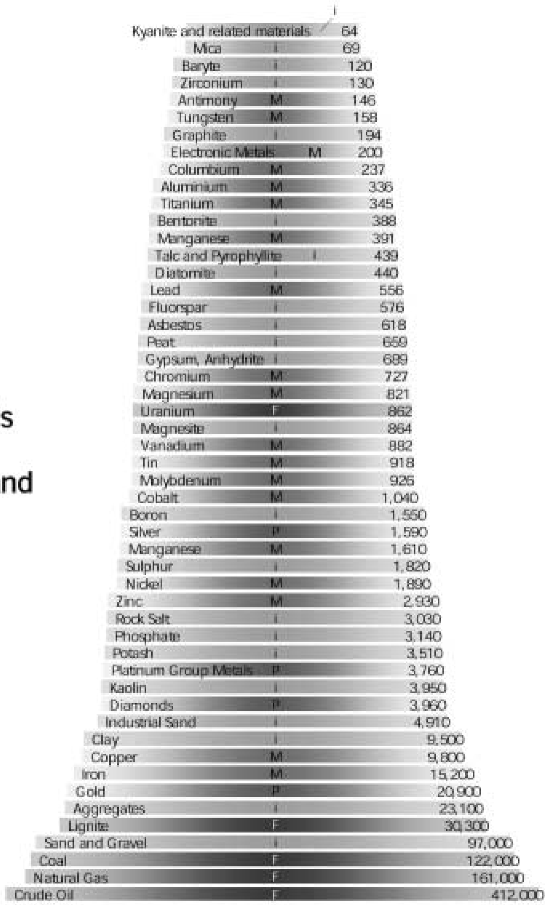


Fig. 4 World minerals production in 1998 by value; in million Euro (right)

the metal nor raw material as such that is important, but the function that can be fulfilled by its material properties, for example, the electrical conductivity of copper or the heat from coal. Other commodities, sometimes using a totally different technology, can also perform these functions. For example, copper telephone wires are used for transmitting information. These have been extensively replaced by fiberglass cable made of silica, whose availability on Earth is limitless. Another solution to the problem of transmitting information is wireless transmission using directional radio antennae or satellites. Each solution requires different materials (Wellmer and Becker-Platen 2001a). In the case of energy, we need heat or motion, which can be supplied by a variety of energy resources.

Later, we discuss how solutions can be found to the requirement of rule 2 to replace the functions of a consumed non-renewable resource and we also discuss problems that occur mainly with aggregates and building materials. We will interpret rule 2 as follows: “The consumption of non-renewable resources should not exceed the amount that can be replaced by functionally equivalent resources or by other solutions”.

However, there is a dilemma and a contradiction between the objectives of sustainable development outlined previously and the practical guidelines of rules 1–4.

There is no creation of wealth without the direct or indirect use of non-renewable resources. As outlined above, the creation of wealth to achieve economic prosperity is one of the three cornerstones of sustainable development in the Rio Declaration of 1992. Even in the information society, an infrastructure is needed, for which construction materials are necessary. Everybody needs energy for transportation and heating, and consumes food, for which fertilizers are required. This aspect is further discussed, especially for the aspect of construction materials.

There are two kinds of problems dealt with by rules 2, 3, and 4 of the Enquete Commission: source problems (from where does mankind get its necessary resources in the future) and sink problems (the return of natural resources or their products to the environment). This article deals mainly with source problems, i.e., rule 2 of the Enquete Commission and the exploitation of non-renewable resources, and deals with rules 3 and 4 later in this paper.

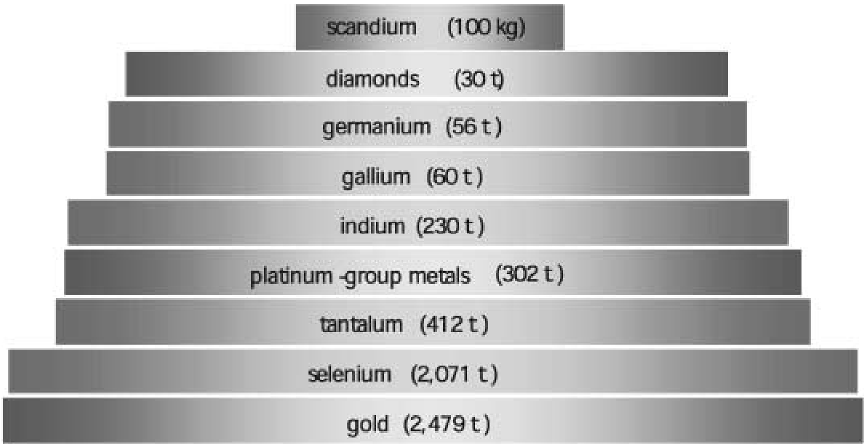


Fig. 5 The top of the quantity pyramid of Fig. 3 showing the precious metals, precious stones and "electronic" metals (Wellmer and Becker-Platen 2001b, courtesy of USGS, Deposit Modeling Symposium)

Usage and consumption statistics for mineral and energy resources

Present usage and consumption data

Current annual world usage and consumption of mineral and energy resources is about 32×10^9 tonnes (t), worth about 0.82×10^{12} Euros. Figure 3 shows a bar diagram giving the annual consumption and usage figures for all natural resources by quantity; Fig. 4 is an equivalent diagram based on value.

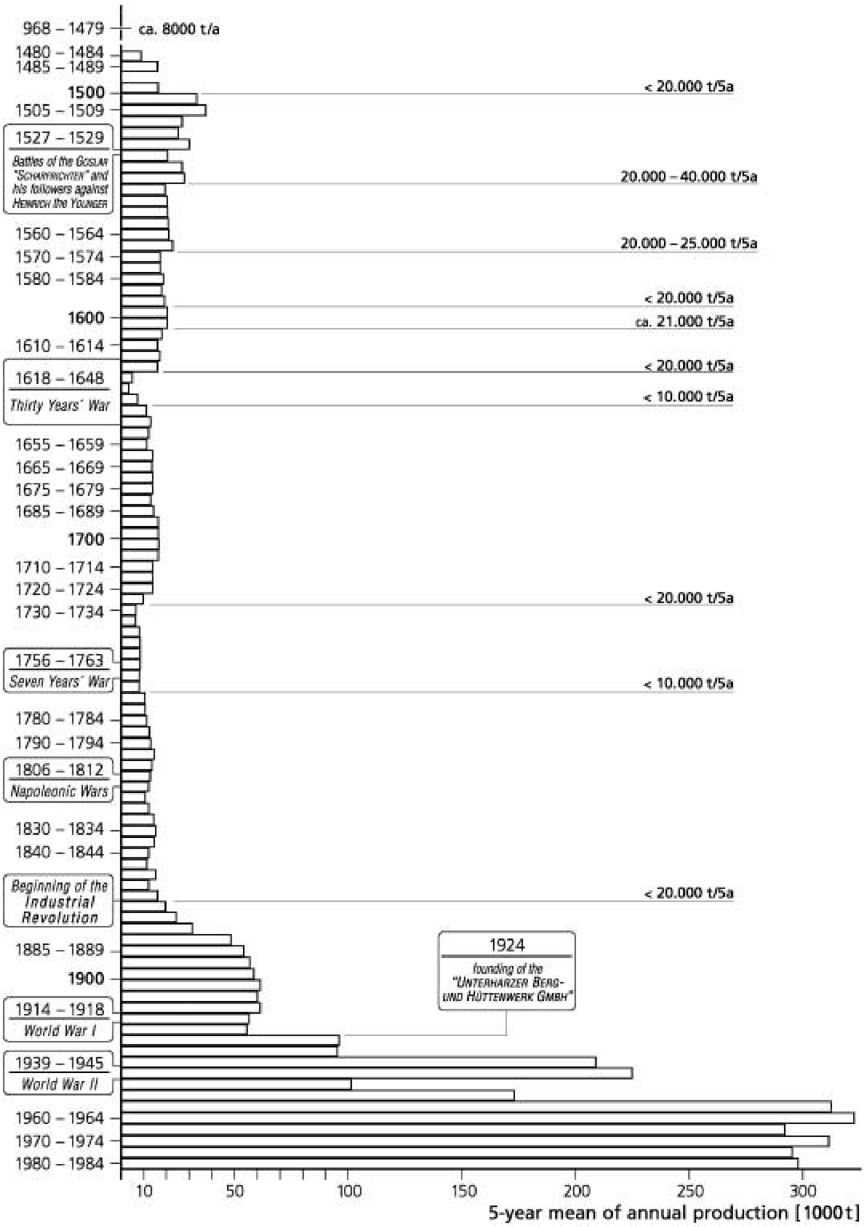
A distinction between usage and consumption is made for recycled, secondary resources, which are discussed later. Some metals such as copper and lead can be recycled without degrading the quality, i.e., without downgrading. So one may speak of usage except for the losses that always occur in recycling and re-smelting and have to be considered as consumption. In contrast, energy is consumed or the plants consume fertilizer minerals such as potassium and phosphate. These cannot be recycled. Raw materials such as cement, limestone, and marl are consumed because a chemical reaction is necessary in the cement furnace to produce cement. The cement product concrete can be recycled, but it cannot replace the original cement, limestone, or marl raw materials, but it can replace other materials to a certain extent, such as sand and gravel as aggregate.

A comparison of Figs. 3 and 4 shows that the base of the pyramid in both cases is the aggregates and energy resources required to meet our basic needs for housing, heating, and transportation. Most of the non-metallic resources are in the lower half of the quantity pyramid, whereas most of the metals are in the upper part. Only nine metals are used and consumed in quantities of more of than 1 million t annually: iron (Fe) (by far the largest metal commodity), aluminum (Al), copper (Cu), manganese (Mn), zinc (Zn), chromium (Cr), lead (Pb), titanium (Ti), and only since 1999 nickel (Ni). The very top of the quantity pyramid is, of course, made up by the precious metals and semi-precious and precious stones, represented in Fig. 3 by the most important precious stone, diamond. In the value pyramid (Fig. 4), gold, the smallest metal commodity in terms of quantity, has a higher total value than iron, the largest one. The special and "electronic" metals, such as indium, gallium, or germanium, are also at the top of the quantity pyramid (Fig. 5). They are the most important commodities in our information technology society, essential for electronic components in measuring technology and control engineering technology, which are the key elements for increasing the efficiency with which we utilize our resources, especially our energy resources. They are used annually only on the order of tens or hundreds of tonnes, but they are critical components for the efficiency of utilization of resources that are used and consumed in the order of millions and billions of tonnes (Wellmer and Becker-Platen 2001b). The aspect of improving the efficiency of resource utilization will be discussed later.

Historical considerations

Few people realize how much the production, usage, and consumption of natural resources have accelerated, especially since World War II. The absolute number of tonnes of gold of the fabulous riches, for example, of the medieval Nibelung kings, the Egyptian pharaohs or the original peoples of Latin America, such as the Moche culture in northern Peru or the Aztecs, is far too large in most people's imagination. In 1323–1324 the Mali Sultan Mansa Musa went on a pilgrimage to Mecca. He carried with him 11 t of gold, which caused a significant inflation in Egypt. The ratio of gold to silver dropped for several years from 1 oz gold/14 oz silver to 1 oz gold/8.5 oz silver (Green 1999). Today, the Bank of England auctions off 20 t of gold bimonthly in order to prevent market disturbances. From the end of the Roman empire at about A.D. 500 until the discovery of the Americas by Columbus in 1492 the estimated total gold production was about 2,500 t, more or less the same as a single year's world production today (Wellmer and Becker-Platen 2001a). Two more examples illustrate this trend:

Fig. 6 History of raw ore production from the Rammelsberg mine (Germany) from 968 to 1984 (after Dennert 1986)



1. The famous Rammelsberg mine in the Paleozoic Harz Mountains in Germany, a polymetallic SEDEX-type deposit, was in production for over 1,000 years, from 968 to 1988. In the Middle Ages it rarely produced more than 30,000 t/a of copper and zinc, for 6 weeks production at the end of its lifetime, over long periods it only produced 10,000 t/year (Fig. 6). Using a formula for the optimum lifetime of a deposit today (Taylor 1977), the deposit today would have been exhausted in 15 years.
2. From medieval times until 1820, the iron ore district of Styria in Austria never produced more than 8,500 t/year. This is about 3 days production by the Donawitz steel mill in the same Austrian iron ore district today, which is not a very large steel mill. A modern large steel mill, for example, in the Ruhr area in Germany, produces this amount in 12 h (Ameling 2000).

Figure 7a shows the relative production trends of the "old" metals gold (Au), tin (Sn), copper (Cu), and iron (Fe) with two examples of so-called "young" metals, taking the total production up to today as 100 %. Of these four metals, iron is the "youngest". The beginning of its use in the Middle East marks the birth of the Iron Age at about 3,400 years ago; gold, tin, and copper have been used even longer. Figure 7a clearly shows that, in 1945 at the end of World War II, the cumulative production of these metals at that time was less than 50% of the present day cumulative production. A comparison of this trend with the trends of "young" metals such as aluminum or nickel shows that the ratio between cumulative production before and after 1945 is even more pronounced (Fig. 7b).

Regional distribution of usage and consumption of natural resources

The regional distribution of usage and consumption should be discussed before a discussion of whether modern day usage and consumption of mineral and energy resources can be sustained and reconciled with rule 2 of the Enquete Commission, i.e., substitution of functionally equivalent resources for non-renewable resources.

It is tempting to correlate the increase in mineral and energy resources production, consumption, and usage with the increase in world population, which, in October 1999 topped 6 billion people (1900 ca. 1.6 billion, 1950 ca. 2.4 billion, and 1965 ca. 3.2 billion, Fig. 8). However, the bulk of mineral and energy resources consumption takes place in industrialized countries, which have had only a very modest population increase. The large increase in population has occurred mainly in the developing nations. We are living in an “inverse world”. About 25% of the world population lives in industrialized nations, but they consume 70 to 80% of the world’s energy and mineral resources, with a few exceptions, like coal, to be dealt with later.

This uneven usage and consumption pattern, however, represents an opportunity to find a solution to the problem of securing the future supply of mineral and energy

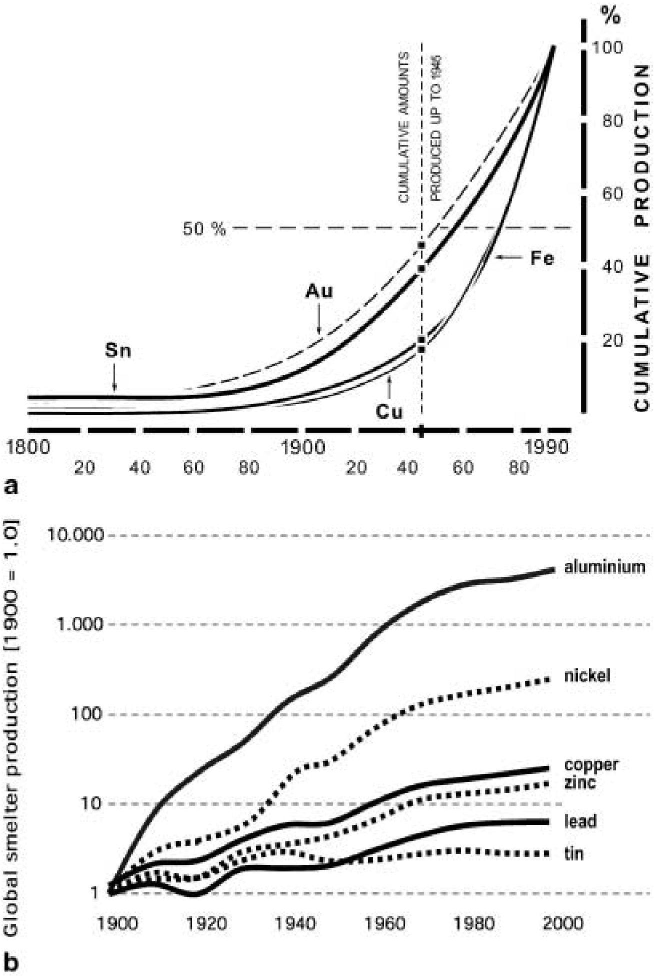


Fig. 7 **a** Cumulative world production of iron, gold, copper, and tin (Wellmer and Becker-Platen 2001a, courtesy of Encyclopedia of Life Support Systems, EOLSS Publishers, Oxford, UK). **b** Relative development of the use of the “old metals” copper, zinc, lead and tin and the “new” metals aluminum and nickel

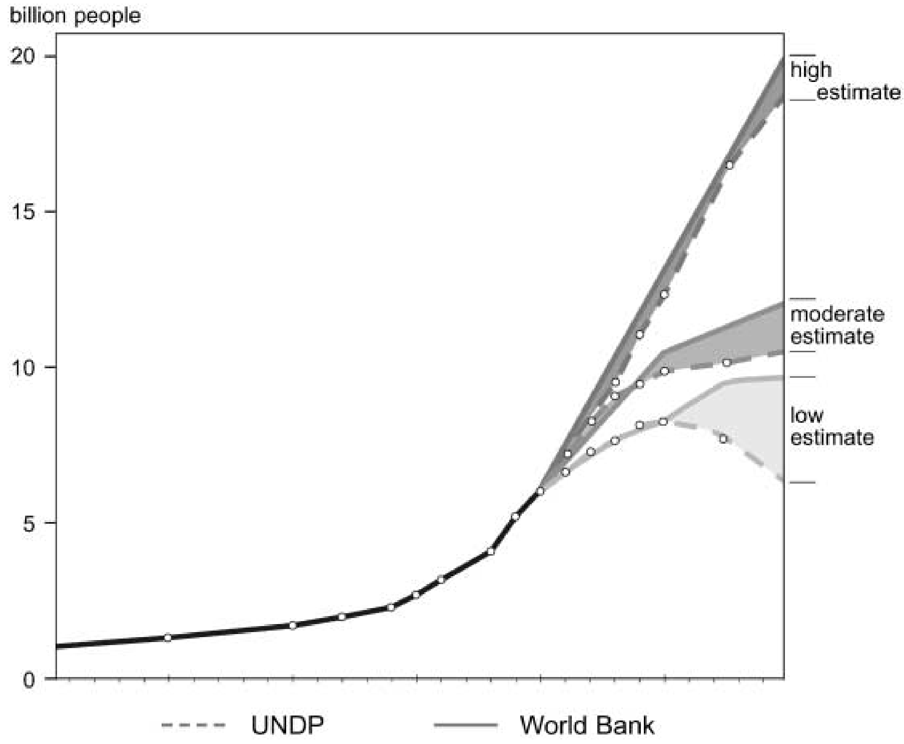


Fig. 8 Global population development

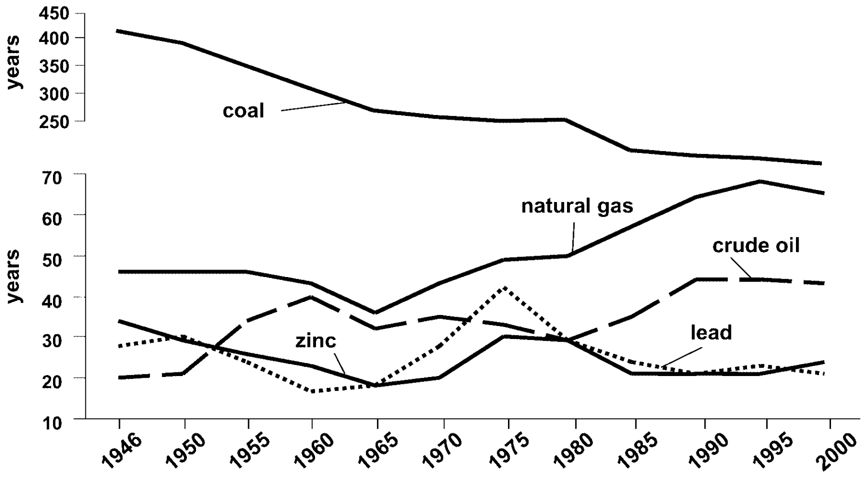


Fig. 9 Development of reserve/consumption (R/C) ratios for coal, natural gas, crude oil, zinc, and lead

resources. The efficiency of production and utilization of mineral and energy raw materials will have to be increased. This requires investments in research and development, which can be much more readily undertaken in the relatively rich, industrialized nations than in the relatively poor developing nations. Efficient technologies can then be adopted by the developing nations to meet the natural resources needs of their growing populations. This implies that the developing nations can start much higher on the learning curves for an efficient use of natural resources than the developed nations, an aspect to be discussed later. The possibility of developing countries starting with efficient technologies is an important contribution to the intrageneration fairness demanded by Agenda 21.

The future availability of mineral and energy resources

Lifetime of reserves

The future availability of resources is usually estimated using the expression “reserves lifetime” (or “life index”), which is defined as the known reserves divided by the current annual consumption, i.e., a reserves/consumption ratio (R/C ratio). In practice, this R/C ratio is a completely inappropriate measure of future availability and the expression “reserves lifetime” is a wrong interpretation. This ratio is influenced by many factors, such as the type of deposit, the statistical distribution of reserves according to deposit size, the cost of exploitation, the price of the commodity, the intensity of exploration, the development of technology, and the ratio of known deposits attracting immediate investment to those “on the shelf”, waiting for a future investment, and others (Wellmer and Becker-Platen 2001a). The R/C ratio is nothing more than a statistical “snapshot” of a dynamic system. Therefore, it is necessary to consider developments over time. The figure says more about the need for innovation than about true availability.

The factors influencing the R/C ratio are specific for each commodity. This is the reason why each commodity has a different R/C ratio, as shown for some examples in Fig. 9. The consideration over time shows whether this ratio is stable, i.e., showing that a dynamic balance is being maintained. As Fig. 9 illustrates, this is certainly the case for lead and zinc over a period of 50 years, although the R/C ratios vary only between 20 and 25 years. This R/C ratio has remained the same since 1950, despite an increase in production from 1.7 million t of lead and 2.2 million t of zinc in 1950, to 3.0 million t of lead and 8.0 million t of zinc in 1999. The same equilibrium is observed for crude oil, which has an R/C ratio between 40 to 45 years, despite an 6.4-fold increase in production from 538 million t in 1950 to 3,444 million t in 1999. Only for crude oil can we make a reasonable prediction. Because peak production for conventional crude oil, the so-called depletion midpoint, will be reached between 2010 and 2020 (Hiller 1999), we will probably see a change of the R/C ratio after that time. The natural gas R/C ratio has only recently reached its apparent equilibrium of 60 to 65 years because the natural gas market is a much younger market than that for crude oil. The R/C ratio for coal is high and decreasing. Coal seams can be easily extrapolated, i.e., there has been no need for continuous exploration. Enough reserves were known as a basis for investment to increase hard coal production of 1.451 million t in 1950 to 3.508 million t in 1999.

Especially the zinc/lead and coal examples illustrate that the R/C ratio can be considered as an indicator of the need for innovation, the available time buffer during which functionally equivalent substitutes for scarce resources must be found, following rule 2 of the Enquete Commission. Although exploration expenditures of companies are influenced by many economic factors, especially commodity prices, Fig. 10 supports the above interpretation of R/C ratios as indicating the need for innovation, displaying a general inverse relationship between R/C ratios and exploration expenditures for a certain commodity.

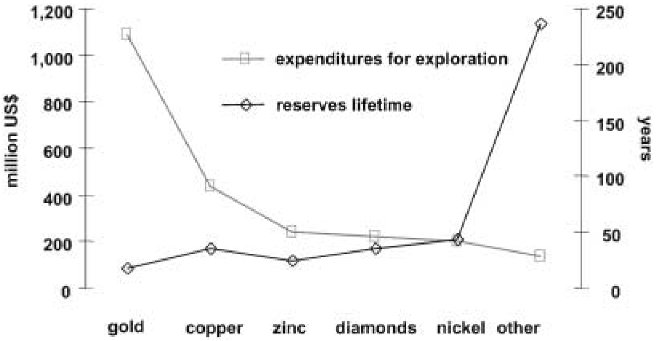


Fig. 10 Distribution of western world exploration expenditures for selected commodities compared with their reserve lifetimes (R/C ratios). Note: Pt and Pd make up about one-third of the "others"

Supply and demand cycle of mineral and energy resources

If one really wants to understand the future supply of mineral and energy resources, one must consider the supply and demand cycle for natural resources. However, it is essential to consider this in relation to one further resource: human creativity. The cycle of supply and demand for natural resources is primarily driven by the price of the commodity, although it should be noted that special aspects, such as increased environmental awareness, also play a role.

The effect of price in the supply and demand cycle can be modeled using the cobweb theorem (Fig. 11). It originated in agricultural economics and was formulated in 1938 by Ezekiel. It assumes an instantaneous reaction of the markets, which is certainly not true in mineral economics, for which long time periods are necessary for mineral or energy investments. But the first two phases of the cycle for natural resources can be modeled very well with this cobweb theorem:

Supply and demand curves are plotted in a graph of price versus quantity in Fig. 11. The higher the price of a commodity, the larger the supply, but the smaller the demand. The two curves intersect each other at point S_1, i.e., demand and supply are in balance. Let us assume the market believes there is a shortage of a commodity because of a strike, or an anticipated strike. The price rises from P_1 to P_2. At price P_2, the quantity a_2 can be produced, i.e., new mines come on stream. However, because of the higher price, demand falls and the price now falls from P_2 to P_3. At P_3, only a smaller quantity a_3 can be produced economically, etc. This shows that supply and demand counteract each other.

The case of molybdenum is a good example of how reality is modeled by the cobweb theorem. At the end of the 1970s molybdenum prices rose significantly (Fig. 12). A shortage was expected. New mines came on stream, like the Highmont mine in British Columbia, Canada, and the Thompson mine in the USA. At the same time, the high price encouraged conservation and substitution measures. As predicted by the cobweb theorem, there was a higher production and a reduced demand. Because capital-intensive mining investments, especially for large open pits as in the case of porphyry molybdenum mines, lead to reduced flexibility, each mine tried to stay in business as long as possible, overproduction was not reduced for a long time and prices fell to a level lower than before the price rise (Fig. 12).

Investment in new mines is based on previous exploration of deposits and expenditure for exploration, normally prompted by a rise in commodity price at the time of the investments in new mines. This rise of prices typi-

Fig. 11 The cobweb theorem (after Ezekiel 1938)

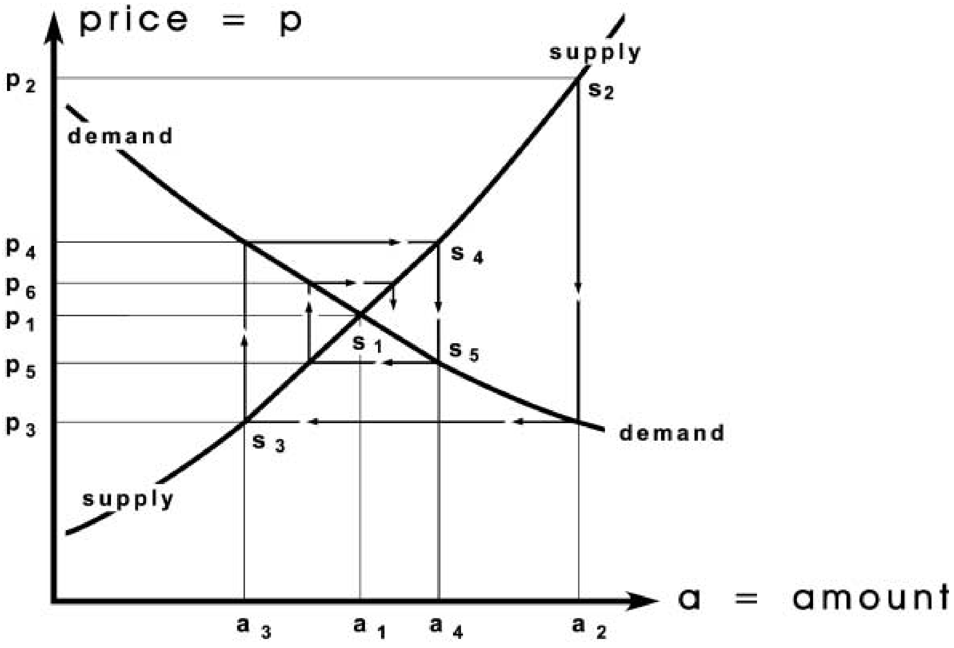
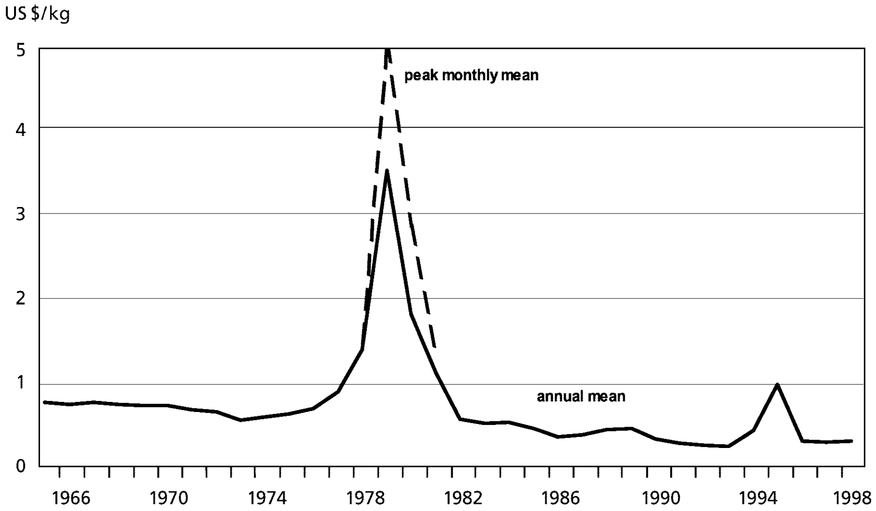


Fig. 12 Development of the relative price of molybdenum in real terms (1995=1)



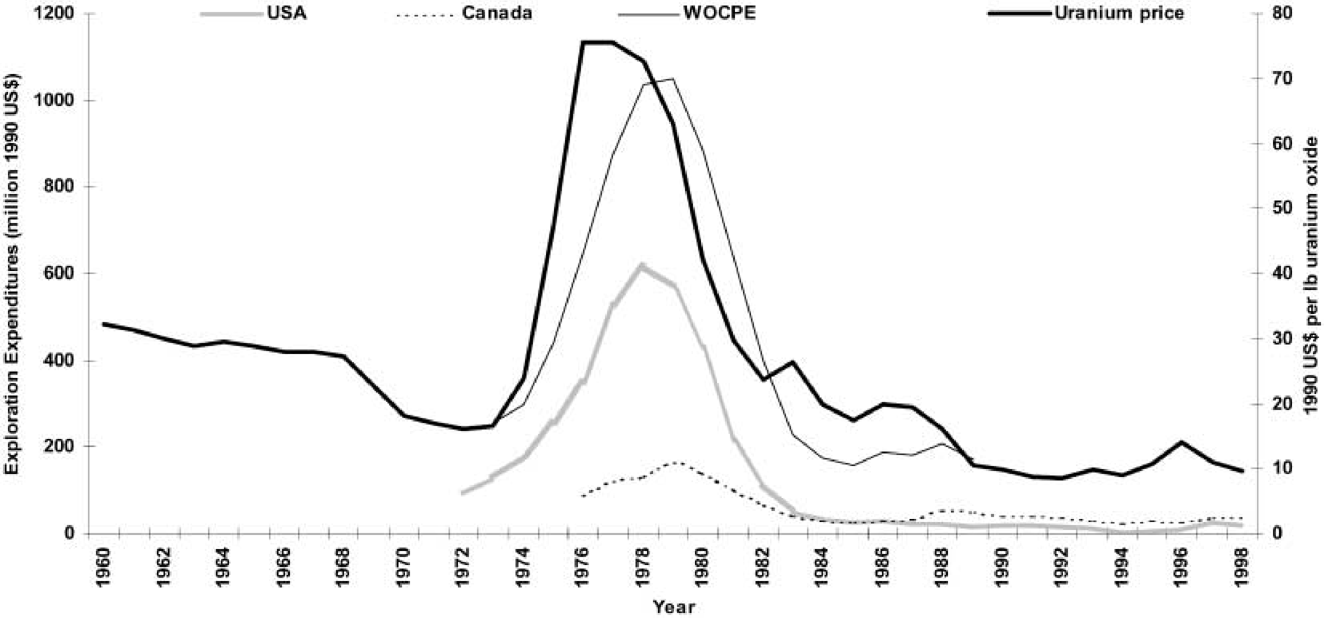


Fig. 13 The time lag of the development of the uranium price and the development of exploration expenditures for uranium in the USA, Canada, and in the World outside Centrally Planned Economies (WOCPE; after Eggert 1992; Cranstone 1997)

cally happens with a certain time lag compared with the expenditure for exploration (Fig. 13). The reason for this time lag is that it takes time to develop important exploration projects – an effect typical of learning curves.

The molybdenum example points to three possibilities for fulfilling the requirement of rule 2 of the Enquete Commission. Functionally equivalent substitutes must continually be found for exhausted resources: (1) exploration followed by investments for exploiting the reserves, (2) conservation by introducing more efficient utilization measures to reduce consumption, and (3) substitution. Other possibilities are improved recycling or finding new solutions, as illustrated above for the case of transmission of information via fiber glass instead of copper wire, or via wireless transmission using satellites. Recycling is an important factor for increasing "eco-efficiency".

Recycling

Recycling and maintaining the same quality level

A commodity that can be recycled in such a way that the new product has the same quality as the original material is "used", but not consumed. This is often true for metals. Table 2 shows the recycling rates for metals in Germany. But even for metals it is unrealistic to believe that secondary materials can eventually totally replace primary ones:

1. For certain applications very pure material is needed, which is more easily produced from primary ores than from scrap material.
2. Electrochemical recycling of the least noble metals, such as aluminum or iron leads to collect more noble metals in the recycling processes. For example, copper and tin are enriched from step to step in recycled iron or steel. There are two solutions to this problem: either to downgrade the recycled product, or to blend the recycled product with primary material to maintain the required quality.
3. The lifetimes of the products have to be considered. For example, the lifetimes of copper products lie between 30 and 50 years. Fifty years ago, annual copper consumption in Germany amounted to 250,000 t and 30 years ago it was 810,400 t. Today, consumption stands at 1.3 million t, in other words, even if 100 % of the metal used 30 to 50 years ago were available as scrap, it would not be sufficient to cover today's needs. A recycling rate of 100 %, however, is not even theoretically possible because there are always losses in the reprocessing stage, as outlined above. Furthermore a recycling rate of 100% would entail higher energy requirements and environmental impacts.
4. A product can be classified according to whether the metal it contains is pure or highly disseminated. An example of a pure metal in a product is the lead in car batteries, which is easily recyclable. Therefore, the regulation that a seller of batteries has to take back old batteries and the relatively short lifetime of these batteries is the reason why lead has a high recycling rate exceeding 50% (Table 2). Recycling such a pure secondary metal requires only 50 % of the energy required to produce lead from primary ores. Examples of highly disseminated metals are zinc in skin cream and in lithopone pigment in paint, or titanium in paint. No businessman would ever think of trying to recover metals from these products. The cost and the required energy would be far too high. Hence, there exists an optimum for a recycling rate that is not 100%. Very little research has been done to determine optimum recycling rates for various commodities. The Federal Institute for Geosciences and Natural Resources (BGR) in Hannover, Germany, has recently commissioned studies to determine the optima for several commodities (Rombach 2001).

Recycling and not maintaining the same quality level

If the quality of the material cannot be maintained in the recycling process, one speaks of downgrading. This is a typical problem in the recycling of plastics. Only in a very few cases, sticking strictly to recycling only one kind of product (PET bottles, for example), has it been possible to maintain the same quality. Even in the case of metals, the problem of downgrading can occur if a metal with a great variety of different alloys has to be recycled, as for example, in the case of aluminum or nickel. The recycled product is frequently of lower quality than the original one. The metallurgists call this the recycling spiral. After each recycling stage a lower stage of the spiral, i.e., lower in quality, is reached.

As already mentioned, the recycling of mineral resources that are changed chemically, e.g., the primary materials for cement, also have to be mentioned here. The cement product, concrete, can be only recycled for lower quality purposes. This falls in the category of waste recycling.

Table 2 Recycling rates of metals in Germany relative to consumption

Commodity	Recycled material (scrap and waste) (%)	Survey years
Aluminum	31.0–35.0	1994–1999
Lead	45.0–59.9	1994–1999
Copper	48.3–54.6	1994–1999
Zinc	34.9–40.2	1994–1999
Tin	8.4–10.4	1990–1994[a]
Raw steel	35.8–40.7[b]	1994–1998

[a] Later data incomplete
[b] As percentage of production

Table 3 Recycling rates of waste products in Germany relative to total available amounts

Raw material	Recycled material (%)	Survey years
Container glass	81	1998
Building demolition rubble[a]	70	1998
Road pavement[a]	93	1999
Fly ash from hard coal-fired plants[a]	99	1999
Gypsum from flue gas desulfurization (REA gypsum)[b]	100	1999

[a] As percentage of the total available amount
[b] Including backfill for opencast mines

Recycling of waste products

Waste should be recycled as much as possible and used to replace other primary resources, following rule 2 of the Enquete Commission to find functional replacements for consumed primary materials, as discussed above. Various countries try to influence the rate of recycling by imposing measures compatible with a market economy. For example, the German Waste Avoidance, Recovery and Disposal Act (BMU 1994) distinguishes between residues for re-use and residues for disposal. Residues for disposal are penalized, thus providing an incentive to find alternatives, i.e., to avoid or to re-use the residues. Table 3 shows the recycling rates for various waste materials in Germany.

The use of recycled materials can be seen as one factor for increasing the efficiency for sustainable development

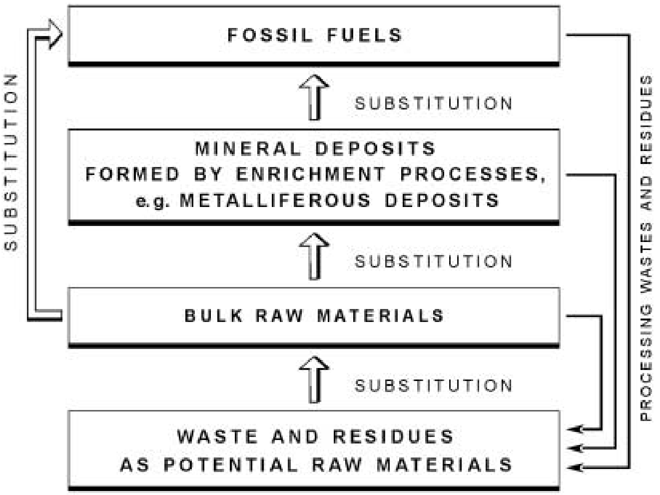


Fig. 14 Hierarchy of mineral resources: resource management for sustainable development (Wellmer and Becker-Platen 2001a, courtesy of Encyclopedia of Life Support Systems, Eolss Publishers, Oxford, UK)

of natural resources. A natural resources hierarchy has been proposed (Fig. 14, Wellmer and Becker-Platen 1999, 2001a): Wastes from the beneficiation or burning of higher value resources are at the base of this hierarchy, for example, ash from coal-fired power plants, which can be used for making cement, replacing primary cement raw materials. The next higher level consists of resources such as construction materials, whose availability from the geological point of view is unlimited in the Earth's crust, and those that, e.g., magnesium or potassium, are present in practically unlimited quantities in the oceans and may be considered practically renewable resources. Non-energy mineral resources whose deposits are created by natural enrichment, e.g., metalliferous deposits and some non-metallic deposits, such as phosphate and barite, follow these. The most valuable resources, the energy resources, occupy the top of the hierarchy. Lower value resources should always replace higher value resources. Resource efficiency is increased in this way, a continuing process that requires learning, as discussed below.

The psychological impact of forecasts

For natural resources, the last century has been called the "mass grave" of forecasting (Sames et al. 2000). If a situation is considered to be real, the consequences will be real (Thomas and Thomas 1928). Hence, the prediction is self-fulfilling. But the opposite situation also exists: the prophecy that leads to exactly the opposite situation than that predicted (Honolka 1976). This is highly relevant for forecasts in the natural resources sector: a forecast of a future commodity shortage taken seriously by industry will automatically lead to actions by industry because a future shortage means a price rise that industry will want to use to maximize its revenue. It sets in motion a process as described above in the discussion of the cobweb theorem. The best example is the Club of Rome predictions (Meadows et al. 1972). The shortages predicted caused an exploration boom, which, in turn, led to new discoveries. Since the price boom in the 1970s, many commodities are cheaper in real terms today than they were before.

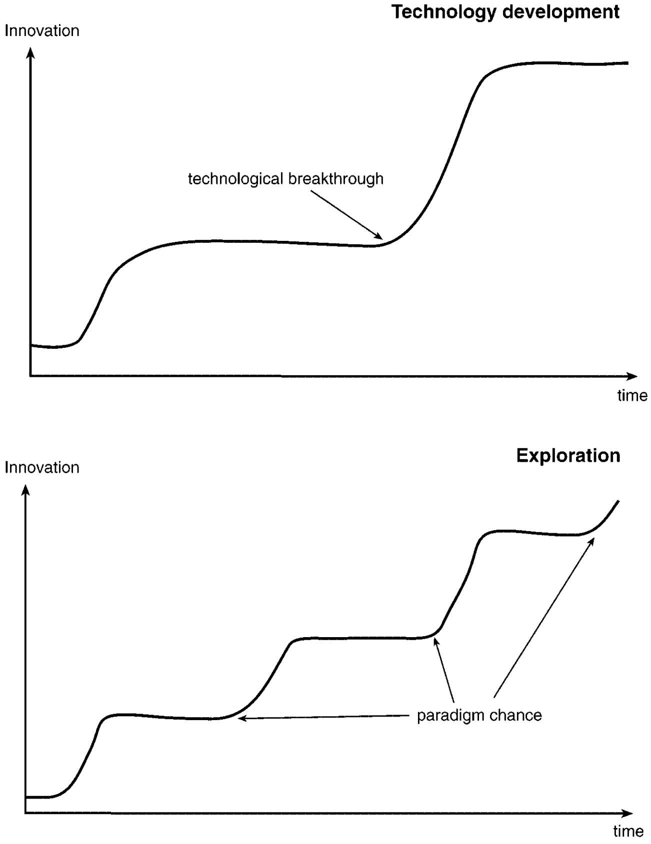


Fig. 15 Model of consecutive learning curves in technology development and in exploration

The learning process

Learning is a process that normally follows an s-shaped, sigmoidal curve. The learning curve is almost flat at the beginning, i.e., the start is difficult. Later on, the learning curve steepens and finally flattens again when a saturation stage has been reached and little or no learning occurs anymore. All the examples given above of methods for replacing non-renewable resources by functionally equivalent resources, or by finding other solutions to the problem as required by rule 2 of the Enquete Commission can be shown to have followed a learning curve (Wellmer and Becker-Platen 2001a) (Fig. 15).

Experience shows that learning curves may start anew with a new technological breakthrough, a radical innovation, or a paradigm change. The function of a technological breakthrough for the learning curves of technological developments is equivalent to a paradigm change for the

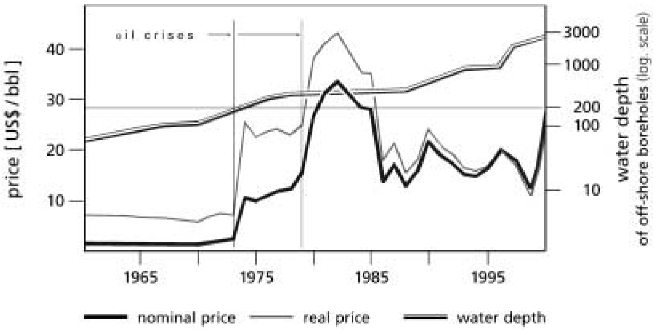


Fig. 16 The development of the price of crude oil in nominal and real terms and the maximum water depths for offshore drilling

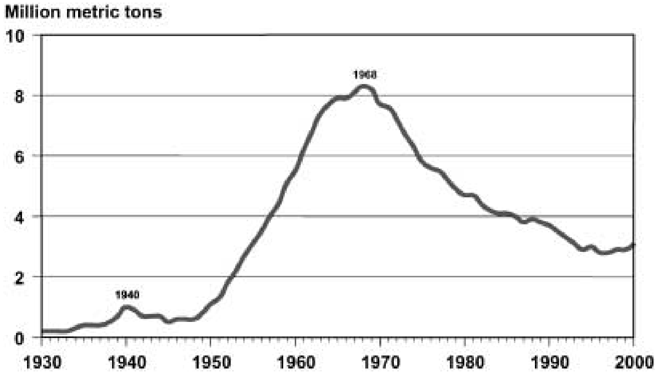


Fig. 17 German crude oil production in the territory of today's Germany from 1930 to 2000

learning curves in exploration (Fig. 15). They are similar, but the sequence of consecutive learning curves is normally faster for exploration (Wagner 1999). Therefore, the learning curves for exploration can serve as a model for those in technology development. In both sectors they are driven by financial rewards, directly (for example, by the discovery of a very economic deposit or a price increase of a commodity), or indirectly (by a penalty, for example, as described above through the German Waste Avoidance, Recovery and Disposal Act). But even if there are sufficient rewards, the learning curve is never vertical. Learning always needs time. The aspects of price and time can be illustrated with two examples from hydrocarbon exploration:

1. Figure 16 shows the development of nominal and real prices of crude oil and the increase in water depths of offshore hydrocarbon exploration wells. The critical water depth of 200 m for drilling in the North Sea was not surpassed until after the first crude oil crises with its considerable increase in price after 1974. This price rise was the "trigger" that started development along the learning curve. When the crude oil price decreased significantly after 1985, the crude oil industry was sufficiently advanced along the learning curve that, despite decreasing prices, it was able to continue to explore deeper and deeper water. The greatest water depth today for an exploration well is 2,953 m (PESGB 2001) and for a producing well it stands at 1,887 m (Society of Petroleum Engineers 2000).
2. In the Third Reich in Germany from 1933 to 1945, there was an unlimited amount of money available for the search for crude oil to "feed" Germany's war machine. As it turned out, the concept prevalent at that time that crude oil in Germany was structurally associated with salt domes was true in some cases, but wrong for the most significant deposits. Only in later times did it became obvious that the major crude oil deposits were associated with large anticlines between the salt domes (Kockel 1997). Prior to 1945, Germany never produced more than 1 million t and the peak of crude oil production was not reached until 1968 (Fig. 17), illustrating the time element necessary for climbing up the learning curve in exploration.

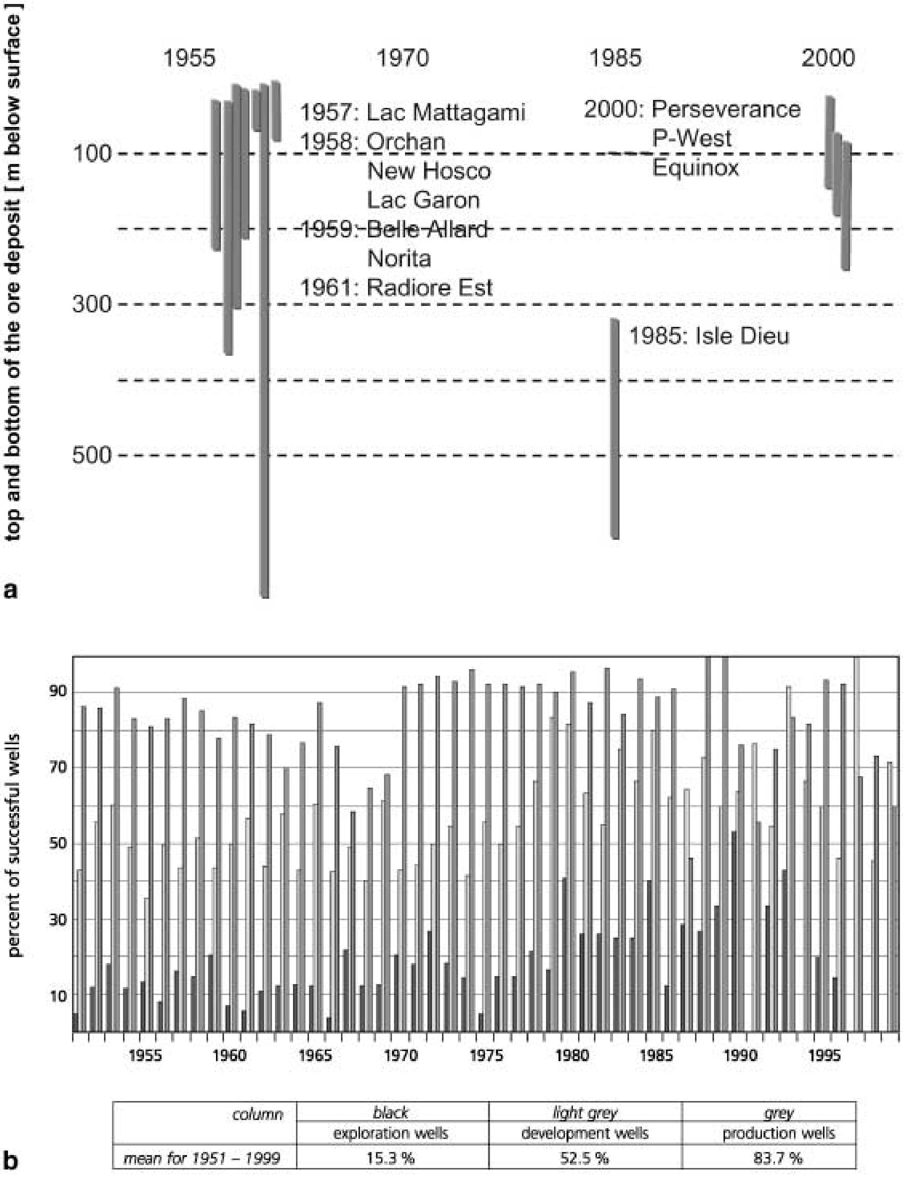
The paradigm change necessary for beginning a new learning curve is a critical element for successful exploration. It is the reason for the cyclical nature of successes typical of exploration shown, for example, in Fig. 18a for volcanogenic base metal deposits in the Mattagami district of Quebec, Canada, or in Fig. 18b for hydrocarbon exploration in Lower Saxony, Germany, where most German hydrocarbons are produced. It is also the reason why more than one company is involved in the discovery history of many deposits because each company starts with its own new learning curve. Sillitoe (1995), for example, provides statistical data about discoveries of precious and base metal deposits in the circum-Pacific region, showing that the number of companies involved up to the successful delineation of a deposit varied from 1 to 11, with a mean value of 2 (Fig. 19).

Successive learning curves can also be observed in the development of technologies for increasing the efficiency of natural resources utilization, as shown, for example, by the learning curves for improving the efficiency of lignite-fired power plants in Germany (Fig. 20).

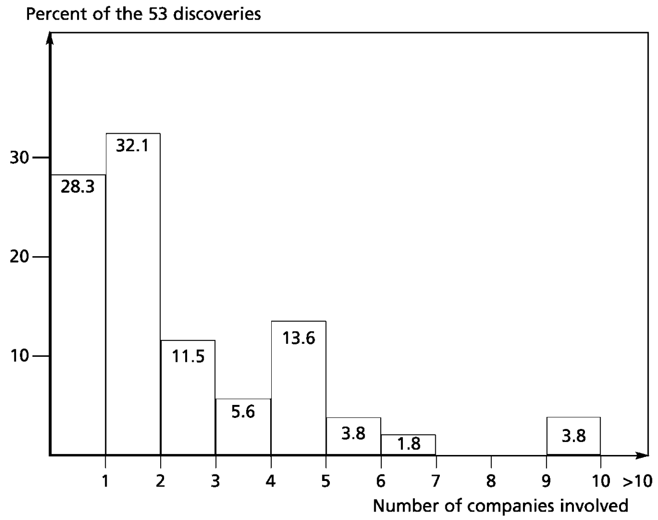
Another example of successive learning curves is provided by the hydrocarbons industry in Lower Saxony in Germany, which has developed a method of vertical and horizontal drilling combined with massive fracs in the wells within the last 20 years (Mannchen 2001):

In the Söhlingen gas field, about 100 km north of Hannover, natural gas was encountered in the Rotliegende Dethlingen Sandstone in 1980. Because of the extreme tightness of the sandstone, an economic production was not possible (the so-called "tight gas" problem). From 1982 to 1985, three additional vertical holes were drilled and special frac tests were made. Some gas could be produced, but production was still not economic. After 10 years, the horizontal drilling technology was sufficiently improved in order to be applied. The first hole was drilled 600 m horizontally within the gas-bearing sandstone and four fracs were generated, finally enabling commercial gas production. So three attempts, i.e., three learning curves, were necessary to finally arrive at the economic goal (Liermann 2001).

Fig. 18a,b Examples of the cyclical nature of exploration successes. **a** Exploration successes in the Mattagami area of Quebec, Canada, for volcanogenic copper–zinc deposits. **b** Exploration successes for hydrocarbons in the northwestern Lower Saxony basin in Germany



column	*black*	*light grey*	*grey*
	exploration wells	development wells	production wells
mean for 1951 – 1999	15.3 %	52.5 %	83.7 %



Certainly, more technological breakthroughs creating such staggered learning curves will be necessary to fulfill rule 2 of the Enquete Commission to find functional replacements for non-renewable resources.

The basic condition for such innovations and technological breakthroughs, generally, is research and development. Returning to the concept of sustainable development formulated in the Rio Declaration of 1992 to achieve the three-cornerstone concept of conserving the basic needs of life, enabling all people to achieve economic prosperity, and striving towards social justice, it is obvious from the above discussions that much learning is

Fig. 19 The number of companies involved from the start of exploration to the successful end of exploration for 53 base metal and precious metal discoveries in the circum-Pacific region (after Sillitoe 1995)

Fig. 20 Development of the efficiency of German lignite-fired power plants; DEBRIV (German Association of the Lignite Industry; Wellmer and Becker-Platen 2001b, courtesy of USGS, Deposit Modeling Symposium)

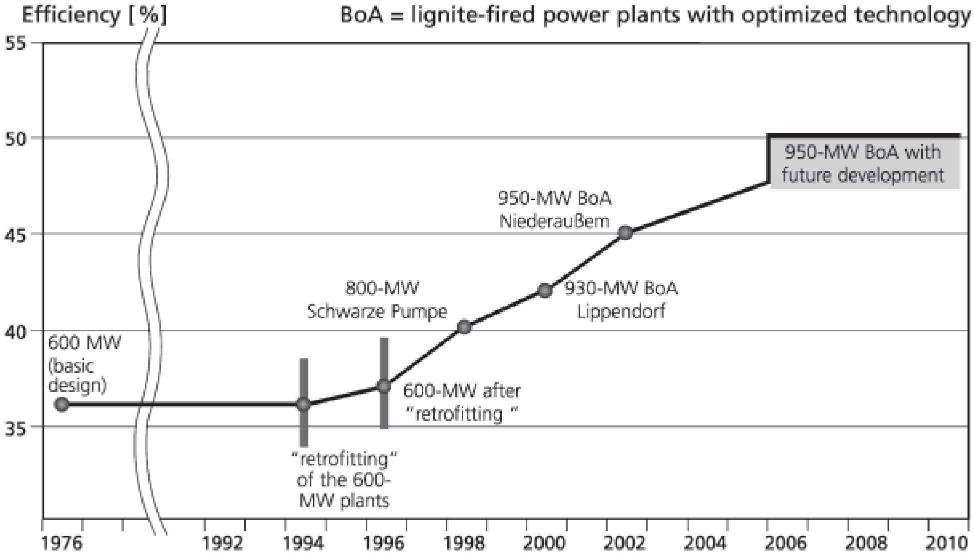
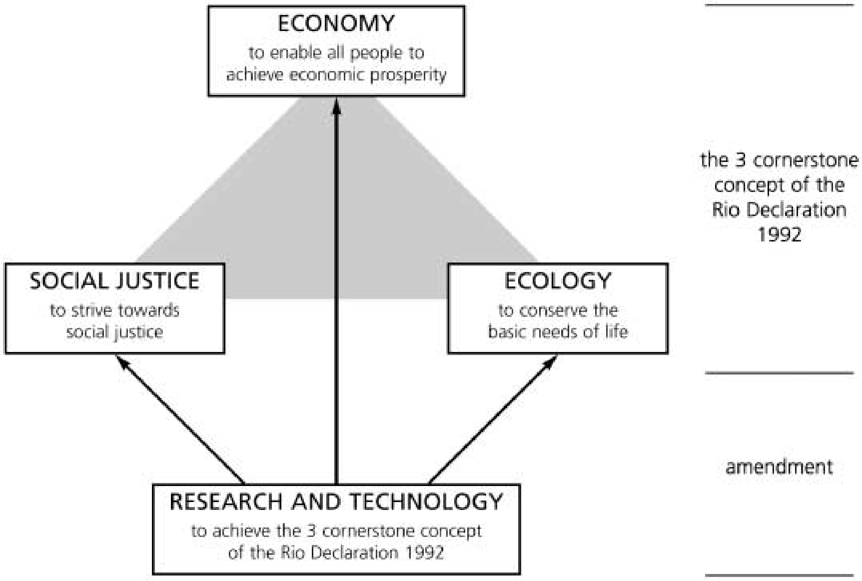


Fig. 21 The three-cornerstone concept of the 1992 Rio Declaration (economy, ecology, and social justice) extended to a four-cornerstone concept that includes research and technology (Wellmer and Becker-Platen 2001b, courtesy of USGS, Deposit Modeling Symposium)



required to put this concept to practice. Therefore, in Fig. 21, the three-cornerstone concept is amended, adding the need for research and technology to achieve a higher efficiency of natural resources, i.e., in the long run this is the only possibility for achieving sustainable development globally and for finding a solution for intrageneration fairness.

Critical examination of the requirements of rule 2 of the Enquete Commission

Above we discussed rule 2 of the Enquete Commission and how this rule can be fulfilled. We now examine this problem from the point of view of natural resources. The problem will be illustrated with examples for different types of natural resources:

1. The highest degree of inflexibility with respect to the replacement of metals is usually attributed to the steel alloy metals, e.g., chromium, vanadium, manganese, cobalt, nickel, niobium, and molybdenum. The possibilities for recycling and substitution are considered to be low (BGR-DIW-ITE 1986). Again, price is the governing factor, as clearly demonstrated during the cobalt crisis in 1978, when substitutes were developed that were previously unthinkable (Wellmer and Becker-Platen 2001a). Another example for which considerable inflexibility was postulated before the price increase is the search for a replacement for palladium in catalytic converters, initiated by a dramatic increase in the price of palladium. Most of the inflexibility of steel alloy metals stems from standardization. Substituting one alloy metal for another requires another standardization and often licensing process, a

Table 4 Distribution of selected steel alloy metals according to industrial sector in Germany and the USA (after Wellmer 1998)

Vanadium (1993)	USA (%)	Germany (%)	Mean (%)	Standard deviation (%)
Used for iron and steel for example	95	96		
Tools	9	17	13	30.7
Construction	20	22	21	4.8
Pipe	33	20	26.5	24.5
Other	5	4		

Table 5 Distribution of selected steel alloy metals according to industrials sector in Germany, Japan, and the USA (after Wellmer 1998)

Nickel (1994)	USA (%)	Japan (%)	Germany (%)	Mean (%)	Standard deviation (%)
Stainless steel and alloyed steel	49	69	73	63.7	15.3
Non-ferrous	29	10	20	19.7	32.6
Alloys electroplating	16	7	4	9	51.9
Other	6	14	3	7.7	55

Table 6 Comparison of the worldwide energy consumption with fossil and renewable energy reserves and resources (exajoules; status 1998; after BGR 1999; UNEP, UNDESA, WEC 2000)

	1998 energy consumption	Reserves (exajoule per year)	Resources (exajoule per year)
Crude oil	142	12,500	28,500
Natural gas	85	5,400	120,000
Coal	93	16,300	179,000
Nuclear	26	2,000	8,700
Sum of non-renewable energy resources	346	36,200	336,200
		Technological potential	Theoretical potential
Hydropower	9	50	147
Biomass	38	>276	2,900
Solar	9	>1,575	3,900,000
Wind		640	6,000
Geothermal		5,000	140,000,000
Ocean waves		–	7,400
Sum of renewable energy resources	56	>7,600	>144,000,000
Total	402		

Exajoule (EJ=10^{18} J)=34.1×10^6 t tce=22.8×10^6 t crude oil, =29.9×10^9 m^3 natural gas=278×10^9 kWh

procedure industry wants to avoid for economic reasons. This, however, is not a valid argument if we take a global, long-term view. An impression of the substitution potential can be obtained if we compare the industrial sectors in which the alloy metals are used in different regions as shown in Tables 4 and 5. The technological problems to be solved are the same in different industrial regions, whether Germany, Japan, or the USA. But for various reasons different solutions to these problems have been found and developed using different metal combinations (metal alloys).

2. Among the non-metallic natural resources, potassium and phosphate are the most critical ones, as mentioned already. Plants require them as nutrients. They cannot be substituted. Like water they are needed as such. In this respect they have to be considered the most critical commodities. One could speak of a natural resources paradox because, fortunately, the reserves/consumption (R/C) ratios are quite high (81 years for phosphate, 329 years for potassium), giving a substantial time buffer to find solutions. The ultimate source of potassium is seawater, practically a renewable resource. For phosphate it is more difficult to develop an alternative substance with identical properties in respect of sustainability. In contrast to potassium, however, the solubility of phosphates is very low. It is a standard method in archaeology, for example, to use trace concentrations of phosphates in soils to locate and analyze prehistoric settlements. Therefore, with improved fertilizing technology, by adding just the amount the plants need, precision farming and improved recycling of wastes, e.g., manure, the concepts for sustainability can be proposed (Wellmer and Becker-Platen 2001b).
3. With regard to energy resources, rule 2 of the Enquete Commission can, of course, be fulfilled in the long run by using renewable energy resources to replace fossil fuels or nuclear power. Certainly, the potential of renewable energy resources is sufficient to fulfill mankind's energy needs (BGR 1999; Table 6). For example, 60% of the energy demand in Germany is for heating. For this purpose, we have an unlimited heat reservoir below our feet, which could be used in low-enthalpy geothermal plants. The problem, however, is the present energy price level, making this geothermal energy source unattractive. Hence, even in a market economy system, new technologies that are low on the learning curve need support via subsidies or guaranteed higher prices to compete with mature technologies high on the learning curve. An example for this are fixed higher prices for electricity from renewable sources in Germany. This mechanism enables them to sufficiently advance on the learning curve so that they can compete on their own with the non-renewable energy resources.

   Renewable energy resources can also be used for the transportation sector, going the hydrogen route, by generating hydrogen by electrolysis using renewable energies. At present the hydrogen route stands at the

Table 7 Approved exploitation and lifetimes of sand and gravel in Baden-Württemberg, southwestern part of Germany (after BBR 1999)

Region	Approved reserves (10^6t)	Mean annual production (10^6t)	Lifetime (years)
Stuttgart	2.0	0.18	11.0
Franken	0.3	0.04	7.5
Ostwürttemberg	0.9	0.09	10.0
Mittlerer Oberrhein	99.0	13.32	7.5
Unterer Neckar	1.1	0.36	3.0
Nordschwarzwald	0	0	0
Südlicher Oberrhein	92.8	13.9	6.5
Schwarzwald-Baar-Heuberg	0.9	0.18	5.0
Hochrhein-Bodensee	28.2	4.5	6.0
Neckar-Alb	2.0	0.13	15.5
Bodensee-Oberschwaben	19.8	7.0	3.0
Donau-Iller (Baden-Württemberg part)	48.6	4.9	10.0
Baden-Württemberg total	295.6	44.6	–7

end of a “decarbonization” learning curve. Over a time span of 120 years, a decarbonization of 35% has been achieved, from coal to crude oil to natural gas. The hydrogen/carbon ratios for coal, crude oil, natural gas, and hydrogen are <1:2:4:∞ (Winter 2001). At present, carbon intensity is decreasing year by year by about 0.3% because of an increased use of natural gas, nuclear power, and renewable energies.

4. Surprisingly, it is very difficult to develop a concept for bulk construction materials that fulfills rule 2 of the Enquete Commission. Theoretically, these materials, e.g., sand and gravel, which are at the base of the quantity pyramid of all consumed natural resources (Fig. 3) and make up the second lowest level in the natural resources hierarchy (Fig. 14), are available in unlimited quantities in the Earth’s crust. However, competing land claims for settlements and infrastructure, water protection, or nature protection areas increasingly reduce the available reserves. In an excellent study for Switzerland, it was shown that such a development would lead to shortages already in the early 21st century (Jäckli and Schindler 1986). Table 7 shows available gravel resources with real lifetimes according to exploitation licenses in Baden-Württemberg in the southwestern part of Germany.

Part of the needed construction materials can be replaced by recycled materials. A recent study shows that, however, this amounts to a maximum of 10–15% of the materials needed (Bundesverband Baustoffe-Steine und Erden 2000). Some of the materials could be replaced by renewable resources such as wood. In countries such as the USA or Canada, it is much more common to build houses from wood than in Germany. However, only 21% of the sand and gravel used in Germany is used for houses, 26% for industrial buildings, 53% for public construction projects (Bundesverband der Deutschen Kies- und Sandindustrie e.V. 2001, personal communication). Especially for bridges, tunnels, etc., gravel or similar materials will always be needed; they will never be built with renewable resources.

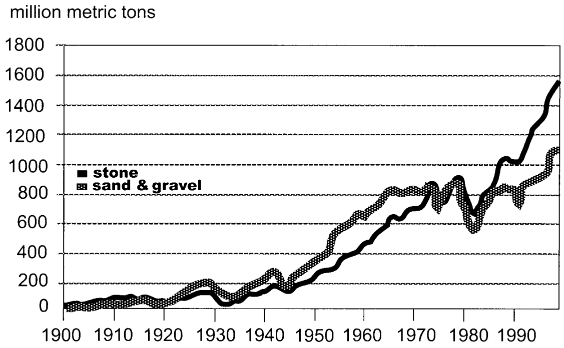


Fig. 22 Development of the consumption of sand and gravel and aggregates in the USA (Barsotti and Morse 2000)

Crushed rock, which is already transported over large distances, could be a substitute for sand and gravel. It can be excavated in open pits far from competing land claims, not disturbing the population acoustically or optically. In Germany more than 1 million t of crushed rock is imported from Norway and from Scotland by sea, rivers, and canals. The most southern inland port for such material in Germany is Aschaffenburg in northern Bavaria. The crushed rock used as an aggregate for the concrete in the tunnel beneath the English Channel, for example, came from the Glensanda pit in Scotland, which is an isolated site, accessible only by ship. From there crushed rock is exported as far as southern US ports. In the USA, crushed rock has significantly overtaken sand and gravel as an aggregate since the mid-1970s (Fig. 22).

Another possibility to conserve the increasingly scarce gravel reserves is to reduce the proportion of gravel in concrete and increase the sand content. In research on “sand-rich concrete” (DBU 2000), a special additive has been developed that increases the processing of the concrete. This additive permits the gravel content in the German type B25 concrete to be reduced from 1,287 to 331 kg/m^3, and the sand content can be increased from 686 to 1,375 kg/m^3 (Fig. 23). The sand that is produced in large quantities, together with gravel, often cannot be used. This new additive permits optimal utilization of the deposits and means less land is required for the gravel pits.

Hence, a possibility for fulfilling the requirements of rule 2 of the Enquete Commission for the construction materials at the base of the quantity and value pyramids (Figs. 3 and 4) might be to consider crushed rock as the ultimate resource that is available in unlimited quantities on Earth, or to accept that a certain contradiction exists between the objectives of sustainable development and rule 2 of the Enquete Commission as a practical guideline.

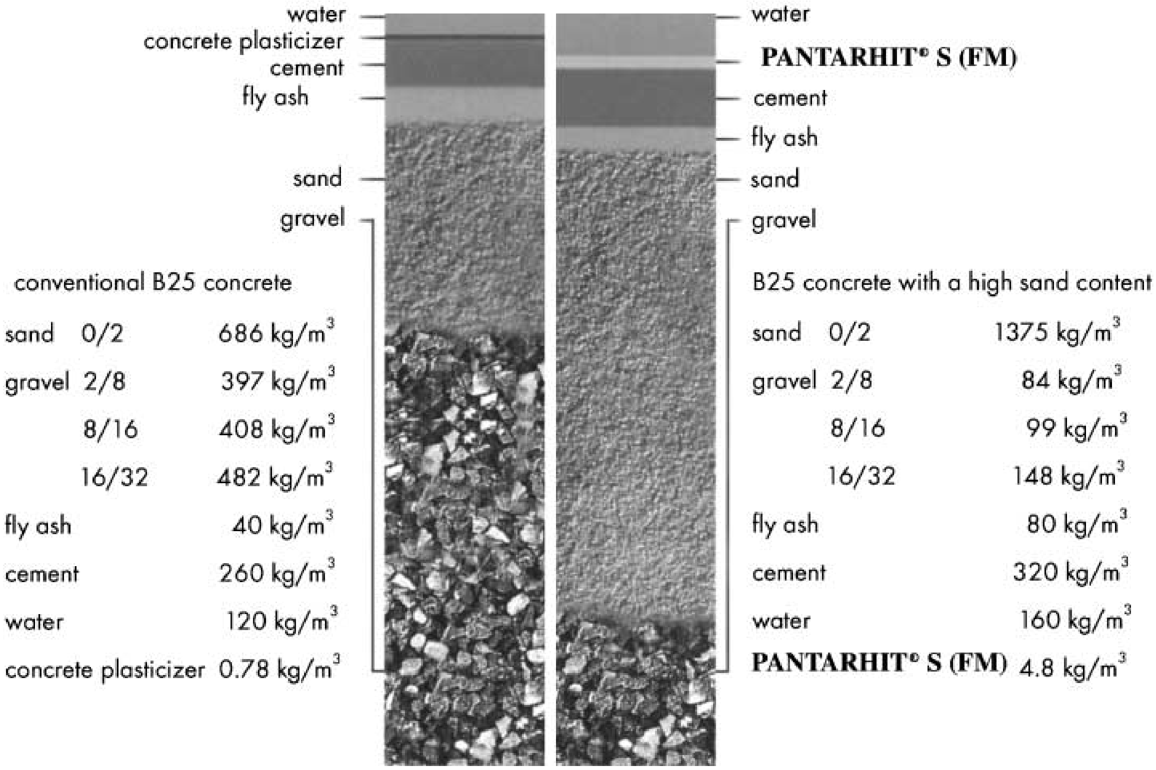


Fig. 23 Comparison of conventional concrete with concrete with a high sand content (DBU 2000)

Transfer of learning from industrial to developing nations

Above we developed concepts for fulfilling rule 2 of the Enquete Commission, which says that consumption of non-renewable resources should not exceed the amount that can be replaced by functionally equivalent resources, or by other processes. We showed that research and technology are necessary and that advancement along a learning curve corresponds to increasing resource efficiency. The money for research and development is mostly spent by the relatively rich industrialized nations rather than by the poorer developing nations. The newly developed technology has to be transferred so that the developing nations can start higher on the learning curve than the industrialized nations did. But developing nations still have to go through their own learning curves to reach a high level of resource efficiency. The metallurgical industry may be taken as an example. Smelters produce not only metals, but also residues, such as slag, and in the case of smelters processing sulfidic ores, e.g., copper and zinc ores, also sulfuric acid. In industrialized nations, all residues can, in most cases, be used today in other industrial sectors, e.g., slag is used in the construction industry, sulfuric acid in many chemical processes. Hence, residues at the base of the natural resources hierarchy in Fig. 14 are used again, replacing primary resources. This requires, however, a developed chemical industry, which a developing nation generally does not have when it starts to industrialize using its own natural resources.

The most suitable commodities for developing nations to start on their own learning curve of resource efficiency are gold and coal.

First, the advantage of mining gold is that there is practically no market entrance barrier for gold, which for other commodities can be significant. Any quantity of gold, even very small amounts from small-scale mining can be sold. Gold mining, in practice, is “money mining” (in German: Goldbergbau ist Geldbergbau).

Because of the absence of a market entrance barrier, gold mining also attracts risk capital more easily than other commodities. This can be observed in developing nations that changed their mining code, giving foreign investors a secure framework for investment, such as Ghana and Tanzania. The first ones to invest under these conditions are “junior” companies, which are risk takers to a high degree. Only at a later stage, after junior companies have established themselves successfully by discovering deposits or even operating mines, do the “senior”, i.e., traditional, mining companies move in (Wellmer and Dalheimer 1998). With other commodities and with higher market entrance barriers, the threshold for attracting investments is normally much higher and, therefore, the development of a natural resources industry is slower.

Gold mining has been severely criticized because it is to a large extent a monetary metal and, therefore, at least concerning its monetary portion, does not serve an industrial purpose. More over, the beneficiation of gold ores normally requires the use of cyanide, which can be very harmful to the environment if not used competently.

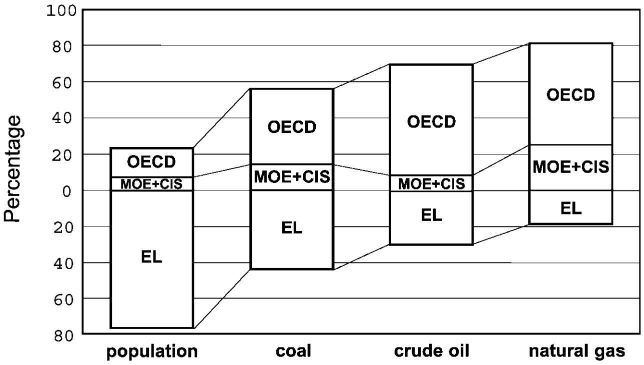


Fig. 24 The distribution of population and the consumption of fossil fuel resources in industrialized and developing nations (*MOE* central and Eastern European countries; *GUS* the countries of the former Soviet Union; *EL* the developing countries)

Without playing down the dangers of the use of cyanide, it has to be pointed out that beneficiation using this process is very well established and is applied in many parts of the world without any harmful effects. These aspects will be further discussed later. It is also an element of learning to master a technology such as gold ore beneficiation using cyanide. On the way to industrialization of developing countries, more and more complex industrial processes have to be mastered with local personnel. This mastering of increasingly more difficult technology also follows a learning curve. Using a technology like gold ore benefication, applying cyanide can be a step on this learning curve.

Second, above it was stated that we live in an “inverse world”, a 25/75% world: 25% of world’s population living in industrialized nations use 70–80% of the natural resources. There are a few exceptions, coal being one of the more evenly distributed, about 50/50% (Fig. 24). Many developing nations have coal deposits that they want to use to the maximum extent to save on energy imports. These coals are often of low quality and/or contain a high amount of sulfur. To use these coals and meet internationally acceptable environmental standards, advanced technology has to be imported, usually from industrialized nations. As discussed above, this enables developing nations to start higher on the learning curve than the industrialized nations started originally. It also points to a moral obligation of industrialized nations to use all available energy resources, including renewable resources, and to advance the energy efficiency of all kinds of energy resources as examples to be followed by developing nations.

The sink problem of natural resources and the resilience of the environment

Mining and reclamation

So far we have only dealt with rule 2 of the Enquete Commission for the use of non-renewable resources. We now also have to consider rules 3 and 4, which deal with the resilience of the environment and the carrying capacity of our Earth system.

“He who mines must dig”. This is unavoidable, even though it has an environmental impact. In a recent study by Neumann-Mahlkau (1997), it was shown that anthropogenic mass movements have reached the same order of magnitude as geogenic mass movements (about 35 versus 37 billion m^3/year). We have, however, learned a considerable amount in the last 30 years, enough to reduce such impacts. There is a legal term for this in the Anglo-American legal system: good miner’s practice, i.e., adhering to a “code of best practice”, meaning a high professional standard, always using the best available technology, taking into account economic considerations (BATNEEC = best available technology not entailing excessive costs). With respect to reducing environmental impacts, the mining industry has moved along a long learning curve. It originally started in the Cologne lignite area, where Elector Maximilian Friedrich in 1784 enacted a recultivation order, which in 1865 was taken up by Prussian mining law (Hartung 1997). The learning curve steepened in 1939, when the German lignite mining industry was forced by law to save the topsoil for later reclamation of the lignite open pit mines. Typically, the learning curve started first in densely populated areas or countries such as those in Central Europe, where competing land claims became apparent first. Today, for example, even in semi-arid areas in Western Australia without any population and with only very extensive sheep raising, dumps for open-pit gold mines have to be fitted morphologically into the landscape. In most countries, mining companies have to post bonds with government authorities to ensure that mine sites are reclaimed according to professional standards. BATNEEC has advanced in almost every industrialized country today to the point that areas used to extract natural resources are practically not “consumed” areas anymore, but “borrowed” areas for temporary use. These “borrowed” areas are minimized to a large extent as can be seen, for example, with the development of the large interconnected mines in the German coal mining area in the Ruhr Valley. In Germany, for example, all land temporarily used to exploit natural resources has to be recultivated for use as industrial, agricultural or forest land, for recreational purposes, or as a nature reserve (renaturation). Frequently, it can be observed that new biotopes with special characteristics develop on recultivated sites and merit to be protected as much as the original biotopes before mining (Bayerische Akademie der Wissenschaften 2000, Stein 2000). The mining industry is progressing further on this learning curve. Kippenberger (1999) developed a model of an “ecological mine”, in which no residues are left above ground. This model has been put to practice already by the fluorite–barite mine at Wolfach in southern Germany’s Black Forest.

Aspects of beneficiation

Chemicals are normally used for beneficiation. It is a standard procedure of BATNEEC to recycle the water, including the chemicals, via a tailings dam as much as possible and to make sure that effluent concentrations remain below threshold values and only a minimal amount of chemicals reaches the environment. However, accidents in the past, especially those involving tailing dams, which cause considerable damage to the environment, have led to widespread public criticism of the mining industry. Although the environmental damage should not be played down, it has to be pointed out that proper geotechnical methods for the construction and safe management of tailings dams and proper planning methods for possible overspills are available.

Certainly, one of the most critical elements of beneficiation is the poisonous substance cyanide used in the processing of gold ores, but also in other beneficiation processes. Few people know that cyanide is used safely in a variety of industrial processes. Strict guidelines to ensure that no damage is done to the environment are necessary. One target group is local small-scale miners. For developing nations, the necessary transfer of know-how and training can be obtained from technical cooperation agencies of industrialized countries in projects with the local small-scale mining community. The other target group is junior companies described above as risk takers, a group that is important in the start-up of a mining industry in developing nations. Government authorities and psychological peer pressure of the mining community has to make sure that the risk-taking psychology is not applied to environmental safeguards via “taking short cuts”. The community of major mining companies is working – also on a learning curve – to establish environmental guidelines that are enforced even at the furthest, most remote mine from the main offices of the parent mining company. With regard to the use of cyanide, an important initiative has been taken by the United Nations Environment Programme (UNEP) to develop an international code to ensure that no damage is done to the environment (Balkau 2000).

International and national guidelines for sustainable development

The above-mentioned principles of “good miner’s practice” and BATNEEC are general guidelines for adherence to the highest standards. Some examples of concrete guidelines are mentioned here:

1. The so-called Berlin Guidelines of the International Round Table on Mining and the Environment (Carl Duisberg Gesellschaft 1999).
2. The Sustainable Development Charter of the International Council of Metals and Mining (ICMM) whose members are major international metal mining and smelter companies (ICMM 2001).
3. Australia’s Best Practice Environmental Management in Mining – a partnership between the Australian Government’s Environment Protection Agency and the Australian mining industry (EPA 1995).
4. For the International Finance Corporation (IFC) of the World Bank Group, compliance with its Environmental, Health, and Safety Guidelines is the expected standard for investment into projects, in addition to compliance with applicable local, national, and international laws (IFC 2001).
5. The Global Mining Initiative, launched in 1999 by 27 of the world’s leading mining companies, sponsoring a major study: “Mining, minerals and sustainable development”, which will be discussed in 2002, coinciding with the 10th anniversary of the UN Conference on Environment and Development in Rio de Janeiro (Wilson 2000).
6. The Prospectors and Developers Association of Canada (PDAC) intends to assemble, organize, and make accessible current information on responsible environmental management practices in the exploration sector in the form of on e-manual “Environmental management practices for global mineral exploration” (PDAC 2001).

Concluding remarks

Ways and means have been discussed for finding solutions to the intergeneration and intrageneration challenges posed by the concept of sustainable development with regard to the use and consumption of energy and mineral resources. So far, the mechanisms for continually finding new possibilities for the substitution of non-renewable resources have worked in our market economy system. In the opinion of the authors, there is no reason to believe that these mechanisms will not function in future. To find functional replacements for non-renewable resources, to bridge the gap between the industrial and developing nations, and to fulfill the requirement that the environment and the sink capacity are not overused, technological advances have to be made so that we can continue to advance on the learning curve. The motor for advancement on a learning curve in a market economy will always be financial rewards, either directly from the price of commodities, or indirectly by penalties, e.g., for overusing environmental capacities.

A far more pressing problem for mankind lies in another area (Wellmer and Becker-Platen 2001a): food for an ever-increasing population. Fresh water and soil are needed for growing food. In many arid and semi-arid areas, fossil water is used today, which has to be considered a non-renewable resource in the medium term. Huge quantities of soil, which in the medium term also have to be considered as a non-renewable resource, are lost every year because of erosion by water and wind, thus reducing the amount of arable land. Contamination of the soil can also be a serious problem. Thus, the concept of carrying capacity and natural attenuation is a very critical one with regard to soil.

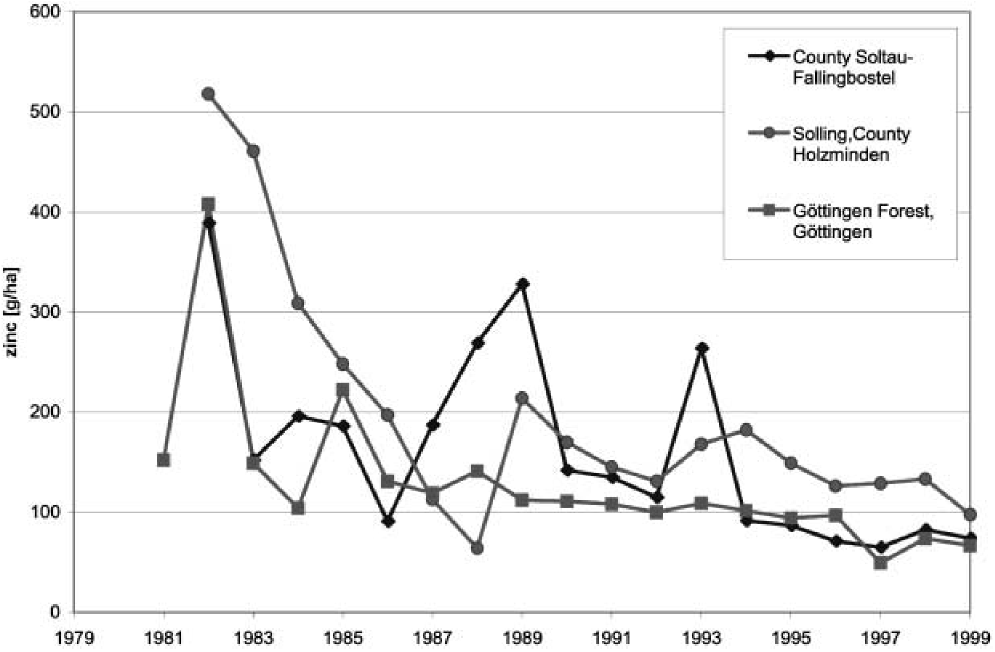


Fig. 25 Annual particulate deposition of zinc (g/ha) on forested observation plots in Lower Saxony (courtesy of Forest Research Institute of Lower Saxony)

Table 8 Mean concentration of heavy metals in sewage sludge used in agriculture (mg/kg dry mass; after Umweltbundesamt 2001)

Element	1991–1994	1995	1996	1997	Legal limit	Trend in 1997 with respect to 1991–1994 (=100%) (%)
Lead	93	73	67	63	900	–32
Cadmium	2.1	1.5	1.5	1.4	10[a]	–33
Chromium	59	52	52	46	900	–22
Copper	286	277	273	274	800	–4
Nickel	31	24	23	23	200	–26
Mercury	2.1	1.3	1.3	1	8	–52
Zinc	1,076	863	831	809	2,500[a]	–25

[a] For light soils with a clay content of <5% or a pH of 5–6, the values for Cd and Zn are 5 and 2,000, respectively

Some examples illustrating the importance of soil and water are given here: two examples to show how measures to protect soil and groundwater are becoming effective, and a third to show the need for developing monitoring methods and for research on transfer processes.

1. The annual input of zinc (g/ha) into the soil from atmospheric emissions has been monitored for more than 20 years in three forested areas of Lower Saxony. Zinc input in 1982 amounted to 400–500 g/ha, in 2000 it was less than 100 g/ha (Fig. 25), documenting the effectiveness of current environmental protection measures, in this case improved flue gas filters to reduce particulate emissions.
2. Limits for the concentration of heavy metals in sewage sludge used as fertilizer are fixed by the German sewage sludge regulations (BMU 1992). Average concentrations of heavy metals in sewage sludge decreased up to 1997 by 4% for copper to 52% for mercury (Table 8). The heavy metal concentrations have thus decreased to 5% of the limit for chromium, for example, and 32% for zinc.
3. Studies on pharmaceuticals used in animal husbandry have been conducted in northwestern Lower Saxony, where there is a high concentration of intensive livestock farming. In this region, 150,000–200,000 kg of pure medicinal substances are used annually. The most important groups of medicines are tetracyclines (52%) and sulfonamides (19%) (Winckler and Grafe 2000). A maximum of 50% of the tetracyclines is degraded in the animals or in the liquid manure. Thus, it can be assumed that approximately 37,000–50,000 kg of tetracycline reach the soil every year. Soil studies have found concentrations of 1–32 ppb (µg/kg soil) in topsoils regularly fertilized with liquid manure from pigs (Hamscher et al. 2000). In a number of cases, this exceeds the EMEA limit (EMEA 1996; EMEA = European Agency for the Evaluation of Medicinal Products) of 10 ppb for soils (100 ppb after the summer of 2001). No tetracyclines were found in subsoils (35–90 cm depth) or near-surface groundwater (Hamscher et al. 2000). The mobility of tetracyclines in the soil and their influence on the soil must the subject of further studies. Does acidification of the

soil increase desorption of the active substance? What is the effect on the soil bacteria? Does the massive application of antibiotics in agriculture promote the development of antibiotic resistant microorganisms?

These examples for soil and water illustrate the efforts already undertaken, which will be necessary in the future to conserve our soil and water resources and to not overuse the carrying capacity of our Earth system. It may seem to be a paradox: for his future, man should be more concerned with renewable resources than – with the exception of soil – with non-renewable resources.

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References

Ameling D (2000) Stahl – eine Werkstoffindustrie im Wandel. Erzmetall 53(10):595–602

Balkau F (2000) Cyanide management in gold mining: an international code. Int Counc Metals Environ Newslett 8(3):4

Barsotti AF, Morse DE (2000) Industrial minerals 1999. Industrial minerals in the United States. Mineral Eng June 2000:21–69

Bayerische Akademie der Wissenschaften (2000) Bergbau-Folgeschäden und Ökosysteme. Rundgespräche der Komm für Ökologie, vol 20. Dr. Friedrich Pfeil, München

BBR (Bundesanstalt für Bauwesen und Raumordnung) (1999) Vorsorgende Sicherung oberflächennaher Rohstoffe in Regionalplänen. Forschungen, vol 91. Bundesamt für Bauwesen und Raumordnung, Bonn, pp 1–131

BGR (Bundesanstalt für Geowissenschaften und Rohstoffe) (1998) Bundesrepublik Deutschland – Rohstoffsituation 1998 Rohstoffwirtschaftliche Länderstudien XXI, Hannover

BGR (Bundesanstalt für Geowissenschaften und Rohstoffe) (1999) Reserven, Ressourcen und Verfügbarkeit von Energierohstoffen. Rohstoffwirtschaftliche Länderstudien XVII, Hannover

BGR (Bundesanstalt für Geowissenschaften und Rohstoffe) (2000) Bundesrepublik Deutschland – Rohstoffsituation 1999. Rohstoffwirtschaftliche Länderstudien XXIII, Hannover

BGR-DIW-ITE (Bundesanstalt für Geowissenschaften und Rohstoffe, Deutsches Institut für Wirtschaftsforschung, Institut zur Erforschung technologischer Entwicklungslinien) (1986) Versorgungslage bei Rohstoffen. Hannover

BMU (Bundesminister für Umwelt, Naturschutz und Reaktorsicherheit) (1992) Klärschlammverordnung (AbfKlärV). Bundesgesetzblatt I 1992:912–934

BMU (Bundesminister für Umwelt, Naturschutz und Reaktorsicherheit) (1994) Gesetz zur Vermeidung, Verwertung und Beseitigung von Abfällen. Bundesgesetzblatt I 1994:2705–2728

Brundtland GH (1987) Our common future. World Commission on Environment and Development. University Press, Oxford

Bundesverband Baustoffe – Steine und Erden (2000) Der Bedarf von mineralischen Baustoffen. Frankfurt/Main

Carl Duisberg Gesellschaft (1999) Report on the International Round Table on Mining and the Environment, Section for Protection of the Environment and Natural Resources. Berlin

Cranstone D (1997) Mineral exploration in Canada. Geowiss 15(10–11):323–330

DBU (Deutsche Bundesstiftung Umwelt) (2000) Ökologisches Bauen (2. Auflage). Osnabrück

Dennert H (1986) Bergbau und Hüttenwesen im Harz vom 16. bis zum 19. Jahrhundert dargestellt in Lebensbildern früherer Persönlichkeiten. 2. Auflage Pieper, Clausthal-Zellerfeld

Eggert RG (1992) Exploration. In: Peck MJ, Landsberg HH, Tilton JE (eds) Competitiveness in Metals – the impact of public policy. Mining Journal Books Ltd. London, pp 21–67

EMEA (European Agency for the Evaluation of Medicinal Products) (1996) Note for guidance: environmental risk assessment of veterinary medical products other than GMO-containing and immunological products. Communications for Veterinary Medical Products/055/96, EMEA, London

Enquete-Kommission "Schutz des Menschen und der Umwelt – Bewertungskriterien und Perspektiven für umweltverträgliche Stoffkreisläufe in der Industriegesellschaft" des 12. Deutschen Bundestages (1993) Verantwortung für die Zukunft: Wege zum nachhaltigen Umgang mit Stoff- und Materialströmen. Economica, Bonn

EPA (Australian Environment Protection Agency) (1995) Overview of best practice environmental management in mining. EPA, Canberra

Ezekiel M (1938) The cobweb theorem. Q J Econ 52(1):255–280

Green T (1999) The millennium in gold, 1000–1999. The essential guide to prices, production and key events. Information Press, Oxford

Hamscher G, Sczesny S, Abu-Qare A, Höper H, Nau H (2000) Stoffe mit pharmakologischer Wirkung einschließlich hormonell aktiver Substanzen in der Umwelt: Nachweis von Tetracyclinen in güllegedüngten Böden. Dtsch Tierärztliche Wochenschr 107(8):332–334

Hartung M (1997) Wege zur Gestaltung der Bergbau-Folgelandschaft im rheinischen Braunkohlerevier. Braunk Surface Mineral 49(4):379–385

Hiller K (1999) Verfügbarkeit von Erdöl. Erdöl, Erdgas, Kohle 115(2):50–54

Honolka H (1976) Die Eigendynamik sozialwissenschaftlicher Aussagen: Zur Theorie der self-fulfilling prophecy. Campus, Frankfurt/M

ICMM (2001) http://www.icme.com/html

IFC (International Finance Corporation) (2001) Environmental health and safety guidelines. www.ifc.org/enviro/pollution/guidelines.htm

Jäckli H, Schindler C (1986) Möglichkeiten der Substitution hochwertiger Alluvialkiese durch andere mineralische Rohstoffe. Beitr Geol Schweiz Geotech Ser 68:1–177

Jeffery WG (1998) A world of metals: finding, making and using metals. The International Council on Metals and the Environment, Ottawa, Ontario

Kant E (1784) Beantwortung der Frage: Was ist Aufklärung? Berlinische Mschr 1784, quoted from: Gesammelte Schriften – Preuß Akad (ed) Berlin, Abt 1, B 18

Kippenberger C (1999) Stoffmengenflüsse und Energiebedarf bei der Gewinnung ausgewählter mineralischer Rohstoffe – Auswertende Zusammenfassung. Geol Jahrb R H Sonderh 10:1–52

Kockel F (1997) 50 Jahre Geotektonische Karte von Nordwestdeutschland 1:100,000 – Grundlagen, Entstehung und wirtschaftlicher Nutzen. Z Angew Geol 43(1):35–41

Liermann N (2001) Söhlingen tight gas development. Paper from the Annual Meeting Wirtschaftsverband Erdöl- und Erdgasgewinnung e.V. 31.5.2001, Wolfsburg

Mannchen H (2001) High Tech bei der Erdgas-Förderung. Das Erdgasprojekt Söhlingen Z-14 setzt neue Maßstäbe. Technik und Leben 2/01, Verein Deutscher Ingenieure, Hannover, pp 11–12

Meadows DH, Meadows DL, Randers J, Behrens WW (1972) The limits to growth: a report for the Club of Rome's project on the predicament of mankind. Universe Books, New York

Neumann-Mahlkau P (1997) Anthropogenic material flow – a geological factor. Proc 30th Int Geol Congr 2 and 3, pp 61–66

PDAC (Prospectors and Developers Association of Canada) (2001) PDAC environmental manual. Mineral J 337(8665):467

PESGB (Petroleum Exploration Society of Great Britain) (2001) Oil company key facts – Unocal Corporation. PESGB Newslett 6/2001:48

Rombach G (2001) Optimum der Nutzung von Sekundärmetallen – Ökonomische und ökologische Grenzen des Metallrecyclings. Institut für Metallurgische Prozesstechnik und Metallrecycling, RWTH Aachen

Sames C-W, Kegel K-E, Johannes D (2000) Millennium – 100 Jahre Bergbau im Rückblick. Erzmetall 53(12):759–760

Sillitoe RH (1995) Exploration and discovery of base- and precious-metal deposits in the circum-Pacific region during the last 25 years. Soc Resour Geol Tokyo, Resour Geol Spec Issue 19:1–119

Society of Petroleum Engineers (2000) Regional update. J Petrol Technol 52(8):6

Stein V (2000) Die Zeit danach – Kies und Sand, Rekultivierung-Renaturierung. Bundesverband der Kies- und Sandindustrie, Duisburg

SRU (Rat von Sachverständigen für Umweltfragen = German Expert Commission for the Environment) (1994) Umweltgutachten 1994. Deutscher Bundestag 12. Wahlperiode, Drucksache 12/6995

Taylor HK (1977) Mine valuation and feasibility studies. In: Hoskins JR, Grenn WR (eds) Mineral industry costs. Northwest Min Assoc, WA, Spokane, pp 1–17

Thomas WI, Thomas DS (1928) The child in America. Behaviour problems and programs. A.A. Knopf, New York

Umweltbundesamt (2001) Daten zum Umwelt-Zustand der Umwelt in Deutschland 2000. E Schmidt, Berlin

UNEP (United Nations Development Programme) (1989) UNEP Governing Council Decision 15/2 May 1989, Annex II. GOAR 44th Session Suppl no 25

UNEP, UNDESA, WEC (United Nations Development Programme, United Nations Department of Economic and Social Affairs, World Energy Council) (2000) World energy assessment: energy and the challenge of sustainability. UNDP, New York

von Carlowitz HC (1713) Sylvicultura oeconomica. Braun, Leipzig

Wagner MKF (1999) Ökonomische Bewertung von Explorationserfolgen über Erfahrungskurven. Geol. Jbuch Sonderh 12:1–225

Wellmer F-W (1998) Lebensdauer und Verfügbarkeit mineralischer Rohstoffe. In: Zemann J (ed) Energievorräte und mineralische Rohstoffe: Wie lange noch? Österr Akad Wiss, Schriftenr Erdwiss Komm 12:47–73

Wellmer F-W, Becker-Platen J.D (1999) (eds) Mit der Erde leben – Beiträge Geologischer Dienste zur Daseinsversorgung und nachhaltigen Entwicklung, Springer, Berlin Heidelberg New York

Wellmer, F-W, Becker-Platen J.D (2001a) World natural resources policy (with focus on mineral resources). In: Tolba MK (ed) Our fragile world – challenges and opportunities for sustainable development. 1. Eolss Publishers Co. Oxford, pp 183–207

Wellmer F-W, Becker-Platen JD (2001b) Global nonfuel mineral resources and sustainability. In: Briskey JA, Schulz KJ (eds) Proc 31st International Geological Congress Workshop on Deposit Modeling, Mineral Resource Assessment, and their Role in Sustainable Development. US Geological Survey Circular

Wellmer F-W, Dalheimer M (1998) Trends in der Rohstoffwirtschaft – Die Rolle der "Junior"-Firmen und der Berggesetzgebung für die internationale Exploration. Glückauf 134(9):528–534

Wilson R (2000) The global mining institute. Int Council Metals Environ Newslett 8(3):1–2

Winckler C, Grafe A (2000) Charakterisierung und Verwertung von Abfällen aus der Massentierhaltung unter Berücksichtigung verschiedener Böden: Stoffeintrag durch Tierarzneimittel und pharmakologisch wirksame Futterstoffe unter besonderer Berücksichtigung von Tetrazyclinen. Umweltbundesamt Texte 44/00, Umweltbundesamt, Berlin

Winter C-J (2001) Kraftstoffe im 21. Jahrhundert – nachhaltig. Paper Fachkonferenz Zukunft und Wirtschaftlichkeit von Kraftstoffen, Forschungszentrum Jülich, 13./14.3.2001