

16.7 NONRENEWABLE RESOURCES

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SUMMARY

In the universe of natural resources, minerals are unique in the sense of their nonrenewable profile. Their deposits are finite, either physically or economically, and this implies a special concern about their exploitation, use, consumption, and recycling in a way that could prevent or mitigate their scarcity or unavailability for future generations. The optimal use of resources implies the adoption of a rational classification according to two major factors: geological knowledge and confidence; and the consideration of mining, metallurgical, economic, marketing, legal, environmental, social, and governmental factors (the modifying factors). As a general rule, government action is applied to survey and identify resources, whereas private enterprises concentrate their effort on well-defined reserves. As technology advances, non-conventional sources of minerals could enter into the marketplace, as shown by current research on seawater, seabed nodules, and ultimately space mining, all of which may occupy some place in the supply of minerals for future generations.

Technology is the mainstay of every industry, including mining, due to its ability to change, sometimes in a surprising manner, the way materials are presented to manufacturers and consumers alike. Conservation and sustainability are different sides of the same coin, as the more we conserve the more likely we are to leave an acceptable legacy to our descendants. Thus, environmental legislation has become more and more stringent in industrialized countries over time, reflecting the concern for a high quality of life shared by different stakeholders. In the 1970s many thinkers were concerned about issues like accelerating industrialization, rapid population growth, widespread malnutrition, depletion of nonrenewable resources, and a deteriorating environment. These concerns gave rise to a number of initiatives leading to the design of global

models. The Club of Rome model was one of the most famous and had profound effects on planning efforts and macroeconomic studies developed by a host of nations. It caused panic in some circles, disturbed by the idea of diminishing stocks of raw materials and energy sources that could menace the Western lifestyle. Nevertheless, the need to maintain research groups oriented to the design of global models was paramount and continues until our times. Currently, new frontiers attract the attention of leading mining companies, varying from rainforest tropical environments (South America, Southeast Asia) to ice-covered regions (Northern Canada, Siberia, Greenland, Antarctica). At the same time, as technological innovations develop every year, many mines extend their life-cycle or new deposits become feasible, in such a manner that the phantom of world scarcity is always disappearing.

1. BACKGROUND

Natural resources are undoubtedly the backbone of our civilization. In a broad sense, they refer to all the living and nonliving endowment of the earth, but traditional usage confines the term to naturally occurring resources and systems that are useful to humans, or could be under ordinary technological, economic, social, and legal circumstances. The major classes of natural resources are:

- agricultural land
- forest land and its multiple products and services
- natural land areas preserved for aesthetic, recreational, or scientific purposes
- the fresh and saltwater fisheries
- mineral resources that include the mineral fuels and non-fuels

- the renewable non-mineral energy sources of solar, tidal, wind, and geothermal systems
- water resources
- the waste-assimilative capacities of all parts of the environment.

Some natural resource stocks are renewable by natural or artificial processes while others are nonrenewable – an often-used dichotomy in classifying resources. As renewable, one may cite solar, wind, and tidal energy and farmland, forest, fisheries, air, and surface water. In contrast, mineral ores and fossil fuels exemplify the nonrenewables. Although geological processes may be capable of generating new stocks for a given resource over time (geologic time), the human time scale does not allow coping with such “renewability”.

It is conceded that renewability often depends on appropriate non-destructive methods of management, as with farmlands, fisheries, and waste disposal, since some changes in natural resource systems are irreversible. In the assessment of natural resource stocks, it is important that interactions with other systems and potentially irreversible changes be taken into account. For instance, when coal is strip-mined, flows of groundwater may be interrupted and streams and wells may permanently go dry. Acid from sulphur exposed to rain and air may foul water supplies and kill plants and fish. Thus natural resources must be looked on as parts of larger systems.

One of the most sensitive questions posed by the world's natural resource context is: “How long and under what conditions can human life continue on earth with finite stocks of *in situ* resources, renewable but destructible resource populations, and limited environmental systems?” Some facts are quite clear: first, that some currently vital resource stocks (such as mineral fuels) are finite; that rates of consumption of these stocks have accelerated in recent decades far beyond all historical rates; that some major renewable resource systems (e.g. marine fisheries, and some groundwater systems) are being destroyed; and that environmental capacities are being seriously exceeded. To be more specific about this question, when use of a resource grows at 5 percent per year the rate of use will double in fourteen years. Second, if currently known reserves are 100 times current annual use, such reserves will be exhausted in thirty-six years. Third, even if a huge discovery doubled reserves to 200 times current use, the reserves would last for only forty-eight years.

A second major issue refers to the location of known reserves. World petroleum reserves are huge and more is being discovered each year, but those reserves are not located in the major consuming countries of the western hemisphere. The same is true of bauxite, iron ore, chromium, tin, and natural gas. In the past this had strong geopolitical implications for the vulnerability shown by consuming countries *vis-à-vis* developing countries eager to increase their export earnings. Tense relations between consuming and producing countries prevailing in the past were fortunately replaced by peaceful agreements or contracts signed in present times.

A third issue is the historical “shift away from renewable resources” toward dependence on nonrenewable resources. Some authors interpret the British Industrial Revolution as the substitution of mineral for vegetable or animal substances. For instance, coal became important when charcoal supplies became increasingly costly, both in terms of distance of forests and in terms of undesirable environmental effects. Another example: in the United States, agriculture has shifted from animal power to petroleum-driven machines, from natural fertilizers to those synthesized from natural gas. To some extent, in the 1980s the use of alternative energy sources, for example biomass and alcohol, meant a reversion of this shift. Would this trend be desirable now?

A fourth issue is the contemporary evaluation of “the wisdom of past patterns of resource utilization.” Undoubtedly, there are numerous examples of unwise, shortsighted, predatory exploitation of natural resource systems coupled with their related social systems. The exploitation of coal in Appalachia is quoted as a typical example, even accepting that factors other than coal itself were present, such as monopolistic exploitation, political corruption, and unanticipated technological change. Similarly, were the rich iron ores of the Mesabi Range or of the Iron Ore Quadrangle used up too fast? Was the process of plowing, planting, and abandoning the plains lands shortsighted and unwise? Although many environmentalists and historians condemned those practices, they are not so simple to judge.

A fifth issue closely related to the former is whether or not we have correctly understood “the role and importance of natural resources and environmental services” as factors in our past economic growth. Apparently, too many analysts have placed a great emphasis on the growth of technology and improvement of human capital, as compared with the role of raw material inputs and also the increasing use of the environment for waste disposal. It is possible that these inputs were more important than recognized and, more importantly, they may not be freely available for future generations.

A sixth issue is the growing dependence on “increasingly low quality reserves” of natural resources. In other words, the grades of all metallic ores currently in use are far below those exploited in the past. For many resource stocks, one finds a continuous spectrum of quality versus quantity, implying greater reserves at the cost of exploiting poorer ores. Copper ores are a famous example: in North America ores containing 0.3 percent copper or less are currently being mined, implying the need to move, process, and dispose of 333 tons of ore to get 1 ton of metal. It is known that seawater contains incredible stores of minerals, but the energy requirements for recovery are, in most cases, prohibitive. One question arises: Will energy availability permit the exploitation of these resources or must we forget them as usable reserves? Since the 1970s this question has been partially solved by the increasing supply of resources originated from developing countries showing richer grades than their counterparts in the

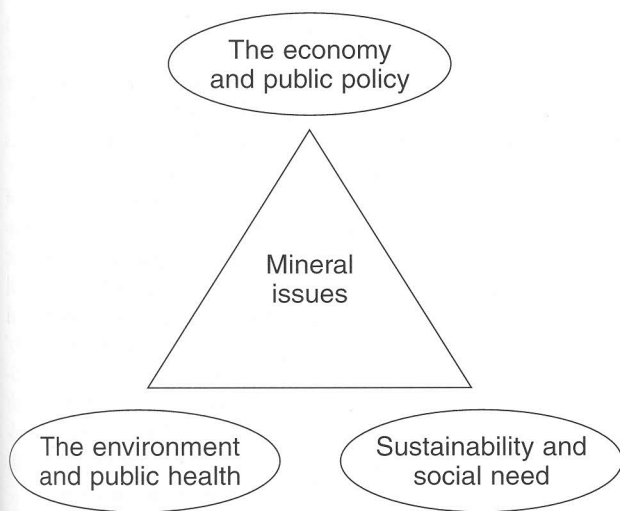


Figure 1. Mineral issues and basic human needs

Source: USGS (1998). USGS Mineral Resources Program. A *National Perspective*. USGS Fact Sheet FS-008-98.

industrialized world. In the case of copper, for instance, only in Chile are there more than six large mines averaging at least 1.3 percent copper. For other ores and minerals, the shift to the developing countries meant that inferior reserves remained a problem just for developed countries, not necessarily meaning a worldwide scarcity.

A seventh issue, closely related to the previous two, is the evolution of limiting global environmental conditions. It is conceded that the most widely discussed item is the buildup of carbon dioxide in the upper atmosphere, mainly as a result of fossil fuel combustion, and deforestation. This has to do with global changes, affecting the Earth's temperature and climate (greenhouse effect). Other examples are found in the increasing pollution of oceans, crucial as carbon dioxide sinks and oxygen sources, and in the build-up of persistent toxins in the soils.

An eighth issue is the role to be given to "market processes in determining how resources will be managed over time." Of course, markets have historically played an important role in determining exploration activity and rates of use. In addition, it has been convincingly demonstrated that changing relative prices has largely introduced technological innovation. Yet most countries, including the United States, have shown a great ambivalence, professing the virtues of free enterprise while, through price controls and bureaucratic regulation, refusing to let the pure market work. The concern with market processes has grown with the end of the planned economies, in 1989, as the former socialist countries move – some of them gradually, others faster – to a market economy system. Anyway, can market processes work in a socially responsible way in the natural resources area? What will be the role of State? More recently, privatization programs all over the world have brought the redesign of the role of State, which tends to remain solely as the entity responsible for the formulation of policies at a high level, and also as the regulating and co-ordinating actor.

2. DEFINITION AND CLASSIFICATION OF RESOURCES AND RESERVES

The distinction between resources and reserves is not limited to geological and mining aspects, but it extends into some political and economical implications. As a sizeable number of mining and petroleum companies use to be public-owned, maintaining stocks traded in stock exchanges around the world, the need was detected to obtain reliable reports from those companies by investors, funding agencies, governments, and other stakeholders. Therefore, government authorities and regulators have decided that these reports should be presented under principles of transparency, materiality, and competence. This policy would protect investors from biased or incomplete information about company assets. This concern was originally raised in Australia, back in 1989, and was later shared by several other countries. That explains why the US Securities and Exchange Commission now regulates the reporting of exploration information, resources, and reserves, by entities subject to the filing and reporting requirements. Decisions as to when and what information should be publicly reported are the sole responsibility of the entity owning the information, and are subject to US SEC rules and regulations. These rules and regulations vary from time to time, and at any given time may not be consistent with the content of the proper guide.

Geologists, mining and petroleum engineers, and other professionals operating in the mineral field to describe and classify mineral resources, including energy materials, have used various terms. The US Geological Survey, for example, collects information about the quantity and quality of all mineral resources, in its own territory and abroad. Long-term public and private planning must be based on the probability of discovering new deposits, on developing economic extraction processes for currently unworkable deposits, and on knowing which resources are immediately available. This means that resources must be continuously reassessed in the light of new geological knowledge, of progress in science and technology, and of shifts in economic and political conditions.

Despite general agreement on reserve definitions by mining and petroleum professionals working in industry and finance, geologists, engineers and economists working in academia and government resisted attempts to develop definitions of universal applicability, arguing that the needs of commerce are different than those of resource availability estimates and national planners. In spite of the need for a standardization of definitions and concepts, differences in definitions continue to cloud the absolute meaning of resources and reserve definitions published by technical societies and regulatory bodies.

2.1. Resources

The USGS definition of "resource" is a concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth's crust in such form and amount that

economic extraction of a commodity from the concentration is currently or potentially feasible. To start with, mineral resources are classified into two broad categories: identified and undiscovered resources. This feature is unique to the mineral kingdom, as for biological resources there is no meaning about "undiscovered resources" for technical reasons. "Identified resources" are those resources whose location, grade, quality, and quantity are known or estimated from specific geologic evidence. They include economic, marginally economic, and sub-economic components. "Undiscovered resources" are resources, the existence of which are only postulated, comprising deposits that are separate from identified resources. Undiscovered resources may be postulated in deposits of such grade and physical location as to render them economic, marginally economic, or sub-economic. To reflect varying degrees of geological certainty, undiscovered resources are divided into two parts: hypothetical and speculative resources. Hypothetical resources are undiscovered resources that are similar to known mineral bodies, and that may be reasonably expected to exist in the same producing district or region under analogous geological conditions. If exploration confirms their existence and reveals enough information about their quality, grade, and quantity, they will be reclassified as identified resources. Speculative resources are undiscovered resources that may occur either in known types of deposits in favorable geologic

settings where mineral discoveries have not been made, or in types of deposits as yet unrecognized for their economic potential. If exploration confirms their existence and reveals enough information about their quantity, grade, and quality, they will be reclassified as identified resources (see Figure 2).

Mineral resources are sub-divided, in order of increasing geological confidence, into Inferred, Indicated and Measured categories. Portions of a deposit that do not have reasonable prospects for eventual economic extraction must not be included in a Mineral Resource. It follows that the term "Mineral Resource" covers deposits which have been identified and estimated through exploration and sampling, and from which Mineral Reserves may be defined by the consideration and application of technical, economic, legal, environmental, social, and governmental factors.

An "Inferred Mineral Resource" is that part of a mineral resource for which tonnage, volume, grade, and mineral content can be estimated with a low level of confidence. It is inferred from geological evidence and assumed but has not a verified geological and/or grade continuity. It is based on information gathered through appropriate techniques from locations such as outcrops, trenches, pits, workings, and drill holes which is limited or of uncertain quality and/or reliability. An Inferred Mineral Resource has a lower level of confidence than that applying to an indicated mineral resource.

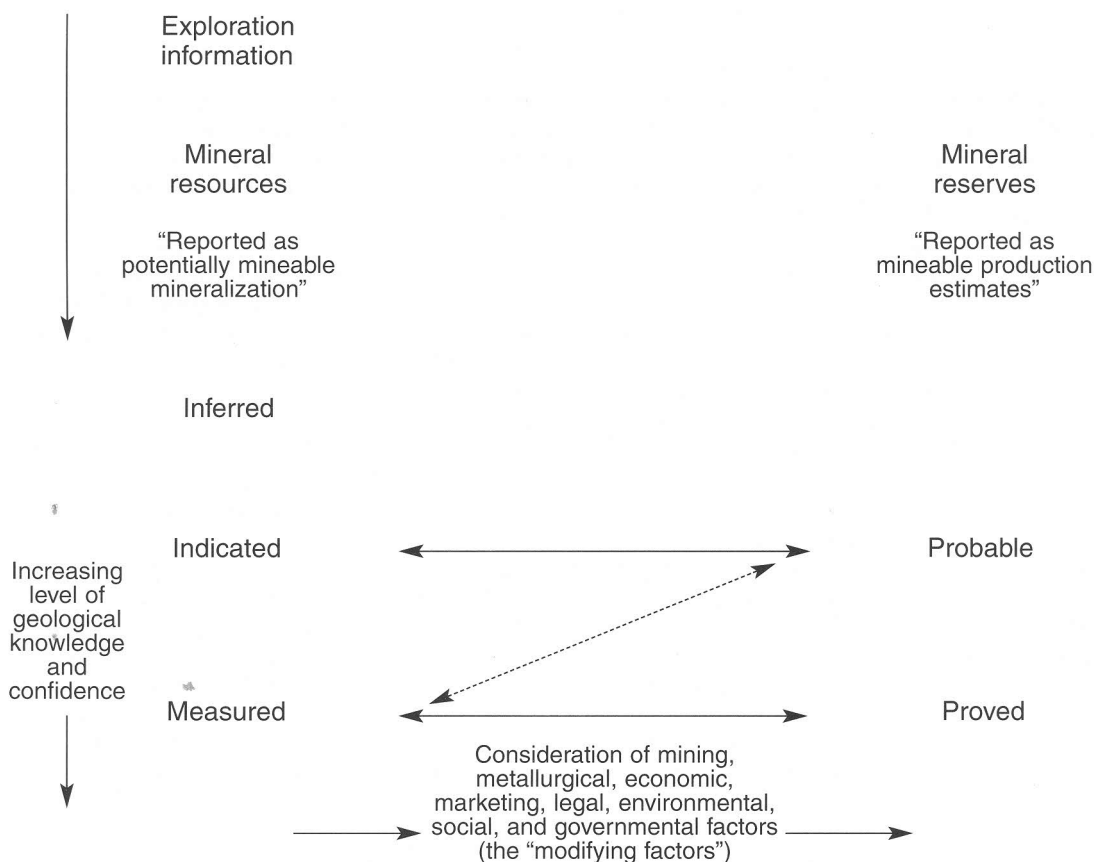


Figure 2. General relationship between exploration information, mineral resources, and mineral reserves

Source: SME (1999). *A Guide for Reporting Exploration Information, Mineral Resources, and Mineral Reserves*, Preprint, March.

An "Indicated Mineral Resource" is that part of a mineral resource for which tonnage, volume, densities, shape, physical characteristics, grade, and mineral content can be estimated with a reasonable level of confidence. It is based on exploration, sampling, and testing information gathered through appropriate techniques from locations such as outcrops, trenches, pits, workings, and drill holes. The locations are too widely or inappropriately spaced to confirm geological continuity and/or grade continuity but are spaced closely enough for continuity to be assumed. An indicated mineral resource has a lower level of confidence than that applying to a measured mineral resource, but has a higher level of confidence than that applying to an Inferred Mineral Resource.

2.2. Reserves

A "Mineral Reserve" is the economically mineable part of a measured or indicated mineral resource. It includes diluting materials and allowances for losses, which may occur when the material is mined. Appropriate assessments, which may include feasibility studies, have been carried out and include consideration of and modification by realistically assumed mining, metallurgical, economic, marketing, legal, environmental, social, and governmental factors. These assessments demonstrate at the time of reporting that extraction is reasonably justified. Mineral reserves are subdivided in order of increasing confidence into "Probable Mineral Reserves" and "Proved Mineral Reserves."

A "Probable Mineral Reserve" is the economically mineable part of an indicated and, in some circumstances, Measured Mineral Resource. It includes diluting materials and allowances for losses that may occur when the material is mined. Appropriate assessments, which may include feasibility studies, have been carried out and include consideration of and modification by realistically assumed mining, metallurgical, economic, marketing, legal, environmental, social, and governmental factors. These assessments demonstrate at the time of reporting that extraction is reasonably justified. A Probable Mineral Reserve has a lower level of confidence than a Proved Mineral Reserve.

A "Proved Mineral Reserve" is the economically mineable part of a Measured Mineral Resource. It includes diluting materials and allowances for losses, which may occur when the material is mined. Appropriate assessments, which may include feasibility studies, have been carried out and include consideration of and modification by realistically assumed mining, metallurgical, economic, marketing, legal, environmental, social, and governmental factors. These assessments demonstrate at the time of reporting that extraction is reasonably justified. The choice of the appropriate category of Mineral Reserve is determined primarily by the classification of the corresponding Mineral Resource and must be made by the "Competent Person" (a person who is a member of a professional society for Earth scientists or mineral engineers, or has other appropriate qualifications).

Petroleum is the world's major source of energy and is a key factor in the continued development of world economies. As pointed out previously there is a growing awareness worldwide of the need for a consistent set of resources and reserves definitions for use by governments and industry in the classification of petroleum reserves. The classification system is summarized in the Figure 3. The classification shows a great similarity with that for mineral reserves in general. Resources are defined as including all quantities of petroleum, which are estimated to be initially in place; however, some users consider only the estimated recoverable portion to constitute a resource. It should be understood that reserves constitute in this classification constitute a subset of resources, being those quantities that are discovered in known accumulations, recoverable, commercial, and remaining. Two aspects in this classification which are important to highlight are the inclusion of a resource uncertainty category (low, most likely, and high) and of the resource status category. Resource uncertainty categories can be used to define the best estimate range of uncertainty of any resource and provide a basis for estimation tracking which will indicate potential bias in evaluation methodology. Resource status category can be used to define the maturity of projects and to provide a basis for portfolio management.

Every year new exploration efforts worldwide lead to the discovery of additional resources that augment the physical endowment of world nonrenewable resources. The experience of recent decades shows that the increment of available resources exceeds the consumed part of those resources, giving a positive balance favorable to the well-being of future generations. In other words, currently there is no scarcity problem regarding nonrenewable resources. As stated in the Strategic Plan for the US Geological Survey:

Today most resources are available, for a price, somewhere in the global economy. Oil and gas are relatively abundant and accessible, even if geographically distant. Minerals are available in necessary quantities from a variety of sources. Global economics, rather than national self-sufficiency, drives decisions on when and where to buy most resources.

2.3. Mineral supply

Many mineral commodities (oil, coal, bauxite, iron, and so on) are typically extracted as single or individual products. Others are produced as joint products from the same deposit or ore body. In such a situation, it is possible to distinguish among mineral resources (mainly metals) the main products, co-products, and by-products. A main product is by definition so important that it alone determines the economic feasibility of a mine. When two metals must be produced to make a mine economic, both influence output, and they are considered co-products. A by-product is produced in association with a main product or with co-products. Its price

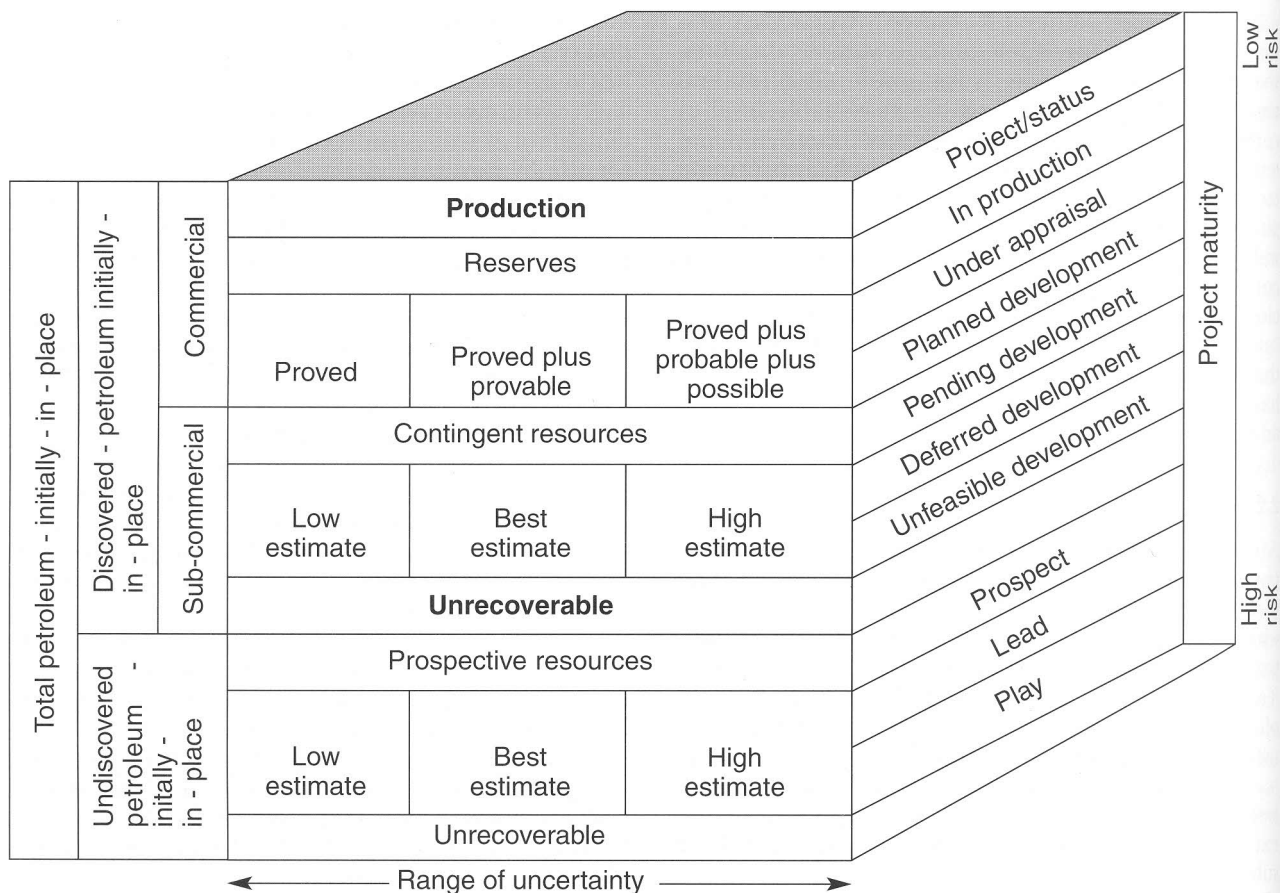


Figure 3. Resources and reserves categories used for petroleum and natural gas

Source: Modified from SPE/AAPG/WPC – Petroleum Reserve Definitions (2000).

has no influence over the mine's output, though usually it does affect by-product production. It is important to emphasize that some metals, such as gold and silver are main products at some mines, co-products at other mines, and by-products at still other mines. To determine the total primary supply for such metals, it is necessary to assess main products, by-product, and co-product supply and then add them together.

Before assessing the general shape of the supply curve, we need to distinguish two types of metal markets, producer markets and competitive markets. Firms in producer markets quote the price at which they are prepared to sell their product. These markets, characterized by a few major sellers, have relatively stable prices, though when demand is weak, actual prices may fall below quoted producer prices as a result of discounting and other concessions. Examples of metals sold in this market are magnesium and steel. In competitive markets, price is determined by the interaction of supply and demand and is free to fluctuate as much as necessary to clear the marketplace. Many buyers and sellers are very common in such markets, and price is often set on a commodity exchange, such as the London Metal Exchange (LME), IPE (International Petroleum Exchange), and New York Mercantile Exchange (NYMEX). Manganese, silver, oil, and gas are commodities sold in competitive markets.

2.4. Mineral demand

Mineral commodities are rarely final goods, gold bullion being the obvious exception. Generally the demand for a mineral commodity is derived from the demands for final goods. Since demand is really a set of attributes, rather than a mineral commodity *per se*, in many end-uses one mineral produced can replace another.

The main determinants that are often considered in demand studies are income, own price, prices of substitutes and complements, technological change, and government policies. Income is one the most important variables affecting mineral demand. Gross domestic product (GDP) or industrial output is employed for this purpose. Malenbaum (1978) proposed a measure called "intensity of use," defined as the amount of material consumed per unit of GDP, which has an inverted U-shape curve type (Figure 4). Countries in early stages of economic development have had low intensity of use (low consumption and low income); as they begin to industrialize, they invest in basic industry, infrastructure, and other material intensive projects, which cause their intensity of use to rise. As development proceeds the demand for basic goods are satisfied and the consumption shifts away from manufacturing toward the service sector.

Demand tends to fall with increase in price and rise with a decline in price. The reason for this inverse

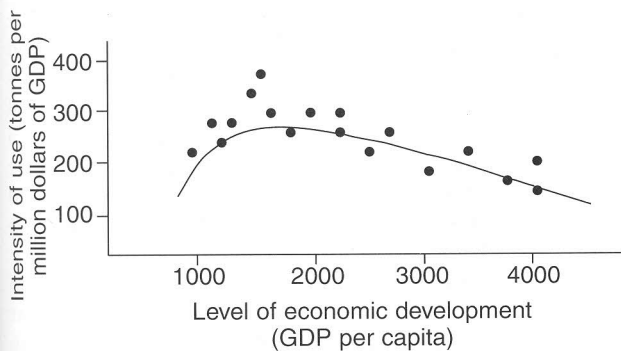


Figure 4. Relationship between intensity of use of steel and per capita income in OECD bloc countries, 1950-90. GDP is measured in constant US\$ 1990 dollars.

relationship is that higher mineral price increases the production costs of the final goods in which it is used. Another reason is that firms may respond to the higher price by substituting another mineral commodity whose price has not risen. As with changes in own price, changes in the prices of substitutes and complements affect mineral demand primarily by inducing firms to alter the nature of their production processes.

New technology can alter mineral demand in several aspects. First, it can reduce the amount of a mineral commodity required in the production of a specific item. For example, aluminum in new alloys used in a beer can. Second, new technology can affect the ability to compete in a particular end-use market. For exam-

ple, the introductions of polyvinyl chloride (PVC) in plastic pipe capture a sizable market share for home building that belonged traditionally to copper and other mineral commodities. New technology can also change the number and size of end-use markets. For instance, the advent of the automobile gave rise to a major new market for petroleum, steel, and lead.

Government policies influence metal supply and demand in a variety of ways. Environmental regulations and state severance taxes tend to increase costs and reduce supply.

The relationships between supply of and demand for a commodity are better understood through Figure 5.

3. ROLE OF TECHNOLOGY

Technology has multiple influences in the mining and petroleum industry. Let us start at the exploration stage. Exploration techniques are used to locate and evaluate mineral deposits for potential mining and metal extraction. In the twentieth century important advances were achieved in exploration geology, mapping and surveying, geophysics, geochemistry, and drilling technology. In the production stage, technology can contribute to competitiveness by increasing productivity or product quality, by addressing circumstances unique to a process, company or country, or by assisting producers to adapt to changing consumer demand.

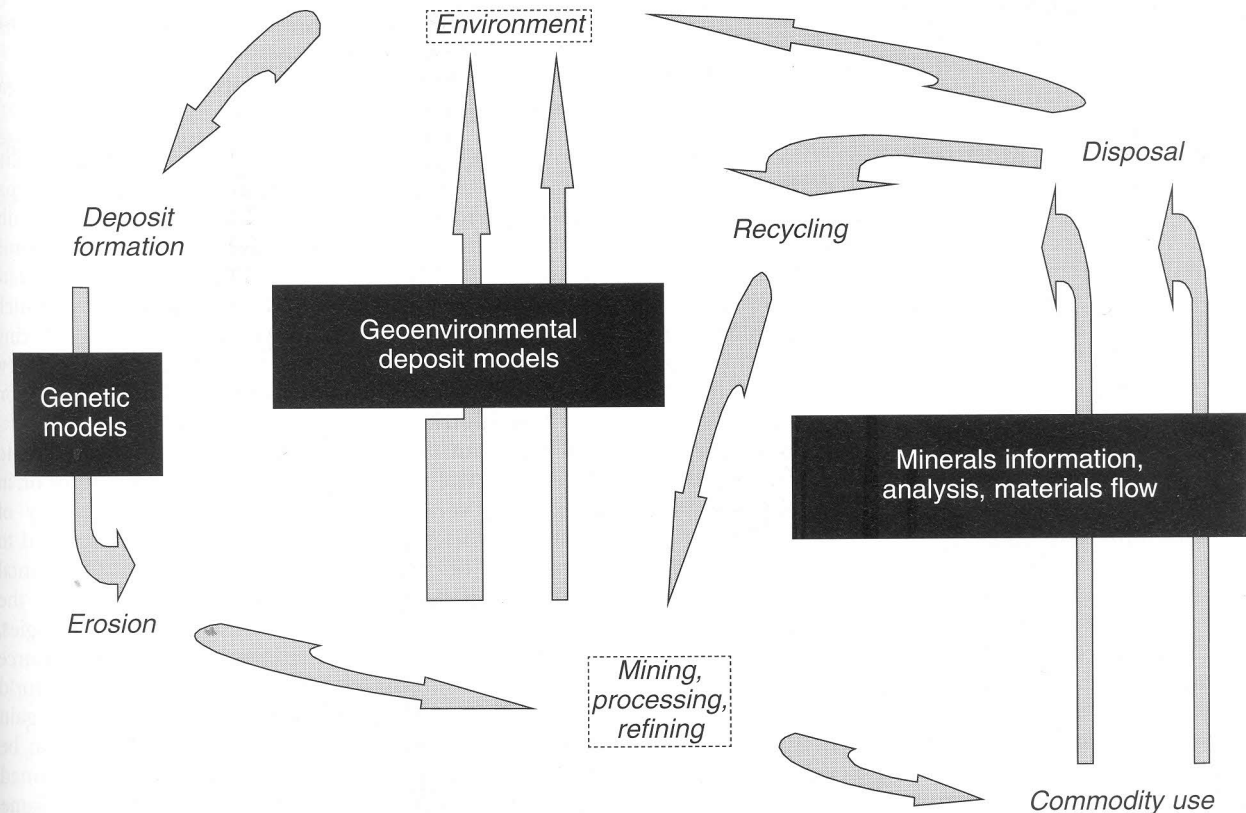


Figure 5. Life-cycle models of a mineral commodity

Source: USGS (1998). USGS Mineral Resources Program. *A National Perspective*. USGS Fact Sheet FS-008-98.

Although technologies can diffuse rapidly across international and corporate boundaries, it is still possible to create a comparative advantage from investments in research and development (R&D). One advantage comes from being the first to apply a technological advance, since a two to three year lead-time usually accrues to the originator and first implementer of the technology. The rapid diffusion of the technology reduces but does not eliminate this advantage. Another advantage comes when the technology is related to special conditions not prevalent elsewhere (for example, high labor costs, unique ore deposits, and national environment standards).

Instead of innovative new technologies that could contribute to a comparative advantage, most technological advances in the industry have been incremental – stepwise improvements of existing equipment and processes – rather than major breakthroughs. Incremental advances are certainly beneficial, but they may not be sufficient in the face of strong competition from other nations based substantially on nontechnological factors (richer deposits, government subsidies, more lax environmental legislation).

Technology can contribute to a competitive advantage in three ways. The first is through exclusive access to a technology that increases the productivity of a mine or improves the quality of the product. Given the speed with which information travels between firms and countries, this advantage is temporary, but the first firm or country to implement a valuable technology may acquire a comparative advantage for several years before it spreads to others in the industry. New technologies have their greatest impact when they can be integrated into the design of a new facility, however, and most new mines and processing plants are being built in developing countries.

The second way in which technology can contribute to a comparative advantage is when it addresses conditions or circumstances unique to a firm or country. Factors that affect developed countries to a greater degree than other countries include high labor costs, low ore grades, and more stringent environmental regulation. These factors therefore provide targets of opportunity for R&D that will provide a comparative advantage for operations in those developed countries. Technologies to concentrate metal from low-grade ores, to increase labor productivity, and to reduce the cost of meeting environmental standards, would all contribute more extensively to firms in developed countries than to others.

The third way in which technology may affect competitiveness is by allowing commodity producers to adapt to changing consumer demand by producing commodities that meet new quality and performance needs. Competition between materials becomes most intense when systems undergo extensive redesign, but such opportunities are not frequent. For instance, the automotive design cycle is about ten years in duration (component changes alone may take three or more years to implement), and in aviation the design cycle is at least that long, especially for commercial aircraft. Metal producers in industrial-

ized countries may earn a comparative advantage relative to both developing metal producers and producers of nonmetallic materials by collaborating with designers and fabricators in the development of the next generation of manufactured products. In aviation, for example, aluminum producers devote funds and personnel to efforts to develop alloys and metal processing techniques that meet the requirements of the next generation of aircraft.

There is an adage in the minerals and petroleum industry that discovering a good new deposit is better than trying to improve the yield from a poor one with the use of advanced mining and processing technologies. This rationale explains the shift of exploration effort to the new green field frontiers in the developing countries. Nevertheless, the mining and petroleum companies continue to invest in new exploratory technologies, for example:

- spatial and spectral image resolution to penetrate foliage and surface cover
- digital geophysical coverage magnetically, gravitationally, radiometrically, and spectrally to a scale of one-half mile or so
- 3D seismic technology providing a better picture of the composition and sub-surface rock layers
- improved drilling/sampling techniques and analytical methods to increase basic geophysical knowledge
- deep drilling such as epithermal zones reaching 4,500 to 8,000 meters
- horizontal drilling technology for higher recovery rates and expanding the size effective size of the resource base compared to the amount that was previously available
- advances in deepwater systems for oil and gas resources.

Improvements in databases and increased availability of information would allow smaller aggressive companies to perform effective exploration without prohibitive expense. Another research advance that could revolutionize the industry would be a more complete general theory of ore genesis and deposition, which would not only improve the probability of discovering new deposits but also aid in the development of new mines and the selection of more efficient extraction methodologies.

3D seismic surveys enable the oil companies to determine the efficiency of extraction strategies or, in enhanced recovery applications, the efficiency of water flooding and carbon dioxide flooding used to drive the oil toward producing wells. Horizontal drilling and deepwater technology helps bolster the productivity for petroleum firms. Both technologies, with 3D seismic, extend the effective size of a resource base that is economic to exploit at the present world price of oil. Horizontal drilling achieves this gain largely by increasing the amount of oil that can be profitably extracted from mature and abandoned fields. Deepwater technologies achieve the same benefit by extending the number of the new fields that can be profitably exploited, and by increasing the average size of the fields discovered.

Present mining technologies are designed to achieve high labor productivity and to handle large volumes of rock or ore. Mining machines, especially those used in surface mines, have huge capacities but very high unit capital costs. This mining technology was developed and implemented mainly in the United States for metal and surface coal mining. Mass production technology for underground coal mining was also initially developed in the United States. Long wall technology, which is regarded by many as the most effective underground coal mining method and which will form most of the basis of future development, was imported from Europe.

By its nature, mining involves intimate interaction with the rock mass. Unfortunately, geological conditions are variable and unpredictable by available means on the scales relevant here. A mining system must therefore have substantial cognitive abilities to recognize and react to unpredictable variations. Currently, the trained and experienced operator provides all cognitive abilities. If the operator's burden is to be eased and mining automation is to become a reality, more and more cognitive ability will have to be imparted to the inanimate part of the system. A number of obstacles hamper the development of intelligent mining systems. Some of these are fundamental and confront the designers of any automated system that must operate in unpredictable conditions (for instance, space or battlefield autonomous vehicles). Others are intimately related to mining (for instance, fragmentation of rock, prediction of variations in the geological environment, navigation in a confined underground space). It seems logical to assume that mining research will have to solve its specific problems, accessing data from other fields by soliciting the aid of high-technology companies with related experience.

At least four areas of research can be identified that address the problems to be overcome:

- Geosensing, or the ability to first, predict variation in the ore body, second, sense the closeness of geological disturbances (e.g. faults), and third, obtain in site measurements of grade variations, would improve the likelihood of discovering new deposits and contribute to the design of more effective mining equipment. The feasibility of automated mining relies on this data for the navigation and control of an intelligent system. Although clearly related to aspects of geophysics and geochemistry, this research area must aim for resolution and accuracy that has not hitherto been attempted.
- Non-explosive rock fragmentation would be a great advantage to the mining industry and is a basic component of automated mining systems. Considerable advances have been made in recent decades in the mechanical extraction of softer rocks, especially in the area of hydraulic mining. Non-explosive extraction offers enhanced safety through better control and continuity of operations, leading to improved production capacities.
- Intelligent mining systems incorporating advanced

levels of cognitive ability in inanimate components of the system would allow new approaches in mining and reduce the exposure of operators to hostile working environments.

- In-site mining is a potentially revolutionary mining method that could greatly improve mining economies and allow a human-free working environment, exploitation of low-grade mineral resources, and retention of waste underground.

Mineral processing has a critical role in determining the yield and quality of concentrates for smelting or other product preparation steps. Most current mineral processing technologies were invented (if not implemented) in the nineteenth century. This is true of comminution, gravity, magnetic, and electrostatic separation, and flotation processes.

The energy inefficiency of the comminution or pulverizing process has been known for over a century, yet there have been no major developments in this technology. Except for blasting and the potential applications of alternative energy forms, comminution depends entirely on conversion of electrical energy to motion in crushing or grinding machinery. There is a marked analogy between problems of improving efficiencies in comminution and flotation. Both systems involve interaction between relevant properties of the materials processed and dynamic characteristics of processing machinery. With both, machine evolution has had the goal of providing for a number of functions, often with different requirements, in a single unit. As a result there must be a compromise, with less than optimum execution of all functions. This compromise is evident in the mechanical flotation cell. The critical requirements are to provide optimum conditions both for stable particle/bubble attachment and for gravity separation of bubbles from pulp.

Another area where technology shows its strength is the field of advanced or new materials. Rapid technological developments in the last few decades have given rise to an increasing number of composite materials, ceramics, and electro-optical materials. They have been substituting successfully for metals in many traditional markets. Substitution of these advanced materials is not, as had earlier been predicted, due to soaring mineral prices resulting from exhaustion of low-cost reserves in the 1970s. Instead, the switch from metals to advanced materials is largely occurring as a consequence of performance characteristics. Thus, fiber optics are replacing copper in telecommunications because with fiber optics a single cable of dimensions similar to a hair strand can carry about 500 times more messages than the conventional copper cable. In the automotive industry applications for composite materials and ceramics have been considered in order to achieve weight savings, improve manufacturing techniques, or obtain greater fatigue or corrosion resistance.

It is obvious that modern technology provides many options, competition between materials is vigorous, and manufacturers will continually evaluate the

merits of rival materials before deciding which commodity combines the best performance characteristics with the greatest economy.

4. NON-CONVENTIONAL SOURCES

In a previous item, a broad classification of "Undiscovered Resources" was given, which is based on existing models of mineral deposits, either untouched, being developed, or under exploitation. However, during an exploration program achieved by a geological team, one may find something less valuable, like a prospect or more valuable, like a deposit, depending on quality and quantity of ore, and other factors. In some examples, there is no model of mineral deposit yet contemplating that mineral assemblage, but this does not imply that in the future such a prospect could evolve to a commercial deposit. The bottleneck refers to the technological capability to do so, converting a mineral resource into something useful. The non-conventional sources are formed by this stock of materials whose utilization by man is far from proven.

4.1. Seawater

Seawater is a typical example of a source for an endless number of chemicals that are available, unfortunately at a high cost by today standards. Approximately 3.5 percent of seawater is composed of dissolved compounds. Sodium and chloride are the predominant ions in seawater, and the concentrations of magnesium, calcium, and sulfate ions are also substantial. Other elements in relatively high concentrations are: potassium, bromide, boron, strontium, and fluoride.

Theoretically, all these elements can be extracted from seawater in the future. Based on available technology, only economics will lead to its extraction or not, unless some geopolitical factors (war, supply disruption, etc.) intervene in the decision process.

Regarding life, in addition to carbon, the nutrients essential for living organisms include nitrogen and phosphorus, which are minor constituents of seawater.

Although the sea is a major storehouse of minerals, it has been little exploited; given the relative ease with which minerals can be obtained above sea level, there is no pressing need to exploit the sea at the present time. In addition, the technology required to exploit the sea and seafloor economically has not been developed, and there is also a general lack of knowledge regarding the resource. Nevertheless, as a potential source of mineral wealth, the sea can be divided into three regions: seawater, beaches and continental shelves, and the seafloor.

While seawater is an important source of magnesium, by far the most common minerals extracted from seawater are salts; especially common table salt (sodium chloride, NaCl), the chlorides of potassium and magnesium, and the sulfates of potassium and magnesium. These minerals are mined by evapora-

tion, very often in large, shallow ponds with energy being supplied by the sun.

The criteria for the production of salt by the evaporation of seawater are:

- a hot, dry climate with dry winds
- land available and the sea nearby
- a soil that is almost impermeable
- large areas of flat ground at or below sea level
- little rainfall during the evaporating months
- no possibility of dilution from freshwater streams
- inexpensive transportation or nearby markets.

4.2. Seabed nodules

The floors of the great ocean basins consist to a large extent of gently rolling hills, where slopes generally do not exceed a few degrees, and the relief does not vary by more than a few hundred meters. The mean depth of the ocean is 3,800 meters. The dominant seafloor sediments are oozes and clays, and the most important mineral deposits known (but not yet exploited) are phosphorite and manganese nodules. From an economic standpoint, the manganese nodules (actually concretions of manganese dioxide) are more important. These nodules are found in a variety of physical forms, but their average size is about three centimeters. The most significant authigenic sediments in the ocean basins today are metal-rich sediments and manganese nodules. Metal-rich sediments include those enriched by iron, manganese, copper, chromium, and lead. These sediments are common at spreading centers, indicating that processes at the centers are responsible for their formation – specifically, hydrothermal circulation is the controlling factor. Deep-sea drill cores have revealed the presence of metal-rich sediments on top of ancient oceanic crust away from ridge crests. It can be inferred from this that the processes controlling their formation existed in the past, but with variations. Which type of enriched sediment is deposited depends on the degree of mixing between the hydrothermal water deep in the crust at a spreading center and the cold seawater percolating down into the crust. Little mixing produces sulfides, liberal mixing yields manganese-rich crustal material, and intermediate conditions give rise to sediments enriched in iron and manganese.

Manganese nodules are pebbles or stones about the size of walnuts that are built of onion-like layers of manganese and iron oxides. Minor constituents include copper, nickel, and cobalt, making the nodules a potential ore of these valuable elements. Mining of manganese nodules has been the subject of study and experimentation since the 1950s. The nodules grow very slowly, about one to four millimeters per million years. They are found in areas of slow sedimentation, usually five millimeters per thousand years or less. The North and South Pacific hold the greatest concentration of manganese nodules; in some places, the nodules cover 90 percent of the surface of the ocean floor.

Two significant mysteries surround manganese nodules. Drilling and coring in the sediment column

has shown that nodules are vastly more abundant at the seafloor than below it, and that the rate of growth of nodules is ten times slower than the lowest known sedimentation rates. If this is the case, the nodules should be quickly buried and should be common in the sediment below the seafloor. Current theories for explaining these observations propose that bottom currents keep areas of nodule growth free of sediment deposition and that burrowing organisms nudge and roll the nodules in the process of feeding, thereby keeping them at the surface of the seafloor. Observations in the deep sea support both explanations.

Two means of bringing nodules to the surface on a commercial scale seem to have merit. These are the deep-sea drag dredge and the deep-sea hydraulic dredge. Both are still in a test phase and remain to be proved as commercial operations. One of the major problems is to guarantee a continuous operation.

4.3. Space mining

Space mining has modern roots in work done twenty years ago, but at that time developing space resources was far-fetched science fiction to anyone hoping for a quick financial return. Since then, a scientist named John Lewis has done more than anyone else to make space resource development a vibrant field of research and development. These researchers are meteoriticists, astronomers, and cosmochemists, they understand that most meteorites are pieces of asteroids, and they recognize that some near-earth asteroids (NEAs) are easier to reach and far easier to return material from than our own moon. Lewis and others have studied how to develop two types of raw materials: those that are rare, valuable, and being depleted on Earth but plentiful in space; and those that are common both on Earth and in space but are expensive to launch from Earth and vital to space colonization and resource development.

Four developments have brought space mining into industry's grasp. First, professional and amateur astronomers have discovered more than 400 NEAs, plotted their orbits, estimated their sizes, and (for a few) determined their compositions. David Rabinowitz and Eugene Shoemaker have estimated that 2,000 NEAs larger than 1 km across exist. Second, the monopoly on deep-space launches once held by Cold War superpowers has been broken by competition from space agencies in Europe, Japan, and Russia and by private launch services, reducing the cost of access to space.

Third, technological advances and the transfer of military technology following the cold war have led to advances in materials, computers, robotics, and deep-space propulsion. Finally, streamlined management of federal space projects has reduced the costs of solar system missions. US government projects such as Clementine, Discovery, and New Millennium serve as models for cost-conscious corporate managers of space technology projects. Robotic missions now cost one-fourth of what equivalent projects cost six years ago; other missions impossible

then are practical now. The net effect is that robotic space mining is now a concept that dollar-minded businessmen can consider.

People have found uses for virtually every accessible material. Human habits and industry have exploited large amounts of abundant, inexpensive substances (such as sand and gravel) and small amounts of rare, costly ones (such as gold and platinum).

Space resources and space industrialization may revolutionize the way we do things on Earth and in space and enhance the quality of life on this planet. In a future without space mining, we will ultimately either be forced to exploit difficult new sources of energy and minerals, or have to live with diminishing supplies and their eventual depletion in the long-term.

The availability of metals currently depends on how abundant they are in Earth's upper continental crust, which is the chief reservoir of our metals. Earth's core will forever sequester 99.9 percent of our planet's gold, rhenium, and platinum-group metals (or PGMs: platinum, palladium, iridium, osmium, rhodium, and ruthenium). They have very low abundances in earth's upper continental crust – and thus are very valuable – because most sank into the interior as the core was forming.

Some metallic asteroids have roughly the same abundance of gold and PGMs as does Earth's core. These objects, the cores of larger asteroids shattered by huge impacts, are not all equal, however. Besides having a wide range of sizes and lying at different distances from earth, they vary greatly in PGM and gold abundance. This makes the hunt for the richest metallic NEAs a challenge, but one worth the effort.

The study of iron meteorites tells us that the first material to solidify in the cooling cores of some asteroids is extraordinarily rich in PGMs, 100 to 200 parts per million in some cases. On Earth, we mine deposits typically containing 2 ppm of gold, and narrow veins containing 30 ppm of precious metals are exceptional.

A researcher has tried to model how exploiting such an object could affect production rates and market prices. A metallic asteroid 1 km across containing 185 ppm of PGMs, rhenium, germanium, and gold would have 780,000 metric tons of precious metals. At recent market prices, these metals would be worth over \$10 trillion (nearly the gross domestic product of the United States for a year). Importing this much metal over a period of fifty years would cause precipitous drops in the market value of these metals; the total market value would decline to about US\$900 billion total, or US\$17.7 billion per year. As asteroid mining builds over the next century, the result for people on earth may be a new metallurgical revolution as metals such as platinum, palladium, and iridium become abundant and relatively inexpensive. The price of iridium, for instance, may fall to between the present values of silver and copper.

Ordinary chondrite asteroids, which never melted extensively or formed a core, contain a cosmic abundance of precious metals scattered in grains rich in iron and nickel. Although concentrations of precious

metals in this type of asteroid are not as high as in some metallic ones, robotic asteroid miners could have an easy time with ordinary chondrites. Electromagnets could scoop up and separate the metal from the asteroid's soil, a simple task where gravity may reduce a 60-tonne load of metal (equivalent to an M-1 tank) to less than 30 kg.

Water in space will be crucial for the space economy within twenty years. Besides providing water for humans and agriculture in space colonies, water can be electrolyzed to yield hydrogen and oxygen for rocket propellants, chemical industries, and fuel cells to power vehicles and mining equipment.

Superheated water also can be used to propel "steam rockets," an efficient way to move large masses through interplanetary space. Water will be shipped into low-Earth orbit to help boost satellites to geosynchronous orbit, and to place mining and transport equipment onto trajectories to the moon and asteroids. If ice is as abundant at the moon's south pole as some scientists think, it will probably be the first extraterrestrial water to be mined. A more valuable source of water in the long run will be carbonaceous chondrite asteroids, in which chemically bound water makes up 1 to 20 percent of their mass. Because NEAs have little gravity and some have orbits similar to Earth's, it takes less energy to deliver mass into low-Earth orbit from some of them than it does from the moon.

Silicon, germanium, arsenic, selenium, indium, gallium, and phosphorus mined from metallic asteroids may be used to help fabricate thin-film photovoltaics that are both lightweight and flexible. These efficient devices could be used in the construction of solar power plants in earth orbit (which would beam the energy they generate to our planet) and on or near the moon, Mars, and asteroids (to power mining and human bases) should efforts to make fusion energy practical fail.

Engineers and scientists from many companies, universities, and national laboratories across the United States are studying how to produce water, oxygen, and hydrogen from lunar, Martian, and asteroidal materials. The recent discovery that ice may exist in shadowed areas near the moon's south pole may make the task easier, or at least more certain. Hauled to low-Earth orbit, asteroidal or lunar water may satisfy markets that already would be worth billions of dollars annually.

The first small-scale demonstration of rocket fuel production using indigenous Martian resources may be attempted during a NASA Mars mission in 2001. Later missions may depend on this technology for the return to Earth of Martian rock samples. A sample-return craft would be sent to Mars with ascent stages unfueled. During about eighteen months on the surface, a micro rover could collect geological samples and load them onto the return craft. Meanwhile, the fuel tanks would be filled using methane produced by the chemical reaction of hydrogen brought from Earth with carbon dioxide from the Martian atmosphere. Many more Martian rocks could be returned using this innovative strategy, than if all

the propellants were hauled from Earth. Ultimately, water from Martian ice or minerals will be used for Martian exploration.

Although the long-term value to society of moon rocks sold as jewelry and collectors' items may be minimal, the scientific value of rocks from an additional lunar site is substantial. A consortium involving a company and a university plans to send two rovers to the moon and market opportunities for pay-per-drive (by telepresence) to theme park visitors. The direct participation of the public in these and other projects may finally break the paradigm of big government-sponsored missions.

5. CONSERVATION AND SUSTAINABILITY

It could have been predicted that the modern conservation movement would have its beginnings not in the settled lands of the Old World but in those areas of the New World where, within the memory of a single generation, there had been extreme changes in the landscape and in the abundance of wildlife. The reaction to the destruction of natural resources in those areas precipitated the formation and growth of the conservation movement. As early as 1832, George Catlin, a US artist and author, first proposed the idea of national parks encompassing major areas in which Indians and wild country could both be preserved. In the same decade the botanist William Bartram and the ornithologist John James Audubon were arousing an interest in wildlife and its conservation. A little later, the writers Ralph Waldo Emerson and Henry David Thoreau presented strong arguments concerning the importance of the continued survival of wild nature to the psychological well-being of mankind. Thoreau became one of the first literary advocates of wilderness conservation. The first textbook on conservation, *Man and Nature*, by George Perkins Marsh, appeared in the 1860s. In the same period the author and naturalist John Muir settled in California and became a leading advocate of wilderness preservation. In 1872 the US Congress proclaimed the Yellowstone region of Wyoming as a national park and also established for the first time a national-government role in the protection and administration of such areas. In 1891 the first of the US forest reserves, forerunners of the system of national forests, was proclaimed in the area around Yellowstone National Park.

Conservation as a national movement owes much to President Theodore Roosevelt, and his immediate advisers. Roosevelt's chief forester, Gifford Pinchot, is credited with having first used the term "conservation" in its present context. Pinchot was to become the leader of the nation's Forest Service and, along with Roosevelt, he advocated a utilitarian, "wise use" approach to conservation. In this, Pinchot and Roosevelt came into conflict with representatives of another school of thought, called "Preservationist" and represented by Muir, over the building of a dam in the canyon of the Tuolumne River in Yosemite National Park, to provide a water supply for San

San Francisco. The philosophy of Roosevelt and Pinchot prevailed and the dam was built, but Muir's ideas lived on with the Sierra Club, of which he was a founder.

The recent history of conservation has been marked by a great expansion of government roles in protecting the environment, and by a growth of public interest in and support for this process. National-park systems, dedicated to the preservation of wild nature and to the provision of outdoor recreation space, have grown rapidly, and national-forest systems, dedicated to the multiple uses of wild-land resources, have also become firmly established. In the United States the conservation of wildlife became a cause of national interest and led to the establishment of a far-ranging system of wildlife refuges and the gradual restoration of most wild animal species to levels approaching, in some cases exceeding, their primitive abundance. On private lands, however, and on government or public-domain lands not specifically reserved as national forests, parks, or refuges, deterioration continued, reaching a peak in the 1930s, when it became widely recognized that those rangelands in the public domain had been disastrously overgrazed and that many privately owned farmlands had been depleted or exhausted. Firm control over the management of lands in the public domain and federal intervention to establish soil conservation on privately owned lands were accepted as appropriate activities for the national government.

Conservation ideas spread widely, being most readily accepted by those countries that had experienced sudden environmental changes. By the 1920s national parks were to be found on all continents. In 1924 the Soviet Union established the first of its now extensive system of natural reserves (*zapovedniki*). Conservation-oriented management of forestlands, which grew more from its origins in Europe than from practices in the United States, also became more widely accepted throughout the world. The scientific basis for the management of wild grazing lands for the sustained production of forage for livestock was established in US national forests in 1913 and soon spread to other countries. Aldo Leopold in the United States, in 1933, wrote a textbook on game management, in which the conservation and management of wild animal life for such recreational purposes as sport hunting and fishing and for direct commodity values on a sustained basis received particular emphasis. Leopold's work drew heavily on earlier studies of animal ecology by Charles Sutherland Elton in England; in fact, the establishment in Europe of wildlife reserves and protective laws as well as the managing of lands to produce sustained crops of wildlife long preceded even Elton's work. Subsequently, the management of wild animals in extensive wilderness areas made major strides in Africa, which possesses unusual wildlife resources, and in the Soviet Union, which retains large areas of wild land.

Regarding minerals, resource conservation and environmental change are closely related. Both concepts deal with scarcity, or even the complete exhaustion in the economic rather than in the physical sense. Simultaneously, the environment suffers an

impact, as mineral bodies themselves are part of the environment. In certain examples, exhaustion and environmental change can be understood as necessary and acceptable; in other cases, one or both must be considered as waste and degradation. The issues to be analyzed are when, where, and for whom each case applies, and these questions only can be resolved in terms of trade offs. To assess the trade offs, one must compare what was gained and what was lost because of production and usage of minerals. Such comparisons cannot be made only in physical units, but should incorporate economic units and, in many cases, social units too. In this discussion, some issues are relevant:

- What quantity of a nonrenewable resource shall be produced and consumed in a given period of time?
- How can the best use of these nonrenewable resources produced in that period of time be achieved?
- How can the renewable resources associated with nonrenewable in nature be better protected?

6. RESOURCES AVAILABILITY: SCARCITY VIEWS

Concerns over the availability of mineral resources needed to maintain the standard of living date back to the eighteenth century, when Thomas Malthus observed the land and resources expanding at an arithmetic rate while population grew at a geometric rate. However, this concern has been sporadic, tending to arise when the markets for resources are tight and prices high, and to decrease when these markets are weak and prices low.

Two schools of thought have been exploring various aspects of resource availability over the last decades. First, the *empirical school* focuses on measuring trends in resources availability over time. This approach requires an appropriate measure of scarcity, for example, physical measures, such as parts per million of a metal in the Earth's crust or the resource base. In addition to physical measures there are economic measures, of which three are commonly used: real price, cost of production for the marginal producer, and the value of mineral in the ground prior to the development of the deposit in which it is found. The economists sometimes refer to this as the pure rent associated with a deposit, which under certain conditions can be similar to the cost of discovery. Both physical and economic measures are accepted, but they may be misleading if not used appropriately.

The best-known study within the empirical school is *Scarcity and Growth* (Barnett and Morse, 1963). These authors assess the trends from 1870 to 1957 for different commodities, suggesting that the resources in general are becoming less scarce rather than scarcer, despite their extensive exploitation over time. The principal factor appears to have been the introduction of new technologies, whose cost-reducing effects

over the last century apparently more than offset the cost-increasing effects of resource depletion. For these reasons, this approach emphasizes the opportunity cost of finding and processing exhaustible resources, rejecting the fixed stock paradigm.

The second approach, called "Theoretical School," determines the optimal use of a fixed stock resource over time and is represented by the contribution of Hotelling (1931), and a voluminous body of subsequent papers. Hotelling's major contribution was to demonstrate that a firm exploiting a fixed resource stock would behave differently from other firms operating in other economic sectors (i.e. wheat or shoes). A firm exploiting a nonrenewable resource needs to recognize that current production incurs two types of costs. The first covers production costs and is similar in nature to the marginal cost considered by all firms. The second is the opportunity cost associated with depleting the fixed resource stock and thus reducing the quantity available for future use. This user cost, as it is commonly called, is the present value of the reduction in future profits foregone by producing one more unit of output during this period.

Another important aspect development by Hotelling with an important implication in resource scarcity theory is that over time the value of a resource left in the ground will rise at the firm's rate of time discount, which reflects the rate of interest that the firm can earn on other investment opportunities. In another form, this finding seems intuitive, because if the value of the resource is not growing at such rate, the firm has an incentive to mine the mineral resource (oil, gas,

metals, etc.) as quickly as possible and place the profits in other higher yielding investments. This finding indicates that resource scarcity will increase over time, because the value of resource in the ground is one of the economic measures of scarcity. This is very controversial, because the literature provides little support for this conclusion of the Hotelling theory and, in fact, finds considerable evidence to the contrary. Some authors criticize the Hotelling approach because we cannot employ the principle of a fixed stock by defining it as the economic portion, estimated under uncertainty about quality and cost. For example, if ultimate production of oil and gas is determined by future costs and prices, the estimated resource cannot be the starting point for estimating costs prices. What actually exist are flows from undiscovered resources into a reserve inventory. This rationale is based upon the fact that there are good reasons to expect reserve replenishments to show diminishing returns over time (see Table 1). As we can see, the estimations of reserves and identified resources for the last fifty years show crescent growth values for the majority of commodities.

Models now exist that presume the resource stock to be heterogeneous and more close to the mineral and oil industry. For example, a firm exploits high-quality, low-cost ore (or oil reservoir) first and then increasingly higher-cost ore until it reaches such poor deposits that the market price no longer covers production costs. In such models, economic depletion may occur without physical depletion, and those firms may cease their operations before all of the low-quality volumes of ore (or oil and gas) are actually consumed.

Table 1. Evolution of the reserves and identified resources during the period 1950–2000 (values in tons, except when indicated)

<i>Mineral commodity</i>	<i>1950 reserves & identified resources</i>	<i>1974 reserves & identified resources</i>	<i>2000 reserves & identified resources</i>	<i>Growth in fifty years (2000–1950)</i>
Bauxite	1.4×10^9	1.6×10^{10}	3.5×10^{10}	25.0 ×
Copper	1.0×10^8	3.9×10^8	6.5×10^8	6.5 ×
Gold	3.1×10^4	4.0×10^4	7.7×10^4	2.5 ×
Iron	1.9×10^{10}	8.8×10^{10}	3.1×10^{11}	16.3 ×
Lead	4.0×10^7	1.5×10^8	1.3×10^8	3.25 ×
Nickel	1.4×10^7	4.4×10^7	1.5×10^8	10.7 ×
Phosphate rock	2.6×10^9	1.3×10^{10}	3.7×10^{10}	14.2 ×
Silver	1.6×10^5	1.9×10^5	4.2×10^5	2.6 ×
Tin	6.0×10^6	1.0×10^7	12.0×10^6	2.0 ×
Zinc	7.0×10^7	1.2×10^8	4.3×10^8	6.1 ×
Coal	6.0×10^{10}	6.5×10^{11}	9.8×10^{11}	16.3 ×
Oil (bbl)	8.0×10^{10}	7.2×10^{11}	1.05×10^{12}	13.1 ×
Natural gas (m ³)	4.7×10^{12}	2.2×10^{15}	1.5×10^{14}	31.9 ×

Source: USGS (several), BP Statistical Review of World Energy (several), The Petroleum Handbook, Royal Dutch/Shell Group of Companies, fifth edition, 1966, IEA (several), UN Statistical Yearbook (several).

The modern models that propose a relationship between natural resources and sustainable development divide society's total capital stock into artificial capital and natural capital. Exhaustible resources are a part of the stock of natural capital, and their exploitation causes the stock of natural capital decline over time. These models demonstrate that sustainable development is possible even if exhaustible resources are essential inputs into production processes, a finding that is somewhat counter-intuitive. However, it must be possible to substitute artificial capital for natural capital in the production process, though the amount of artificial capital required per unit of natural capital can rise as the stock of natural capital declines. Whether this can continue indefinitely, however, is far from certain. The extent to which this is feasible depends on the elasticity of substitution of man-made capital for natural capital.

The fixed stock approach leads to a more cautious and pessimistic outlook. For a time it may be possible to substitute artificial capital for natural capital. Sustainable development based on the continued exploitation of exhaustible resources is thus a difficult challenge, and may in fact be impossible. The opportunity cost (flow stock) has a more optimistic outlook. Technological change, substitution, recycling, new discoveries, and other factors induced by the price system are all likely to help maintain sustainable development even with the growing exploitation of mineral resources.

In the last decade of the twentieth century there was a thorough discussion about the concept of resources. According to some authors, the concept of a finite stock of nonrenewable resources does not have validity anymore. One should consider that mineral resources rather constitute a flow. As resources are being converted to reserves and the latter are continuously exploited, new exploration programs lead to the discovery of untouched deposits not previously known. This sequence or flow goes on indefinitely for all practical purposes. New discoveries happen in two dimensions: vertically, meaning that the depth of a mine is increasing; or horizontally, meaning that new reserves, in new regions or new countries, are revealed in unexplored areas. The ultimate limit in the future would be dictated by: first, a depth where no technology could cope with the kind of environment encountered; or second, the absence of new virgin areas either onshore or offshore for exploration purposes, excluding areas unavailable due to a variety of reasons (environmental purposes, indigenous people reservations, military facilities, urban occupation, other economic uses, and so on).

6.1. Club of Rome approach

The Club of Rome is a center of research and a think-tank founded in 1968 in Rome, based on the principles that the future of mankind is not determined once and for all, and that each human being can contribute to the improvement of our societies. For many analysts, the Club of Rome is considered to be neo-Malthusian, as it launched in its first report *The*

Limits to Growth back in 1972, amid warning signals that the world was becoming short of those resources badly needed to maintain current lifestyles. Highly criticized by many scholars around the world, its gloomy scenarios did not materialize. Anyway, its popularity was not in question, as 12 million copies have been sold, and it was translated into thirty-seven languages. The main academic criticisms came from economists, who claimed that the study failed to take sufficient account of the price mechanism, and from scientists, who thought it neglected the capacity of scientific and technological innovation to solve the world's problems.

Regarding the specific issue of mineral resource exhaustion, the Report to the Club of Rome was instrumental in sparking a vigorous debate on the future availability of those resources, a debate that is still quite active.

Almost thirty years later, it is timely to review some of its original assumptions. First, early concerns that society would literally run out of oil or other nonrenewable resources – the problem of physical depletion – now seems baseless. Historical experience shows that long before we could dig up the last pound of copper or recover the last drop of oil in the Earth's crust costs would rise sharply, choking off demand. Second, a more meaningful way to assess the threat of resource scarcity is the opportunity cost. In this case, as pointed out previously, three measures are widely recognized: trends in the real prices of mineral commodities, trends in the real costs of producing mineral commodities, and trends in the real costs of developing new mineral reserves. Third, it is possible for mineral resources to become *more* available (that is, less scarce) over time. While the depletion of low-cost deposits tends over time to drive costs up and thus increase resource scarcity, the cost-reducing effects of new technology and innovations may more than offset this upward pressure on costs. So trends in mineral resource availability reflect the outcome of a race over time between the cost-increasing effects of depletion and the cost-reducing effects of new technology. Other developments, such as the discovery of new low-cost deposits, may also influence the outcome. It is worthwhile to note that the geography of this availability is marked by the fact that, in general, technological innovations are more commonly oriented to deposits located in the industrialized countries, whereas the discovery of low-cost deposits is currently more common in developing nations than elsewhere. Globally, this presents no serious problem for the consumption of those societies who can afford to pay for those minerals. Fourth, over the twentieth century, the available evidence indicates that the cost-reducing effects of new technology have won this race. Real prices and costs have fallen substantially for most mineral commodities. There is no consensus about this conclusion, as other views point to the fact that price formation mechanisms are established by the major consumers (developed nations) at the expense of the major exporters of minerals: the less developed nations. The cost-reducing strategy is the last resort for an American or

Canadian company, for instance, to resist and dispute a market share in an environment now occupied by prominent companies operating either in the Third World or in the former Socialist countries.

The debate over the availability of mineral resources continues in part because of differing assessments regarding the ability of new technology to continue indefinitely to offset the cost-increasing effects of depletion. Given what we know about existing mineral reserves and resources, population trends, growth rates, income distribution trends among nations, and technological developments, it seems unlikely that metal and other mineral prices will experience a significant increase in real terms over the next several decades.

However, as the real costs and prices for many mineral commodities continued to fall during the 1990s, the focus of the debate over resource availability shifted. Mineral producing firms, thanks to new technology, may not face rising costs, but the environmental and other social costs associated with the production and use of mineral resources will nevertheless soon preclude their widespread use. As a matter of fact the same authors of "The Limits to Growth," twenty years later, foresaw the collapse of modern civilization not due to mineral exhaustion, but because of the environmental damage arising from the production and use of natural resources, rather than their depletion. Once again, the starting point is misleading, as the geography of production is quite different from the geography of consumption. Yet, some authors raise an important question: Is it possible for new technology to reduce the environmental and other social costs associated with mining, just as it has reduced the labor, capital, energy, and material costs in the past? This question is related to what is called "leveling the playing field" between developed and developing nations, which continues to be a challenge for future generations. In the real world, there are numerous instances where environmental or other social costs may preclude mineral exploitation, or where mining is incompatible with preserving resources and other assets that society values high. Those activities that diminish the natural beauty of national parks, the pristine wilderness of remote areas, the culture and mores of indigenous people, and biodiversity are often-cited examples. It is normally conceded that in these situations, no amount of technological change may reduce the costs to acceptable levels, and certain sites may quite appropriately be off-limits to mineral exploitation. This is mainly because there are always countries ready to replace the production ceasing due to the above constraints.

One technological advance in the past century having a tremendous impact on the availability of mineral resources is recycling. In the case of precious metals recycling is a very old practice, as one recognizes that every ounce of gold that has ever been mined and refined is still in use in some form. Recycling has great implications for energy and mineral resource conservation, waste reduction, and pollution prevention. In short, recycling programs reduce the

solid waste stream, saving landfill space and valuable energy and natural resources.

For example, the secondary recovery of aluminum uses 5 percent of the energy required to recover the same amount of aluminum from bauxite ores. At the same time, 62.8 percent of the 102 billion aluminum cans produced in the United States in 1998 were recycled, rather than being added to a waste disposal dump.

Steel is America's most recycled material by weight, reclaiming millions of tons of steel scrap from appliances, billions of steel cans and other steel products, including nearly 100 percent of automobiles in the United States. The recycling rate for appliances continues to rise, as do rates for cans and autos. The Steel Recycling Institute uses the following examples to emphasize how recycling saves valuable energy and natural resources, besides saving landfill space:

- Each year, steel recycling saves the energy equivalent to electrically power about one-fifth of the households in the United States (about 18 million homes) for one year.
- Every ton of steel recycled saves 1,140 kg of iron ore, 650 kg of coal, and 55 kg of limestone.

Lead has an outstanding recycling rate, with batteries, which use 84 percent of the lead mined in the United States, being recycled at a 90 to 95 percent rate.

7. GLOBAL MODELS

Global models have been used to understand complex processes and forecast their effects on several aspects, such as economics, demographics, politics, natural resources and the environment. By definition, integrated global models are computer programs that simulate the world in a very broad, comprehensive manner. Because of these traits, integrated global models can be, and are, used as tools to help us understand processes whose effects cross national borders and whose study crosses disciplinary boundaries.

The most prolific period in history for the activity of forecasters was probably from 1965 to 1976, when a host of theorists were highly concerned with the future of mankind under the threat of famine and potential shortages of raw materials. At that time four critical issues were at stake: food, energy, nonrenewable resources, and technology. The most outstanding forecasters were, in alphabetical order: Bariloche (1976), Dumont (1974), Ehrlich (1970), Forrester (1971), Galtung (1977), Heilbroner (1974–6), Kahn and Wiener (1967), Kahn, Brown and Martel (1976), Kaya (1974), Kosolapov (1976), Leontief (1976), Meadows (1972), Mesarovic and Pestel (1974), Modrzinskaya and Stephanyan (1973), Schumacher (1973), Spengler (1966), and Tinbergen (1976). Nine models were generated in the United States, two in the former USSR, one in Japan, one in the United Kingdom, one in France, one in Netherlands, one in Norway, and one in Argentina.

Authors who summarized the analyses of the above models concluded in the 1970s that there are virtually

infinite quantities of most materials in the Earth's crust, sufficient to support very high levels of consumption for an indefinite period of time. The question thus becomes not a matter of physical constraints but rather of the technologies to exploit these resources, and the economic, political, and environmental constraints on their use. The future of an individual material varies greatly, depending on the pattern of end-uses, possibilities for substitution, and the current distribution of production and consumption. Systematic efforts to improve the efficiency of use of raw materials could save on consumption; the rates of discovery and extraction of primary materials required by an average profile seem feasible in the light of historical and geological evidence. In addition, the possibilities of substitution and alternative use-patterns are very great. It must be remembered that raw materials production again demands energy inputs; if we were to make use of the vast quantities of resources contained in low-grade ores and move toward more sophisticated materials we would require a great deal of energy.

Regarding the role to be played by technology, the forecasters may be divided into two categories: optimists or anti-Malthusian, and pessimists or Malthusian. It is noteworthy that two of the Malthusian forecasters (Forrester and Meadows) considered that the availability of minerals would have a horizon of 250 years. The others did not explicitly name any figure.

Much of the analysis of these forecasters was summarized in the book *World Futures*, which aligns seventeen items of uttermost importance:

1. Geopolitical issues.
2. Political development and change.
3. Social stratification, status and power.
4. Distribution and equality of material living standards and wealth.
5. Social values, and perceptions.
6. Action, order, and conflict.
7. Social services and welfare.
8. Food and nutrition.
9. Health.
10. Work.
11. Leisure.
12. Education.
13. Shelter.
14. Transport.
15. Energy issues.
16. Materials and resources issues.
17. Environment.

Apparently as the result of a bias of social scientists, only the last three items refer to energy, minerals, and environment.

Almost twenty years later, other theorists came into scene who were mostly concerned about six major issues: economics, environment, energy, population, politics, and natural resources. Some of the authors are the same as those who investigated this theme two decades ago. A partial list of the main models is given here: World2, Regional World III, Integrated World Model, Towards a Fossil Free Energy Future, Renew-

able Energy, IEA/ORAU Long-Term Global Energy-CO2 Model, World Integrated Model, Global 2000 Revisited, World3, World3/91, FUGI, GEWS, SARUM, Global Input-Output Model, SIM/GDP, Intl. Futures, LINK, Daisyworld, Threshold 21, Global Recall 2.0, The Global Dilemma, and SimEarth.

The issue of minerals availability lost its relative importance due to several factors: oversupply of reserves and resources for most essential minerals consumed by society; the end of Cold War, implying that the threat of a global war disappeared, and so the need to keep huge inventories (stockpiles) of raw materials in the West; and the emphasis on macro-economic policies which were more cost-cutting than in the past, adopted by most industrialized nations. As a consequence, very few forecasters dedicate any effort to quantifying the time horizon of proved availability of metals and minerals, mainly considering that new discoveries of technology could and can change completely the previous forecasts. Under these assumptions, it is reported that there are enough resources of minerals and fossil fuels to supply 200 years worth of extraction at 1990 rates. It is conceded that the capital cost of finding and developing nonrenewable resources is assumed to rise, as the richest and more convenient deposits are exploited first. In other words, as nonrenewables diminish, the grade of the remaining reserves is assumed to decline and deposits are assumed to get deeper and farther away from their places of use. That means that as depletion proceeds, more capital is necessary to extract a ton of copper or a barrel of oil from the Earth. The rationale behind this behavior is that if nonrenewable resources become scarce, the economy allocates more capital to discovering and exploiting them. It is assumed that the initial resource base can be exploited completely, though as resources are depleted it takes more and more capital to find and extract them. It is also commonly assumed that nonrenewable resources are perfectly substitutable for each other, without cost or delay (to a certain extent). The technologies needed would be implemented without delay as long as there is sufficient industrial or service output to make them possible. Prices are not a first concern because prices are assumed to be intermediary signals in an adjustment mechanism that works instantly (or almost in the real market). Nevertheless, historical prices of mineral commodities show a continuous decline in the long range during the twentieth century. This points to a trend that the mineral industry is less and less profitable over time. Accordingly, only Canada remains as a significant mining nation in the end of the twentieth century for the whole G-7.

8. CONCLUSIONS

Recent decades have witnessed intense discussion about resource availability. The paradigm of a finite stock of nonrenewable resources has been replaced by a flow concept. As resources are being converted to reserves and the latter are continuously exploited, new

exploration programs lead to the discovery of untouched deposits not previously known. The ultimate limit in the future would be dictated by: first, a depth where no technology could operate effectively; or second, the absence of new virgin areas either onshore or offshore for exploration purposes, excluding areas unavailable due to various reasons (environmental purposes, indigenous people reservations, military facilities, urban occupation, other economic uses, and so on). Otherwise, sustained development based on the continued exploitation of exhaustible resources is thus at best a difficult challenge. Sound policies initiatives are needed to redirect society and reverse current trends in population growth, resource use, and material-intensive lifestyles. Attempts to use traditional public policy to replace the efficiencies allocations of the marketplace, rather than strengthen it, are likely to be counterproductive. So a first and essential step is the search for an appropriate and common paradigm for resource availability, based upon a sustainable development where future generations are likely to be better off than the current generation.

GLOSSARY

Advanced materials: Materials that exhibit greater strength, higher strength/density ratios, greater hardness, and/or one or more superior thermal, electrical, optical, or chemical property when compared with traditional materials. Advanced ceramics, metals, and polymers, including composites of these, offer a decreased energy consumption, and better performance at lower cost.

Chondrite: A stony meteorite containing abundant blebs or spheroids of magnesium-rich silicates.

Club of Rome: A center of research and a think-tank, formed by a group of scientists, economists, businessmen, international high civil servants, Heads of State, and former Heads of State from the five continents, who are convinced that the future of humankind is not determined once and for all, and that each human being can contribute to the improvement of our societies.

Comminution: The breaking, crushing, or grinding of rock materials (coal, ore, etc.). The act or action used to reduce solids to minute particles.

Conservation: Any of various efforts to preserve or restore the Earth's natural resources, including such measures as the protection of wildlife, the maintenance of forest or wilderness areas, the control of air and water pollution, and the prudent use of farmland, mineral deposits, and energy supplies.

Depletable resources: Resources that do not replenish at a rate sufficient for reasonable human consumption. The profile of use of the resource depletes a fixed stock.

Global models: Global models are computer programs that simulate the world in a very broad, comprehensive manner. They have been used to understand complex processes and forecast their effects on several aspects, such as economics, demographics, politics, natural resources, and the environment.

Intensity of use: A measure defined as the amount of material consumed per unit of GDP (Gross Domestic Product).

Nonrenewable resources: The absence of renewability means that their deposits are finite, either physically or economically: this implies a special concern about their exploitation, use, consumption, and recycling in a way

that could avoid or mitigate its scarcity or unavailability for future generations.

Recycling: The act of passing again through a series of changes or treatments: to process (as liquid body waste, glass, or cans) in order to regain material for human use.

Reserve: A mineral reserve is that portion of a mineral resource which, after the application of all mining factors, results in an estimated tonnage and grade which, in the opinion of the "competent person" making the estimates, can be the basis of a viable project after taking account of all relevant metallurgical, economic, marketing, legal, environmental, social, and governmental factors.

Reservoir rock: A porous rock whose interstices are occupied by a fluid of interest, such as oil and/or gas, or steam.

Resource: Mineral resource is a concentration or occurrence of material of intrinsic economic interest in or on the Earth's crust (a deposit) in such form and quantity that there are reasonable prospects for eventual economic extraction.

Resource base: The ultimate amount of a resource that is believed to be present.

Seabed nodules: These polymetallic nodules, found on the sea floor, are pebbles or stones about the size of walnuts that are built of onion-like layers of manganese and iron oxides, and minor proportions of other metals.

Space mining: A specialized sector of the mining industry having as its object the Moon, Mars, other planets, asteroids, and comets.

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