Mineral Resources: Stocks, Flows, and Prospects

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ABSTRACT

This chapter focuses on metals as they provide the clearest example of the challenges and opportunities that mineral resources present to society, in terms of both primary production and recycling. Basic concepts, information requirements and sources of consumer and industrial resource demand are described as well as the destabilizing effects of volatile resource prices and supply chain disruptions. Challenges facing extraction of in-ground resources and production of secondary resources are discussed and scenarios for the future considered. The results of the scenarios indicate that particularly energy and, as well, water and land requirements could become increasingly constraining factors for metal production. Key research questions are posed and modeling and data priorities discussed, with an emphasis on areas that require novel concepts and analytic tools to help lessen negative environmental impacts associated with minerals. The challenge of sustainability requires collaboration of practitioners and analysts with a multidisciplinary understanding of a broad set of issues, including economics, engineering, geology, ecology, and mathematical modeling, to name a few, as well as policy formulation and implementation.

KEYWORDS: Mineral resources, stocks and flows, recycling, models and databases, scenario analysis.

INTRODUCTION

Improved understanding of the global challenges and sustainability implications surrounding mineral resources will be critical to management of these resources and guidance of social and technical innovation and related public policy. Mineral resources considered by our group include metals and industrial minerals but do not include fossil energy resources such as crude oil, natural gas and coal. Most mineral resources are relatively abundant in the Earth’s crust, but increasing worldwide resource demand is raising concerns about their scarcity, prices, and environmental impacts. This chapter focuses on metals, because they provide the clearest example of the challenges and opportunities that mineral resources present to society, in terms of both primary production and recycling.

The major metals, including iron and aluminum, are distinguished by their relative abundance in the Earth or their economic importance; other metals are designated as minor metals (see Section 3.1). Demand for most metals is rising, especially for a number of minor metals, which have specialty applications that depend on their unique properties. Assuring adequate supplies of the minor metals is a concern as they are often mined with a host, in most cases a major metal. Accessing both major and minor metals faces geopolitical challenges such as refusal of access to mineral-rich lands, substantial requirements for energy, water and human resources as well as damages associated with use of land for mining and the generation of tailings and other wastes. Recovering metals from products at their end-of-life (EOL) encounters both technical and societal constraints.

This chapter identifies basic concepts and information requirements and describes sources of consumer and industrial resource demand and the destabilizing effects of volatile resource prices and supply-chain disruptions. Then the challenges facing extraction of in-ground resources and production of secondary resources are elaborated. The final sections consider scenarios for the future and discuss key research questions and modeling and data priorities, highlighting areas requiring novel concepts and analytic tools to help resolve environmental challenges associated with minerals.

1. BASIC CONCEPTS AND MEASUREMENT REQUIREMENTS

1.1. Concepts and Definitions

Mineral deposits refer to stocks of mineral resources in the ground: primary production generates mineral flows from these in-ground deposits, and secondary production recovers mineral-derived materials by recycling. The secondary stock includes durable products and infrastructure in use (including strategic stockpiles, which are also a resource stock). Products at the end of their useful lives are available for recycling of constituent materials. Tertiary stocks refer to goods that have been discarded, generally within landfills, which constitute complex mixtures of materials and metals but also plastics and other associated materials included in products for functionality.

The quantification of stocks and flows of minerals is critical to measuring and monitoring performance and for designing and evaluating potential future scenarios for moving toward sustainability. Figure 1 illustrates the flow of a single mineral resource from deposits into the economy. The figure is simplified and does not reflect the flow of connected multi-material products which comprise most consumer goods. After manufacturing, the materials are embodied in products that flow to consumers and increase the in-use stock. The latter stock is decreased as products leave it to flow either to accumulate in landfills (if take-back or other EOL systems are not in place) or are sent to recycling facilities. Landfills comprise a tertiary stock that may be decreased if contents are removed for recycling. Thus flows account for the additions to and subtractions from existing stocks.

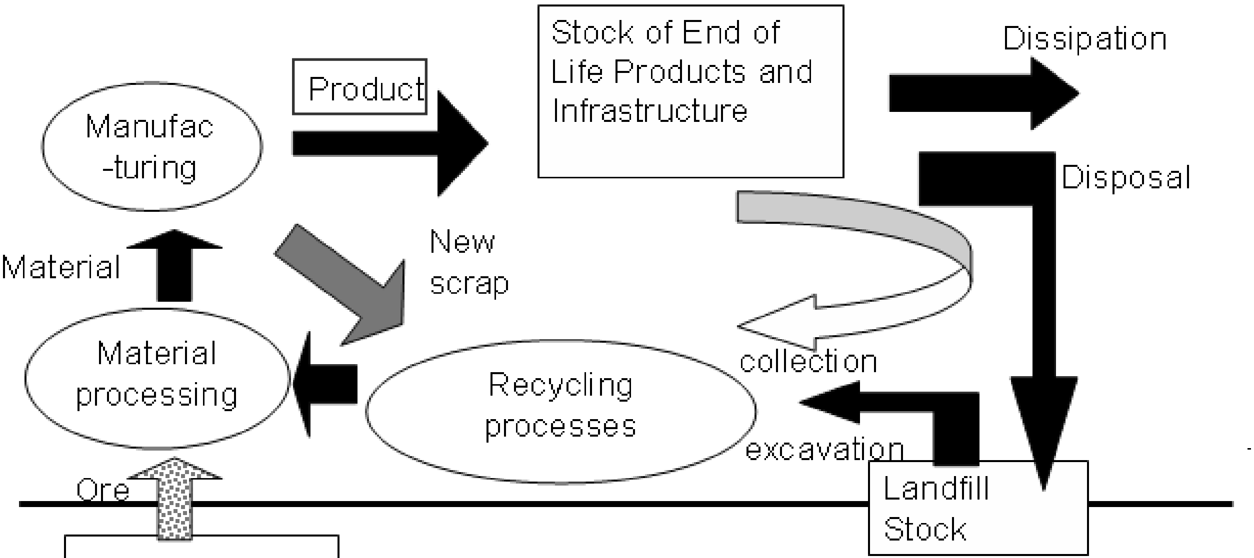

Figure 1. Flow of a single mineral resource from deposit into the economy.

Notes: Rectangles represent stocks, arrows represent flows, ovals represent processing activities. The solid horizontal line represents the boundary between the lithosphere and the anthroposphere. "Product" denotes the stock of in-use products and infrastructure.

1.2. Information Requirements and Database

Studies that examine sustainability issues using material flow analysis (MFA), life cycle assessment (LCA), and input-output (IO) analysis are discussed in Section 5.1.2. Models of fundamental physical and thermodynamic properties of the complex interlinked mixtures of metals, plastics, and building materials (see Reuter and van Schaik 2008) as well as models of potential policies and behavioral reactions will also be required. Below are described basic requirements that are needed to support the analysis of the sustainability of mineral resource use.

The U.S. Geological Survey provides information about identified primary stocks of most non-fuel minerals. The most comprehensive summary of this data is in the Mineral Commodity Summaries, which report reserve and reserve base information for individual countries. Other governments, notably those of Canada, Germany, France, Japan, Australia and South Africa, provide similar information, usually focused on their domestic mineral production. These data are most complete for the major metals and commodities such as copper and phosphate, but less so for minor and by-product metals such as antimony and rhenium. Most production data are generalized and do not include information for specific deposits, although some information of this type can be obtained from annual and 10-K reports of publicly-held companies. Information on the size (grade and tonnage) of individual deposits can also be obtained from these sources, and the U.S. Geological Survey and Geological Survey of Canada provide some databases with information for specific deposit types or commodities. Other databases, particularly on specific deposits, are available from consulting organizations such as the Raw Materials Group, the American Bureau of Metal Statistics, and trade organizations for individual commodities ranging from aluminum to zinc.

As compilations of primary mineral stocks by these and other organizations extend their coverage, we encourage the development of a database format. We recognize that not all mines operate on single deposits and that not all deposits are exploited by a single mine. From a stocks and flows standpoint, this complication is best dealt with by compiling information on mines, although it might be necessary to use deposits for those with no active exploitation. In either case, information that would be useful includes the name of the mine or deposit, its location (latitude and longitude), geological type of deposit, major elements produced and their rate of production, associated minor metals, grade and tonnage of ore extracted, processing method and wastes from processing, and specific information that provides insight into the economic character of the deposit (depth, ore quality).

Data sources for secondary stocks, which quantify durable consumer goods and infrastructure as well as their age and composition, require sources that are entirely distinct from those for primary stocks. One must distinguish products by components and by composite materials vs. individual metals. The complexity of consumer products makes it necessary to consider not only individual materials but also to capture their interconnectedness in products (see Reuter and van Schaik this volume). Some companies and trade groups maintain databases on secondary stocks related to their businesses. The highest priority is to focus on material-intensive, mass-produced products such as vehicles and electronic devices including secondhand use of products in developing and transition economies. A classification of the items comprising the in-use stocks is needed, along with data specifying their average material compositions and lifetimes. Longer-term priorities are to describe tertiary stocks, in particular EOL distribution of a few key consumer products and their logistical recycling constraints.

Models of the fundamental properties of mixed materials can render MFA models scaleable down to product level, a development that is currently under way and will have its own data requirements. Likewise policy-oriented models will require the quantification of parameters describing the behavioral responses of major actors.

For all economy-wide models, an estimate of the maximum annual exploitable supply of a resource in a given country or region is needed. These will depend upon current prices as well as the sizes of the various stocks and the capacity of infrastructure in place for exploiting them both directly and in downstream processes like smelting and refining.

2. MAJOR FACTORS AFFECTING RESOURCE DEMAND AND SUPPLY

2.1. Determinants of Demand

2.1.1. Final Demand, Affluence, and Population

The ultimate purpose of human industry is to provide the structures, goods and services desired by civil society. The most resource-intensive requirements include public and private infrastructure such as roads, dams, buildings, production facilities and housing as well as durable goods including motor vehicles, cell phones and computers. National economic accounts are compiled on a regular basis by national statistical offices in most countries and include IO tables. These tables record the money values of all transactions taking place in that economy in a given year in terms of several dozen to several hundred widely used industrial classifications. The IO tables track flows of goods among industries and, for each industry, several categories of other money outlays comprising value-added. The tables also quantify the value of product flows to several categories of final uses, or final demand, distinguishing in particular domestic consumption and investment, both public and private, as well as foreign imports and exports. Domestic final demand consists of a basket of goods produced by a variety of construction and manufacturing industries. There is of course also final demand for everything from food and clothing to energy and paper clips, all requiring resources for their production either directly as in the case of paper clips or at least indirectly. Typically the items that have longer in-service lifetimes are the most important both for their intensity of material use and for the opportunity provided by this secondary stock for material recycling, but batteries are an example of a product with a short lifetime that are important to recover.

Final demand is driven by the size of the population, its level of affluence, and cultural norms. World population of around 6.7 billion is expected to level off at 9-10 billion by the middle of this century, with virtually the entire increase experienced in the developing and transition countries. The latter already contain most of the world’s population, and their rates of economic growth and increasing consumption are impressive. Consumer aspirations include larger and more comfortable living spaces and personal motorized vehicles, and their governments are putting in place enormous amounts of infrastructure, such as extensive transportation networks in western China (He and Duchin 2008).

2.1.2. Industrial Demand and Technological Change

While demographic realities and lifestyles are major drivers of consumer demand for products and therefore of resource requirements, the other significant influence is technological change in the resource-using manufacturing sectors of the economy. Product innovations affect the composition of final demand while process innovations in mining, material-processing and manufacturing sectors determine the demand (per structure or per unit of product) for specific materials. Abundant materials tend to be relatively inexpensive and therefore widely utilized, and changes in resource availability and price have an enormous influence on substitutions among materials. So obviously does the design of new materials, including the emergence of nanomaterials whose eventual impact on material use is difficult to evaluate. Another important factor is legislation involving use or cost of specific materials including subsidies.

As populations grow and resource use increases the role of recycling will expand. Recycling will never be 100% efficient and varies greatly among different mineral commodities due to their use and functionality in their respective applications. Thus, the need for new primary resources is unavoidable.

2.2. Impacts of Volatile Resource Prices and Supply Chain Disruptions

2.2.1. Volatile Prices

Changes in resource prices have enormous impact on the decisions taken by private corporations because of the direct impact on profits. Stable prices encourage investment in mining and processing (extraction). Unfortunately, prices for many mineral commodities are highly variable and respond to relatively small changes in the balance between production and use. These changes may be a response to short-term events, such as collapse of the wall of a large open-pit mine that shuts down production for a few months, or long-term trends, such as growing demand for a metal because of a technological change. Prices may reflect speculative demand for materials, such as the large investments in raw materials made by hedge funds during the late 1990s and early 2000s. Prices are also affected, either positively or negatively, by government actions ranging from changes in the monetary use of metals, such as departure of the U.S. from the gold standard in the 1970s, to regulations requiring decreased use of metals such as lead and mercury in consumer products, which took place in response to environmental concerns in the 1970s. Finally, prices respond to hoarding or cartel activity, although very few actions of this type have been effective over the long term for mineral products other than oil and diamonds.

The capacity of raw mineral producers to behave strategically when faced with price fluctuations is limited because most are large-scale operations with substantial fixed costs. When short-term prices rise and new operations come online, the incremental output may exceed the change in demand that drove the price upward in the first place, resulting in depressed prices and stressing all operations including the new ones, many of which are closed permanently. Legislation that would allow them to remain dormant for long periods and then be opened and closed as price fluctuates without requiring official approvals at each transition, could be helpful.

Several other factors can help mitigate undesirable effects of price fluctuations. Recycling is very effective during periods of high or increasing prices but risks discontinuation during periods of declining prices. Better product design can lower recycling costs and allow recycling to be competitive over a longer part of the price cycle. High prices can motivate innovation and substitution of the high-priced material such as the recent substitution of cobalt with other metals. However, for many minor elements the flexibility of this approach is limited by special product requirements and functionality.

2.2.2. Supply Disruptions

The increasing complexity of supply chains is another important source of disruption. Specialization and outsourcing have made supply chains longer and globalization has dispersed them geographically, while lean production practices have reduced or completely eliminated the buffer provided by inventories. All of these factors render supply chains more vulnerable to disruptions due to physical threats to production and transport such as natural disasters, military conflicts, terrorist attacks, political turmoil, or epidemic diseases. Other forces for change are market shifts due to imbalances between supply and demand, monopolistic control of sources and transport, or changes in government policies. Countries that have exported their mining and refining industries as well as recycling activities to other countries may be particularly vulnerable. Some industrialized regions and countries, such as the EU and Japan, have created extensive recycling and energy recovery infrastructures. Access to certain materials is often of strategic importance for countries, and government stockpiles to insure national security are one option for mitigating potential supply chain disruptions (NRC 2008).

3. PRIMARY PRODUCTION CHALLENGES

3.1. Major and Minor Metals

Most classifications identify aluminum, copper, iron, lead, nickel and zinc as the major metals, although tungsten and tin are sometimes included in this group. Most other metals are considered minor metals.Although there is no generally accepted definition for this group, they occur largely in low ore concentrations, have relatively low production or usage, and are not traded on major public exchanges such as the London Metal Exchange (LME). Gold, silver and platinum group elements are minor metals in terms of their presence in the Earth, but their high values make them major metals from a commercial standpoint, and they are often called precious metals. The designation of a metal as major or minor may change over time. For example, aluminum was a minor metal before 1900, while today it is the second most commonly produced metal globally and is classified, under any definition, as a major metal. The term minor metal is also used to refer to metals that are special in that they have unique properties, making them valuable for high-tech applications: this is the meaning intended in this chapter. Thus minor metals are in no way of minor importance but simply are not mass produced, making their recycling especially important.

Most minor metals are geologically closely connected to certain major metal deposits so their mine production depends heavily on that host metal. Examples are cobalt and molybdenum, which are linked to copper, while indium and germanium are associated with zinc. Therefore if major metal prices decline and hence also mining activity, the recovery and availability of minor metals also declines. Such by-products or coupled products lead to highly complex demand and supply and price patterns although there are a few examples of minor metals extracted on their own (e.g., lithium and tantalum). The fact that the minor metals are sometimes produced in very few geographical locations makes their supply precarious, e.g., tantalum and niobium. More background on minor metals is given in Hagelüken and Meskers (this volume).

3.2. Land and Land Access

Land considerations pose a major challenge to primary production of mineral resources in two main ways. First, and most obvious to the non-specialist, is the impact on the land of mineral production, involving primary extraction of the ore (mining), processing of the crude ore to isolate the mineral or compound (beneficiation), and further processing to yield a pure metal or other product (metallurgical processing, e.g., by smelting and refining). Open-pit mines include a large hole in the ground surrounded by piles of waste rock that was removed to reach the ore body and by beneficiation wastes (tailings). Underground mines have a tunnel or shaft entrance and tailings, but no pit or associated waste rock unless they are the downward extension of an original open-pit mine.

Mineral operations commonly cover a few square kilometers and are relatively small in area relative to other uses of land such as agriculture and urbanization. In addition to the immediate land disruption, most mineral operations are associated with a “halo” of natural and anthropogenic pollution that impacts surrounding water, soil, and air. Most modern mineral extraction operations are subject to environmental regulations that lessen anthropogenic emissions, but earlier operations were not and their detrimental legacy has created a major hurdle to future mining. While the ecosystem cannot be restored to its form prior to mining, land reclamation is possible. Improved practices and better communication about these practices will be a critical requirement for societal approval and acceptance of mining in the future.

The second land-related challenge to mineral production is access to land for mineral exploration. Although great advances have been made in our understanding of how mineral deposits form and the factors that control the distribution of mineral deposits in Earth, most such knowledge can be extended to depths of only a kilometer or so. The search for deposits is made more difficult by the fact that most deposits cannot be sensed remotely (by force fields such as gravitational or electrical) to more than a few diameters beyond their outer limits. This contrasts with oil and gas exploration in which seismic methods can provide good guidance from relatively great distances. Finally, many deposits that are discovered are too low grade to be mined with current technologies. As a result, mineral exploration must examine very large regions in order to find just one deposit that is economically recoverable. Previous experience with land usage in mineral exploration suggests that the search for new, deeply buried deposits, including sampling the subsurface by drilling, will require access to areas that are thousands of times greater than the area of land that is eventually mined. This means that access to land for mineral exploration will become a critical issue in the future and that land classification schemes should not exclude this important use. It should be recognized in this context that mineral exploration does not usually have a major impact on land and, at most, involves drilling one or more holes from a platform similar in size to a large truck. However, the public’s aversion to mining and potentially increasing difficulty of access in the future could exacerbate geopolitical tensions.

3.3. Energy and Water

When high-grade deposits in the Earth's crust become depleted, mining will shift to lower ore grades, more fine-grained deposits or mining at greater depth. There has been a long-term trend of falling ore grades of the world's metal resources over many decades. In addition, many of the more recently identified ore deposits are fine-grained (although not necessarily lower grade), requiring finer grinding to liberate individual ore minerals. Falling ore grades can be expected to lead to increased exploration efforts to replace the higher-grade deposits. Given the significant exploration effort that has already taken place globally, it is likely that many of these new deposits will be deeper and more widely dispersed than current ore bodies. This deterioration in the quality of metallic ore resources as well as mining at greater depths will have implications for other resources such as energy and water. The effects of declining ore grades on the demand for energy and water for metal production is described in some detail in Norgate (this volume). For copper and nickel, there will be significant increases in demand for energy and water as ore grades fall below about 1% (assuming current technologies). Similar results could be expected for other metals. Most of this increased energy and water demand will be in the mining and beneficiation stages of the metal production life cycle as a result of the additional waste material that must be handled and processed. In addition, increased energy is likely to be required for exploration and identification of future resources, particularly those at greater depth. The availability of secure supplies of energy and water of sufficient quality will be critical factors in the long-term viability of many mining operations and may in fact prevent some deposits from being developed. This will particularly be the case in remote locations, where limited water availability is already causing locally significant problems. Water quality impacts various processing operations, e.g., flotation, flocculation and eventual recovery of water. In addition, water resources could be affected by the release of other waste material, which has serious implications such as contamination of groundwater resources.

While the increase in demand for energy and water for production from deeper or poorer deposits cannot be avoided, it might be possible to limit the magnitude of this increase. In terms of energy, possible options include improved mining practices to reduce the amount of waste to be handled and treated, performing more ore breakage in the blasting stage prior to crushing and grinding of the ore, utilising more energy-efficient grinding technologies, and use of alternative processing routes such as in-situ leaching. Currently, most operations are reliant on fossil energy resources which have significant negative impacts on the environment and result in large amounts of greenhouse gas emissions. With wider use of renewable energy technologies, namely solar, wind, biomass, geothermal, and waste-to-energy, energy may become less of a constraining factor. However, each energy alternative has both costs and benefits which must be weighed, often implying additional material demands (i.e., specialized materials required for fuel cells or photovoltaic panels). Conservation, energy efficiency, and a diversity of low carbon (and low overall environmental impact) energy resources will be required to lessen the impact of energy requirements for mineral extraction in the future. Possible ways to reduce water consumption include treatment and re-use, using water of a quality suitable for the application, and alternative processing routes such as dry processing.

4. SECONDARY PRODUCTION CHALLENGES

4.1. Material and Product Lifecycles and Losses

Mining and mineral processing provide access to raw materials, which are utilized to manufacture a multi-material product. The product is used – and possibly reused after changes in ownership – within a system boundary but also may leave the system boundary such as when embodied in products exported, new or used, from the EU to Africa. When a product eventually reaches its EOL, it might be discarded, treated in a municipal incineration or waste-to-energy plant, go to a defined waste dump or landfill, be stocked, or enter into a recycling chain if the recyclates have sufficient economic value. In the first case any metals contained in the product will most likely be lost, in the second case the waste dump can form a tertiary stock that in the future might be mined for its metal content, and in the third case, a delay could result in recycling or reuse if the stock is again mobilized. Figure 2 shows these options in more detail than Figure 1.

When material enters the recycling chain, it passes through the stages of collection, pretreatment, and end-processing. While they are usually conducted by different stakeholders, the processes are interdependent, for example in that the quality of preprocessing impacts the performance of the subsequent end-processing step, or technological innovation in end-processing might require different output qualities from pre-processing.

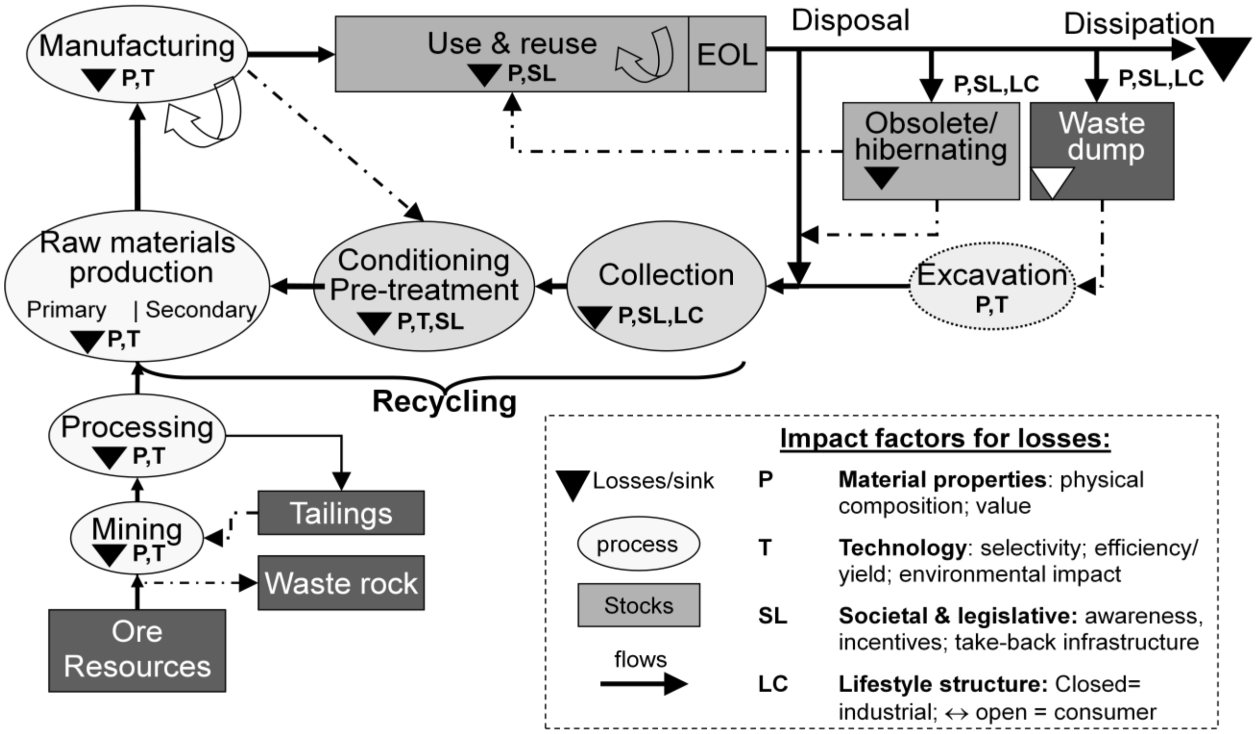

Figure 2. Diagram of secondary production challenges, indicating respective impact factors for losses

4.2. Key Parameters for Lifecycle Losses

Losses of products or materials can occur at various stages along the lifecycle as determined by four main parameters (see Figure 2). First, material properties include the physical composition or degree of complexity determined by the variety of substances contained in the product and their interconnectedness, and the value of contained substances at given market prices. Next, technological descriptors include selectivity to separate target substances, efficiency of substance recovery from individual processes and from the total process chain, processing costs, and environmental impacts. Technological performance is highly impacted by material properties, especially product complexity. The fundamental limits are defined by thermodynamics, physics, and also economics. Costs and environmental impacts include requirements for water and energy, as well as the handling of final waste, treatment of effluents, and off-gas. Third, societal drivers include consumer awareness and initiatives, the availability of take-back infrastructure, the ease of returning EOL products, the legislative framework and its enforcement and control, as well as economic incentives. Finally, lifecycle structure is also key. Fundamental differences exist between closed systems, typical for industrially used products, and open systems for post-consumer products. The latter are characterized by frequent changes of ownership along the lifecycle, high and often global product mobility, a lack of downstream transparency because manufacturers generally lose track of their products, and informal structures in the early steps of the recycling chain, which – if recycling takes place at all – often lead to highly inefficient and polluting ”backyard recycling.” Lifecycle losses in open systems are inherently high. Clearly, closed systems are more transparent, easier to manage and usually have the right conditions to obtain high overall lifecycle efficiencies due to more traceability and control over the lifecycle (Hagelüken and Meskers, this volume). Built infrastructure including dams and roads also accumulate in the technosphere but are generally used for longer time periods.

Material properties and available technologies determine the technical feasibility and the economic attractiveness of recycling, which can be enhanced by appropriate product design, reliant on a database that indicates these properties (Reuter et al., 2005). Citizen iniatives, legislation and life-cycle structure make up the environment for change, and failures often reflect weakness in these factors. A recycling society requires more than legislation and technology – the full system as described above and the interests of the major actors need to be grasped by all stakeholders and subjected to analysis from multiple viewpoints. See, for example, the issue of the Journal of Industrial Ecology devoted to the industrial ecology of consumption (winter/spring 2005). Effective analysis will have to integrate these phenomena with increasing realism.

4.3. Key Requirements, Challenges & Potential Solutions

The main requirements for secondary production are product recyclability (defined by design), an appropriate life-cycle structure and its infrastructure, and best available recycling technologies. Ease of disassembly, the avoidance of inappropriate substance combinations, and built-in features that support product take-back play important roles. Nevertheless, even an optimal design can never guarantee that a product will be recycled. Also critical is an appropriate life-cycle structure, including the active cooperation of citizens supported by legislation and marketing efforts, to help gradually restructure open systems into closed ones. Keeping the product traceable throughout its life cycle and ensuring that recycling at EOL is attractive and will indeed take place are the most crucial measures to close the loop. While a recycling deposit on a new product may help, more fundamental approaches include changes in business models, such as leasing of products or selling functions instead of products. Products with high global mobility like cars require a global recycling infrastructure to ensure their collection worldwide. The subsequent steps in the recycling chain may not necessarily take place in every country but, as in product manufacturing, rely on an international division of labor that benefits from specialization and economies of scale.

Best available recycling technologies maximize recovery of valuable resources in EOL-products. Technology evaluation should follow eco-efficiency principles, meaning that both environmental and economic impacts need to be explicitly considered. Main challenges occur for complex products and new products, which often require innovative processes for material recovery (e.g., photovoltaic panels).

The total life-cycle efficiency is the product of the individual efficiencies of all steps along the lifecycle. The weakest link in the chain has the largest overall impact on losses. Today, in most cases, the weak link is a low collection rate, followed by the use of inappropriate recycling technologies. The lack of recyclability is usually of lesser impact.

Manufacturers of electric goods, electronics and vehicles, can benefit from taking over producer responsibility in a stricter sense. Designing products with good recyclability, collecting them at EOL, and feeding these into controlled, effective recycling chains would generate in-house supplies of raw materials. This would improve supply security for potentially scarce metals as well as deliver an accountable environmental contribution, which is a better proof of a green product than design for recyclability alone. Such take-back and recycling activities can be outsourced as long as the actual material flows are well controlled right to the final destination.

5. PROSPECTS FOR THE FUTURE

5.1. Scenario Analysis

5.1.1. Questions to be Addressed

Consumer demand for material-intensive products will increase with population growth and higher standards of living in developing and transition countries, to some extent offset by changes in lifestyles in rich countries. Technological innovations in industries directly related to material mining, processing, and product manufacture will improve material productivity but also create new requirements for critical materials. Intensive recycling can be anticipated but faces numerous technical, economic, legislative, and behavioral obstacles, and there will always be a need for mining additional primary materials from the lithosphere. These challenges are interdependent and will unfold simultaneously. Different assumptions can be elaborated into alternative scenarios about the future as a basis for assessing the feasibility, costs, and environmental impacts of different ways to address the challenges posed by future more sustainable use of minerals.

Various types of models and databases exist and are under further development for parts of the system, including system-wide optimization models. At one extreme are models of material properties at the atomic or even subatomic levels. At the other extreme are policy-oriented models that are concerned mainly with human behaviors and economic incentives. Section 5.1.2 describes three families of models and applications that cover a wide middle range from given materials to products and technologies and production and consumption activities, Section 5.2 offers an order-of-magnitude look at long-term constraints, and Section 5.3 describes research questions relevant on a several-decade time frame.

5.1.2. MFA, LCA, and IO Analyses

The methodologies of Material Flow Analysis (MFA), Life Cycle Assessment (LCA) and Input-Output Economic Analysis (EIO) have been utilized individually to gain insights on metal stocks and flows and their environmental, and in the case of IO analysis, economic, implications. Increasingly, they are used jointly to address more complex questions (see in particular Suh 2009), and there is still a long way to go for scenario analysis that captures the interrelationships of economic development, consumer behavior and demand, metals and other materials linked to consumer products, the various physical, economic and institutional constraints surrounding mining, interests of multiple stakeholders, and technological innovations both within the minerals sector and in related sectors. More intensive collaboration across disciplinary borders and further expansion of the conceptual frameworks are needed and can be anticipated.

MFA

MFA is a method to analyze the material and energy flows in systems defined in space and time (Brunner and Rechberger 2004). MFA studies have been completed on a number of metals (e.g., zinc, copper) and at various scales. Early MFAs accounted for individual substance stocks and flows in cities or regions (e.g., Wolman 1965, Ayres et al. 1985). In the early 2000s, the first analyses of metal cycles were conducted on national, regional, and global scales (van der Voet et al. (eds.) 2000, Graedel et al. 2004, Hagelüken et al. 2005). These studies informed industry and governments about efficiency of resource use at different stages of the system, losses to the environment, and potential for increased recycling. Both static and dynamic MFA studies have been completed. Static studies (van der Voet, 1996) have concluded that important sources of emissions are often not the large-scale applications of metals, but their unintentional flows as contaminants in, for example, fossil fuels. Dynamic studies have analyzed growth patterns of stocks in use (Spatari et al. 2005, Müller et al. 2006), assessed the impacts of stock dynamics on future resource availability, and forecasted resource demand by linking material stocks with services (Müller 2006, Bergsdal et al. 2007). Global dynamic technology-based MFA models have also interconnected elements and products and linked these to mining and metallurgy as well as environmental impact (Reuter and van Schaik 2008). MFA can be linked with LCA to examine environmental impacts of products or processes during mining, product production, use and waste management.

LCA

LCA is a tool to support systematic assessment of the environmental implications of a product, service or project throughout its life cycle, from resource extraction through EOL [guidelines for completion of an LCA are presented in ISO (2006)]. The environmental performance of mining, extraction and processing of many metals (e.g., copper, nickel) and products has been examined through LCA while fewer studies have evaluated end-of-life aspects, including recycling. Norgate and Rankin (2000) completed an LCA of copper and nickel production and Norgate and Rankin (2001) examined GHG emissions associated with aluminum production. Metals and large numbers of other materials have also been included in LCAs of complex products such as those of automobiles and their components (for a review see MacLean and Lave 2003). Powell et al. (1996) completed an LCA and economic evaluation of recycling, while Rydh and Karlstrom (2002) examined the recycling of nickel-cadmium batteries. The life cycle approach identifies opportunities to minimize the shifting of burdens on the environment from one life cycle stage to another. LCA studies have highlighted environmental burdens associated with metals, materials and products and have informed government, industry and other stakeholders about associated environmental impacts.

IO

Leontief et al. (1983) first used an IO model to quantify the extraction and sector-specific use of non-fuel minerals throughout the world economy in response to alternative scenarios about future demand and technological changes. More recently, Nakamura and colleagues (see, for example, e.g., Nakamura and Nakajima 2005) developed “Waste IO” that involves the compilation of a detailed database about material use in Japan and an IO model that explicitly represents both material use and recycling sectors. The first initiatives linking LCA and IO include those of Cobas et al. (1995) and Kondo et al. (1996). For additional detail see Hendrickson et al. (2006). In recent work, Strømman et al. (2009) integrated LCA data into the database of an IO model of the world economy to examine the environmental and economic impacts on different stages of the aluminum life cycle, of trade-offs between cost and carbon emissions reductions and reduction of carbon emissions. Yamada et al. (2006) and Matsuno et al. (2007) developed methods to track material flows through an economy using Markov chains; however, without an IO model these studies lack an explicit representation of product flows. Duchin and Levine (2009) extended the Markov chain method to relationships between resource flows and product flows by integrating IO modeling of product flows with an absorbing Markov chain approach to tracking material flows. They displayed the properties of resource paths in the case of a static, one-region model, generalized the methodology to a global IO model, and described the features of a dynamic global IO model, where the last tracks stocks of resources, and of the products that embody them, as well as flows.

In summary, MFA tracks material and energy stocks and flows in a defined system, LCA inventories inputs and discharges associated with a product at all stages of the life cycle, and IO models the entire economy, examining economic transactions among sectors, increasingly incorporating MFA and LCA data. All these approaches address parts of the puzzle using actual or illustrative data to take on the broader, challenging questions that are only now taking form. They, along with other scientific and engineering models, provide the foundation for expanding the conceptual scope, the databases, and the methodological “toolbox” for anticipating and addressing future challenges in the provision of society’s material base.

5.2. Constraints on Mineral Availability

We examine how physical availability may in the future be a constraining factor for mineral commodities and whether energy, water or land resources are likely to limit access to them. Several studies (Spatari et al. 2005, Gordon et al. 2006, Müller et al. 2006) have concluded that some in use stocks have reached the same order of magnitude as identified minable resources in the ground. However, Kesler (this volume) demonstrates with the example of copper that undiscovered resources are probably several orders of magnitude larger than those discovered. Today, mining and processing of metals constitute about 7% of total world energy and 0.03% of total world water use. Below we explore potential future demand for copper and associated input requirements. While it is acknowledged that the system is far more complex than the analysis here, the intent is to illustrate some of the key interdependencies between metal extraction and key resources.

Primary (Prim) and secondary (from old scrap) copper production (Sec) are estimated as:

$$\text{Prim} = P*U*(1-r+a*r) \tag{1}$$

$$\text{Sec} = P*U*r*(1-a), \text{ where} \tag{2}$$

P = population, U = per-capita copper use (kg/capita-yr), a = net stock accumulation rate of copper in use, and r = (old) scrap recovery rate.

Estimates (see Table A1 in Appendix) were made for the year 2006 and for two hypothetical future scenarios based on population estimates for the year 2050. Scenario H1 reflects slow growth of copper use with substantial technological improvement and scenario H2 reflects fast growth with low technological improvement.

The impacts of mining lower grade ore on energy and water requirements are estimated for copper based on Norgate (this volume). If the current global average copper ore grade of 0.8% declined to 0.1%, the energy required for primary production (mining, beneficiation and metallurgical processing) is estimated to increase from 95 MJ/kg to 600 MJ/kg assuming current technology. For the two scenarios, 200 and 600 MJ/kg are assumed as technological progress is likely to improve the energy efficiency of mining and processing, although mining at greater depths requires more energy. The latter may be partially offset if ore grades are higher in deeper deposits. The energy requirement for secondary production is assumed to be constant at 15 MJ/kg. Energy requirements for exploration are considered insignificant today and therefore not included in the analysis. These might become critical when exploration focuses on deposits at a greater depth (1-3 km or more). The water required for primary production for the pyrometallurgical production of copper at ore grades of 0.8% and 0.1% are 75 and 477 l/kg Cu, respectively. For the scenarios, 200 and 500 l/kg are assumed.

The primary and secondary production of copper are shown in Table 1. In scenario H1 primary copper production is reduced by 40% from its 2006 value. However, if the entire world were to consume copper at the current U.S. level of consumption along with moderate improvements in recycling (scenario H2), primary production would increase almost seven-fold. Secondary copper production is estimated to increase substantially. These results highlight the importance of understanding the stock dynamics of inuse products for making demand projections (Müller 2006).

The increasing energy and water requirements for copper production for the scenarios and associated percentages of 2006 world use and estimated 2050 world use are shown in Table 1. In 2006, copper production represented 0.3% of world energy use. Under the future scenarios, energy required for copper production would represent 0.2%-5% (based on 2050 world energy use). In 2006, copper production represented 0.03% of world water use, under the future scenarios, they would represent 0.03%-0.8% (based on 2050 world water use).

Table 1: Primary and secondary copper production and associated energy and water requirements: 2006 and hypothetical future scenarios

	2006	H1	H2
Prim[1] [10e9 kg/yr]	14	8	96
Sec[2] [10e9 kg/yr]	3	32	54
Energy required [EJ/yr]	1.4	2.1	58
Percentage of world energy use[3] [%]	0.3	0.2	5
Water required [10e12 l/yr]	1.1	1.6	48
Percentage of global water use[3] [%]	0.03	0.03	0.8

Notes: 1. Primary copper production. 2. Secondary copper production, 3. Values for 2006 are based on 2006 world energy and water use and values for scenarios H1 and H2 are based on estimated 2050 world energy and water use [2050 global energy and water use estimated based on Scenario A1 Nakicenovic and Swart (2000) and Barth et al. (this issue)].

It may be possible to rely much more heavily on renewable sources of energy in the future. Even a steep increase in water use is unlikely to impact the global anthropogenic water budget, but local water shortages that affect mining, such as in parts of Western Australia, may be expected to intensify due to population increase and climate change. In addition, access to land for exploration and mining and impacts of mining on land are also expected to grow. A decline in copper ore grade from 0.8% today to 0.1% will cause an eightfold increase in tailings per ton of copper produced.

We examined whether physical availability may be a constraining factor for mineral commodities, and in particular the limitations imposed by energy, water and land requirements. Despite the simplifications of the model, the results indicate that particularly energy, and as well water and land issues, could become increasingly constraining factors for metal production.

5.3. Research Agenda

5.3.1. Strategic Questions

From a research point of view it is vital to quantify those aspects of consumption that are most intensive in minerals, including housing, household appliances, transportation equipment, and public and private infrastructure. Some scenario alternatives include higher-density living, as in cities vs. suburbs, purchase of appliance services rather than appliances, and sharing of durable goods. Infrastructure in part reflects transport options, such as extensive road systems and private cars vs. dense coverage by public transport. Some of the technological options and associated challenges have been discussed in earlier sections, and the rough calculations of Section 5.2 suggest the importance of a focus on energy use and energy sources.

5.3.2. Modeling and Data Priorities

Given that the challenges come from many directions, a model that represents their interactions is indispensable. Effective modeling, that is both theoretically sound and empirically rich, involves three components: a mathematical formalism, systematically compiled and documented databases, and of course content expertise, in this case that of specialists in minerals and product lifecycles. Typically these three kinds of activities are carried out by three different research communities with less than perfect communication among them and tension between different approaches. Our conviction is that collaboration across these boundaries is absolutely essential for deepening our understanding of the present situation and coming up with realistic and effective scenarios about how it might be restructured for the future.

One compelling modeling requirement is moving from static models, whether MFA, LCA, IO or other, to dynamic models which specify stocks as well as flows and the interrelationships among them, capturing the complexity of interconnected materials in consumer products. Considerable progress has been made in this regard as discussed previously in this chapter as well as in the supporting articles in this volume. However, in combination with these primarily technology and economics based models, approaches are needed (such as scenarios) which are able to capture societal behavioural aspects, policies, and disruptive technologies (innovations that improve products/services in ways that the market does not expect). There remain significant conceptual and data gaps between existing models and databases and those that are needed for modeling the kinds of scenarios capable of meeting the magnitude of the challenges.

Another evident requirement for scenario analysis is the development of databases that make progress toward quantifying worldwide mineral stocks, including estimates of primary, secondary and tertiary stocks, as well as associated flows by region. Flows are limited not only by resource availability but also by the infrastructure in place to exploit it, and this part of the capital stock is particularly in need of characterization and measurement. A major research project in progress will construct a global environmentally-extended IO database with an unprecedented amount of detail on resource flows and some estimates of resource and capital stocks, but the effort highlights the difficulties of moving from a focus on flows to a comparable effort on stocks (Tukker et al. 2009).

It is vital to identify the technological options, existing or in development, that could be utilized at each stage in the mineral life cycle and estimate associated energy, water (and water quality) and land requirements as well as discharges of contaminants and waste associated with each.

In designing and developing the scenarios, dynamic models, and extended databases, researchers with expertise in the minerals sector will need to collaborate with colleagues from many other fields. Beyond the challenges just mentioned, the interrelationships between minerals and all other sectors of the economy must be captured within these models. Thus, a new depth of cross-disciplinary collaboration will be needed to take on the three main components of sustainability -- economic, environmental and social - as well as alternative institutional requirements. All of the modeling approaches discussed in this chapter make important contributions and are essential to tackle the tough issues of sustainability, and in the long term, it is expected that these approaches will converge.

5.3.3. Education and Research

To meet the challenge surrounding the sustainable use of resources, technological innovation across the entire mineral life cycle (e.g., improvements in exploration, mining, and processing methods, product design and recycling system design), new policy instruments, more complete databases, more integrated models, better-informed stakeholders and citizen iniatives, and many types of entrepreneurship are all needed. Meeting these challenges will require a generation of practitioners and analysts with a multidisciplinary understanding of a broad set of issues. This reality provides an exciting research area for graduate students and experienced researchers alike, often working in teams comprised of individuals trained in the fundamentals of economics, engineering, geology, ecology and mathematical modeling to name a few key fields, as well as policy formulation and implementation, prepared - and able - to truly collaborate across disciplinary lines.

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APPENDIX

Table A1. Copper scenarios

Scenario	2006	H1	H2
Population (P) [10e9]	6.5	8	10
Copper use (U) [kg/cap/yr]	2.7	5	15
Accumulation rate (a)	0.67	0.0	0.4
Scrap recovery rate (r)	0.53	0.8	0.6

Assumptions: Population data (U.N. 2007). Average amount of copper entering use in 2006 estimated based on USGS (2009), and transfer coefficients for new scrap generation and copper alloy recycling (Graedel et al. 2004). H1 assumes double the current average global per-capita consumption (1/3 of the current U.S. level) and that copper stock in use has reached a steady state in which the same amount of copper reaches EOL as is entering use. The scenario also assumes a scrap recovery rate of 0.8 (which would require improvements in sorting, processing, and refining technology). H2 assumes a catch-up of all countries to the current level of the U.S., where Gerst (unpublished) determined copper use of 13.2 kg/cap-yr for the year 2000. Stock increase in H2 based on assumption of increase in materials in use and long product residence times. Net stock accumulation rate is assumed to decline in the two scenarios. Scrap recovery rate increases in the scenarios due to declining ore grades and the resulting competitive advantage of secondary resources.