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UNEP

International Resource Panel

Environmental Risks and Challenges of Anthropogenic Metals Flows and Cycles

United Nations Environment Programme

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International
Resource
Panel

Environmental Risks and Challenges of Anthropogenic Metals Flows and Cycles*

* This is report 3 of the Global Metal Flows Working Group of the International Resource Panel of UNEP.

Foreword

Metals are an essential part of our economy as core raw materials for infrastructure and manufacturing of products. Demand is expected to remain strong in the future: in developing countries because of rapid industrialization, and in developed countries because modern technologies will require the use of metals. Meanwhile renewable energy technologies – as part of the transition to an inclusive green economy – are generally more metals intensive than fossil fuel ones.

This report from the UNEP-hosted International Resource Panel, **Environmental Risk and Challenges of Anthropogenic Metals Flows and Cycles**, gives a clear picture of the potential environmental impacts of metals at different stages of the life-cycle while linking with other areas of resource use such as water, food production and energy.

For example, mining can have significant impacts on local ecosystems and landscapes through mining wastes or the pollution of ground- and surface water.

Meanwhile, in a less visible manner, the high energy consumption of metals production adds significant pressure on the global environment through the emission of greenhouse gases.

In addition the complex environmental footprints of metals, and inadequate final waste treatment are cause for concern at the end-of-life stage.

This report concludes that recycling is a positive example towards an integrated approach – for example, producing metals from ore consumes around two orders of magnitude more energy per kg produced metal when compared with recycled metals.

Many possibilities exist that can help to improve recycling rates of metals and increase secondary production — and thus resource efficiency – such as applying best available techniques across the metals value chain and improving product design by designing for resource efficiency.

Handling metals in a sustainable way also means responding to the economic realities, challenges and needs, as well as the imperatives of the social agenda of equity, employment and human well-being. Only a systemic approach can live up to the challenges of sustainable development in the 21st century.

Strengthening the science policy interface was a key outcome of the recent Rio+20 Summit in Brazil—this report by the Panel is an important contribution to that in respect to a core natural resource: namely metals.

Achim Steiner

UN Under-Secretary General and
Executive Director UNEP

Nairobi, Kenya

Preface

Any resource that is extracted and used in our economy and society has potential environmental impacts. The same is true for metals, whose environmental footprints are likely to become even more visible in the future due to the steadily increasing demand for metals both in developed and developing countries. Optimizing metals systems and life-cycles from a point of view of environmental impacts is therefore an integral part of an urgently needed sustainable metals management.

After having analyzed issues of metal stocks in society and recycling rates and recycling conditions and opportunities, the International Resource Panel, hosted by UNEP and established in 2007, therefore decided to address the environmental and energy issues related to the use and the production of metals. This is inscribed in the Panel's mission to contribute to a better understanding of how to decouple economic growth from environmental degradation and escalating resource use. The present report on environmental impacts of metals is part of a series of six reports produced by the Panel's Working Group on Global Metal Flows, which aim at identifying non-prescriptive policy options to improve recycling, sustainable mining and metals utilization through authoritative scientific assessments of global metal flows.

Pressures on the environment and human health occur during the whole life cycle of metals. Mining and refining of metals for example, can cause local environmental and health problems due to the release of toxic substances into the ground- and surface water. Moreover these processes contribute to environmental problems on a global scale as they are very energy intensive and presently use about 8% of the total global energy supply.

The increasing share of metal emissions to the environment coming from non-metal sources such as fossil fuels and phosphate fertilizer or from final metal waste streams entails another significant danger for the environment and human health. A sustainable metals management, using metals to further sustainable development while avoiding environmental impacts as well as side-effects, is an exciting challenge for society.

An increased share of recycling of metals can be expected to alleviate some of the adverse environmental pressures from the use and production of metals. However, increased recycling rates alone will not be sufficient but need to be accompanied by a levelling off of the demand curve for metals. On a local level, substantial efforts in the prevention of adverse local impacts modelled on the example of some more progressive mining companies will remain of significant importance. For these and any other measures seeking to promote a sustainable metals management, it is of great importance to take into account the links with other areas of resource use, such as water, food production and energy.

Providing a scientific baseline knowledge on these impacts from metals use and pointing out options on how to reduce them is urgent, regarding the fact that environmental impacts of metals will be increasing in the future due to the rapidly rising demand for metals, to the development of metal intensive renewable energy technologies and the shift to a metal production based on lower grade ores, which is causing a further rise in energy intensity of extraction and production processes. Because of the crucial role of metals for society, now and in the future, we need to secure their supply and to understand how to minimize the environmental impacts associated with their production and use.

We are very grateful to lead author Ester van der Voet and to all the other experts that contributed to this report for the relevant data and analysis presented, which we feel will certainly be of support to decision-makers in the mission to reduce environmental impacts in an era of growing demand of and greater dependence on metals.

Dr. Ernst Ulrich von Weizsäcker
Emmendingen, Germany

Dr. Ashok Khosla
New Delhi, India

Co-Chairs, International Resource Panel

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Abstract

Metals and their compounds are part of the fabric of modern society due to their unique properties, such as their conductivity, malleability, hardness, lustre, or recyclability. These properties impart a variety of functionality in various present products as well as future "sustainability" enabling solutions. Most of the highly-valued products of modern technology, such as computers, MRI scanners, aircraft engines, and satellites would be impossible without metals. Nonetheless, their production and use, as is true for all resources that we extract and use, are associated with potential environmental impacts. In this report, an assessment is made of the literature on metals flows and cycles in nature and in society, the way they are connected, and the potential impacts related to them. Four areas of attention emerge from this assessment as important information for a sustainable metals management.

1. Local impacts of mining. Mining can cause environmental and health problems due to leaching of toxic substances into the ground- and surface water. Mining can also cause ecosystem degradation. Accidents, e. g. related to tailings dam breaches, can be the cause of severe local surface water pollution. Although mines will always be a manifestation in the local landscape, such adverse impacts can be prevented to a large extent, and remediated after closure of the mine. The progressive mining companies are placing a substantial effort to prevent these adverse impacts.

2. Life cycle energy use. Mining and especially refining of metals is very energy intensive and presently uses about 8 % of the total global energy supply, leading to GHG emissions. In the future, renewable energy technologies applying metals and their compounds/alloys will assist to lower energy related GHG emissions. In addition, the life cycle energy use of metals can be reduced. Industry has developed BAT systems and other measures increasing energy and entropy efficiency as far as is theoretically possible and could improve performance substantially. For the same functionality, the energy gains of reducing the weight in the use phase may outweigh the energy use associated with the production. In addition, life cycle energy use can be decreased by increasing recycling: secondary production is much less energy intensive than primary production.
Despite those developments, the overall amount of energy used for metals production can be expected to increase. The present trend in demand for most metals is still steeply upwards. Establishing infrastructure in developing economies will rise the demand for bulk metals. Novel technologies will lead to an increasing demand for specialty metals. Moreover, the coming energy transition may lead to a demand increase of both bulk metals and specialty metals, since renewable energy technologies are generally more metals intensive than fossil fuel based technologies. On the other hand, process efficiency of mining and refining is increasing, lowering thereby the energy requirement. At the same time, however, the tendency to process lower grades of ore to meet increasing demand leads to a higher energy requirement per kg of metals.

3. Non-metal sources. An increasing share of metal emissions to the environment comes from non-metal sources such as fossil fuels and phosphate fertilizer. For some metals this is presently the major source. Especially in agriculture, closed loop accumulation can lead to high concentrations of metals in soils. A sustainable metals management therefore should include these sources as well.

4. The need for a final sink. For certain metals, a reduced demand leads to an oversupply due to their chemical/geological/designed linkage to valuable carrier metals or other materials. Oversupply also occurs for metals with a former high level of use, where old stocks entering the waste stage form a potential but no longer wanted source of secondary material. But even for metals with rising demand, thermodynamics dictate that cycles can never be completely closed. Those final waste streams need to be immobilized in order to prevent them from being emitted to the environment.

Recycling is an option that can mitigate three out of four of these areas, and that is specifically relevant for metals: metals can be recycled almost indefinitely, with little loss in their technical attributes regardless of the number of times recycled. It reduces the need for primary production with all related impacts of mining and refining. It slows down the need for exploiting low grade ores. Secondary production, including collection and transport, is much less energy intensive and therefore can reduce energy requirements significantly. It should be possible to increase recycling substantially by designing metal systems with this purpose, including not only recycling technologies but also product design. Major benefits can be expected from an increased share of secondary production. However, primary production can be reduced substantially only when secondary production approaches demand. For this, increased recycling rates are insufficient: a leveling off of the demand curve is required. This is unlikely to occur in the next decades, but can be anticipated in the more distant future. Moreover, secondary sources may not be available in large quantities in every part of the world: developing countries still lag behind in building up their infrastructure. This, too, is changing rapidly now.

Finally, a sustainable metals management should not be defined in isolation. There are many links with other areas of resource use, such as water, food production and energy that have to be taken into account. To design such a sustainable metals management, using metals to further sustainable development while avoiding environmental impacts as well as side-effects, is an exciting challenge for society.

Executive Summary

Metals and their compounds have been used in society for millenia because of their unique properties, such as conductivity,malleability, hardness, and lustre. Most of the highly-valued products of modern technology, such as computers, MRI scanners, aircraft engines, and weather satellites would be impossible without metals. Also, metals play an essential role in renewable energy technologies, that are being developed to reduce our dependency on fossil fuels and at the same time reduce greenhouse gas emissions.

Nonetheless, their production and use, as is true for all resources that we extract and use, are associated with potential or actual environmental impacts. Optimizing metals systems and life-cycles from a point of view of environmental impacts is therefore an integral part of a sustainable metals management. The environmental impacts related to metals is the topic of this report. Other aspects such as economic or social issues are equally important from a sustainable development point of view. Technology, crucial as it is, will not on its own address the risk adequately, and broader risk management strategies are called for. These aspects, however, are not treated in this publication.

The number of metals in the periodic system is large. For this report, we concentrate on a selection of metals, starting from the long list of elements as covered in the first report of the Global Metal Flows Working Group on Metal Stocks in Society. Based on three criteria, (1) data availability, (2) societal relevance and (3) environmental relevance we come to the following selection: Al (aluminium), As (arsenic), Au (gold), Cd (cadmium), Co (cobalt), Cr (chromium), Cu (copper), Fe (iron), Hg (mercury), Mo (molybdenum), Ni (nickel), Pb (lead), Pd (palladium), Pt (platinum), Rh (rhodium), Sn (tin), Zn (zinc).

Metals in the Environment

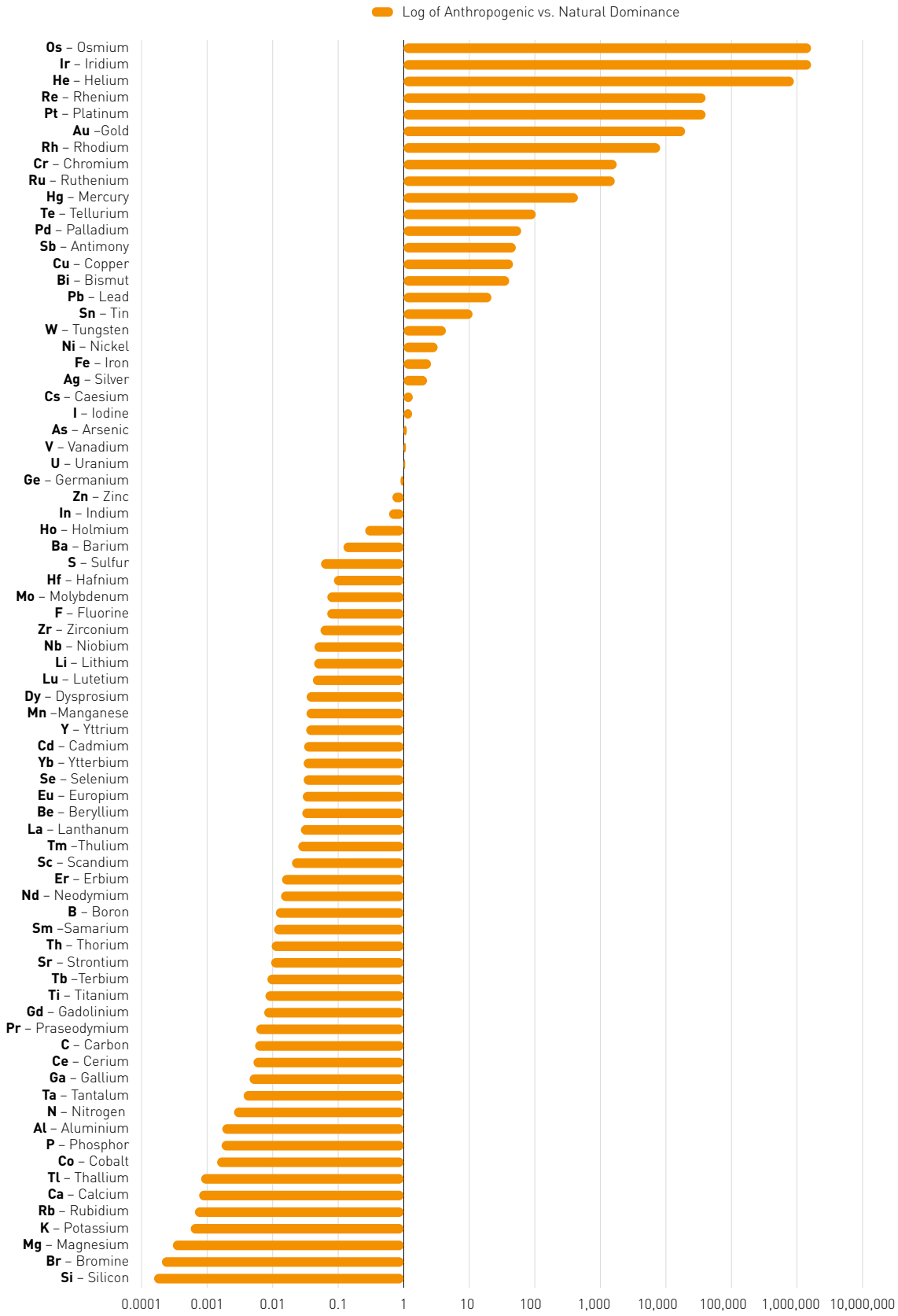
Research into the environmental processes related to metals is long-standing and has led to a large number of publications, as is summarized in Chapter 2. Metals are an essential part of the environment and they are necessary to all living organisms. The anthropogenic input can, however, disturb the natural balance seriously. Metals from natural as well as anthropogenic sources can accumulate in soils and sediments. They enter the food web via plant uptake and through bio-accumulatiaccumulation, which may lead to high concentrations in animals, including humans, in the top of the food chain. Many metals are essential for life. Their intake rate has an optimum. Below that, deficiency symptoms occur, and above it, adverse impacts could occur. Whether or not such impacts occur depends on a number of variables, amongst others speciation, compound, soil characteristics etc.

Impacts on human health occur mostly at the local scale. Such impacts have already led to policies enforcing a reduction in the application of metals such as As, Cd and Hg. Environmental metal concentrations generally are higher now than some centuries back due to losses from anthropogenic metal cycles. The anthropogenic mobilization of metals has increased the magnitude of metal cycles, sometimes with a fraction but in other cases with factors above 100. Figure 1 shows this.

This does not imply that environmental flows and concentrations have multiplied by the same amount. For the most part, the mined metals end up in appliances in society that hardly interact with the environment. Emissions of metals to the environment, excluding landfill, have been estimated to be roughly in the same order of magnitude as the natural sources, weathering and volcanic activity.

Figure 1

Anthropogenic mobilization of elements compared to natural mobilization (Adapted from Klee and Graedel, 2004).



Potential Life Cycle Impacts of Metals

As a general rule, the metals which are produced in large quantities have a lower cradle-to-gate impact per kg than those being produced in small quantities. The difference between the global warming potential of a kg of Fe and a kg of Rh is five orders of magnitude. When multiplied with the annual production, however, Fe is still the metal with the highest impact potential.

Important impacts of the metals' life cycles, as shown in Chapters 4, 5 and 6, occur in the first stages of the life cycle: mining, beneficiation, metal extraction and refining. Potential environmental impacts of primary metal mining and extraction revolve around water (consumption and quality aspects), mine wastes (tailings and waste rock), and energy sources (direct such as diesel and indirect such as coal-fired electricity) with the associated air emissions (sulfur dioxide, greenhouse gases, dusts and particulates). At the local level, mining can have large impacts related to human health and to the degradation of landscape and ecosystems, via mining waste and tailings, process emissions and accidents. Much can be, and in many cases has been, done to reduce these impacts. At the global level, important potential impacts of metal production are related to the use of energy, as outlined in Chapter 4. The energy requirement for producing metals is considerable, as can be seen in Figure 2.

Altogether, the primary production of metals presently contributes 7 – 8 % to total global energy consumption. In the future, this may increase as a result of the processing of lower grade ores, leading to an increase in energy use. The energy efficiency of production processes can be, and is being, increased substantially. The energy required for secondary production is several orders of magnitude less. An increased share of secondary production therefore could reduce energy related potential impacts of metals production substantially.

In the use stage of the life cycle, it is difficult to attribute impacts to metals in metal containing products. Only corrosion from stocks-in-use exposed to the weather is clearly related to the metals themselves. This is becoming a more noticeable source of emissions, since stocks-in-use are growing and point source emissions declining, as a general trend. Besides this, main potential impacts in the use phase are related, again, to energy use. Such impacts generally refer to the product, not the materials embedded in it. Occasionally it is possible to pinpoint a specific role for metals in a comparative sense. For example, it can be concluded that, while aluminium production requires more energy than steel production, energy can be saved in the use phase by using aluminium instead of steel as a base material for cars. An example from Chapter 6 is shown in Figure 3, where the battery electric vehicles (BEV) show an advantage over the standard cars (ICE in

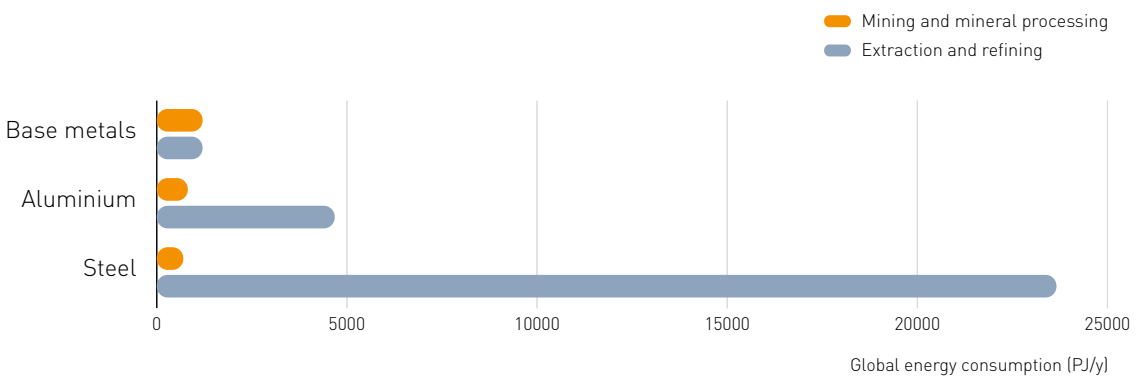


Figure 2

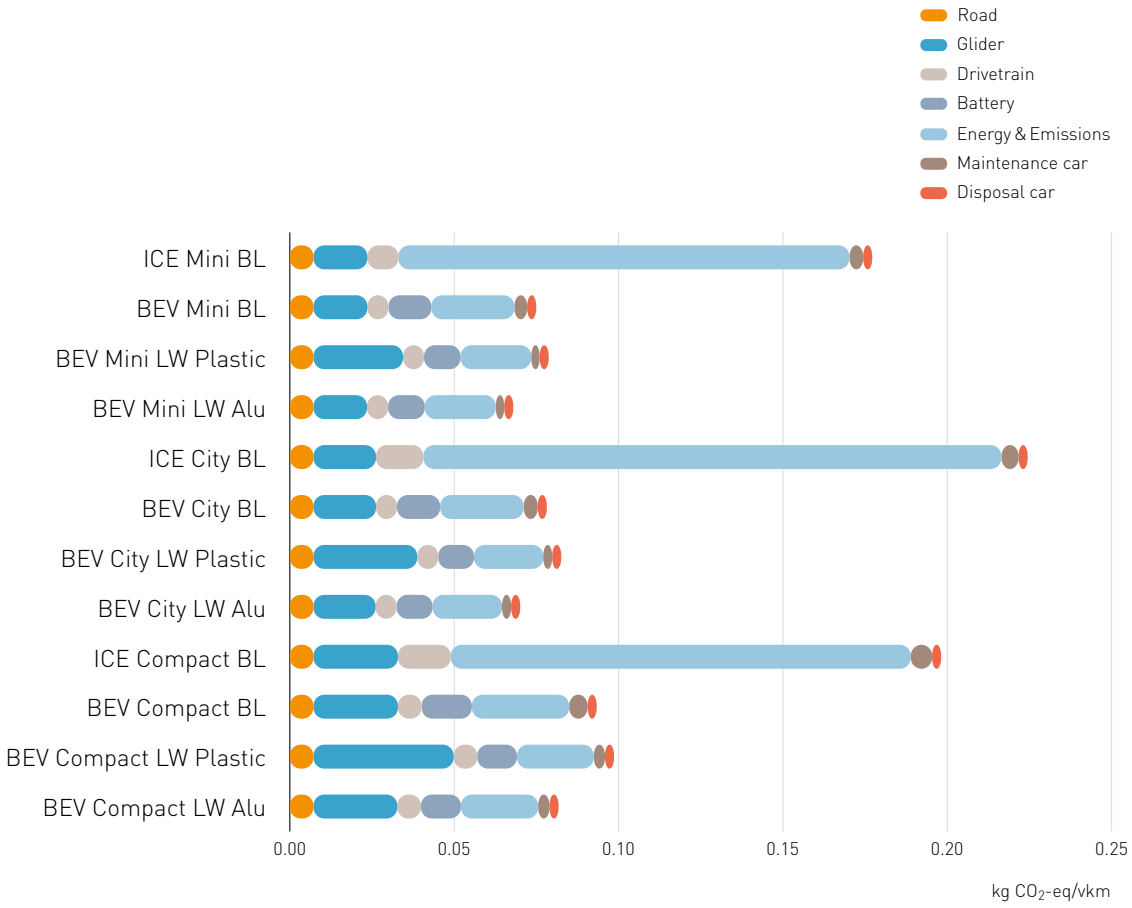
Global energy consumption in PJ/y of primary metal production (Norgate and Jahanshahi, 2010).

Figure 3). GHG emissions in the production phase are higher than for a "standard" car, but emissions in the use phase (light blue, Energy & Emissions in the graph) are much lower.

However, the upscaling of such technologies on a global scale may lead to side-effects in the life-cycle. The metal intensity of renewable energy technologies is generally larger than that of fossil fuel based energy. Figure 4

Figure 3

Global warming potential related to three types of cars, broken down into the various life-cycle stages (Habermacher, 2010).



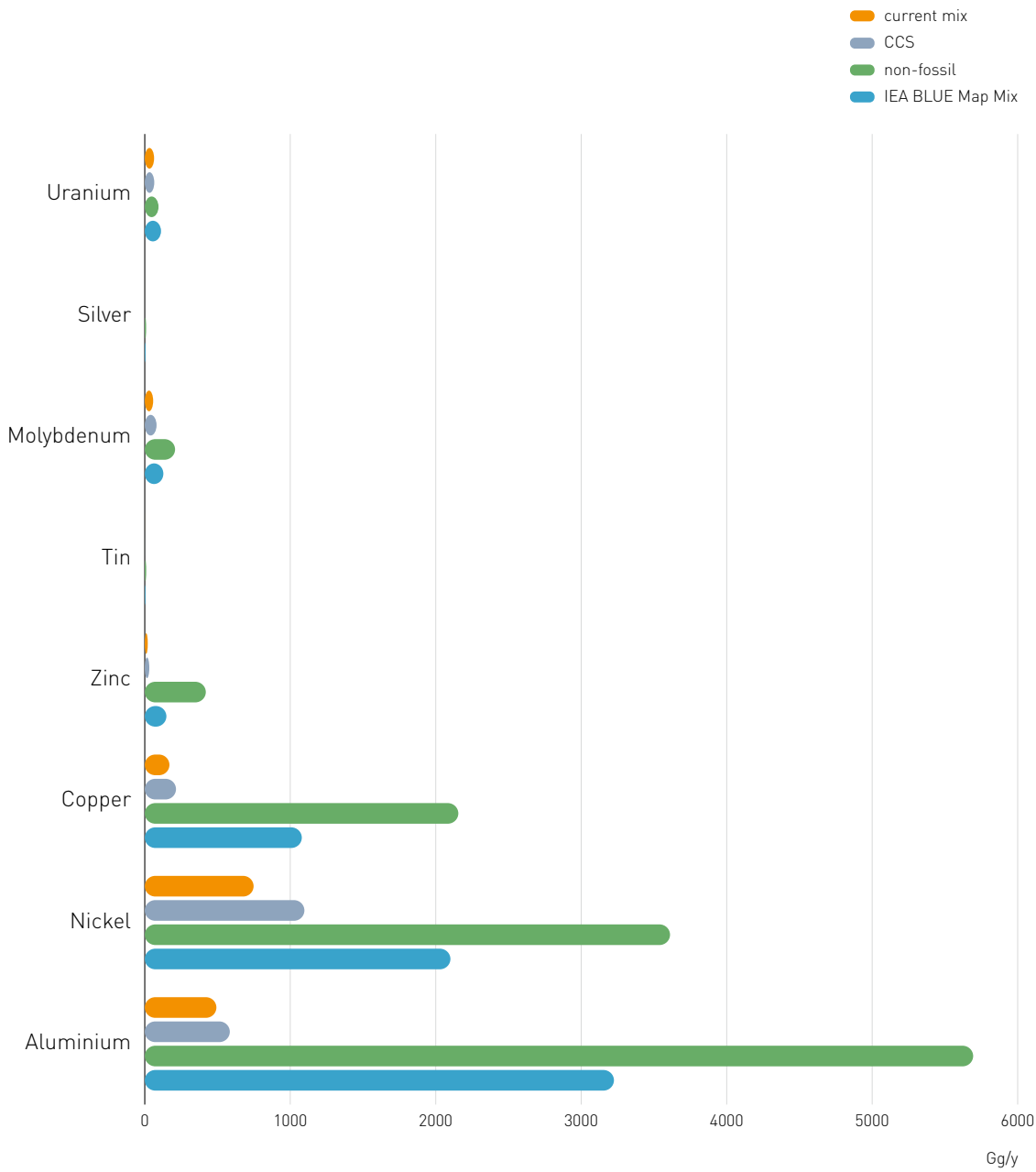
ICE = Internal Combustion Engine
BEV = Battery Electric Vehicles
LV = Lightweight Vehicle
BL = Baseline

Metals are used in many new technologies. Especially renewable energy technologies can be regarded as beneficial for the environment because by using them, emissions related to fossil fuel use are avoided. In those technologies, metals play a crucial role. When comparing those new technologies with conventional fossil fuel based energy production, the reduction of GHG emissions in the energy generating process is evident.

shows the demand for a number of metals for electricity generation at the global level, where the 2007 global electricity production is assumed to be produced with different production mixes. Iron is not present in Figure 4, but it shows the same relative increase as nickel, with which it is used to produce steel.

Figure 4

Material requirements for global electricity systems, to provide the 2007 world electricity production (18.8 E12 kWh), under various electricity mixes (Kleijn et al., 2011)



CCS: current (2007) mix extended with carbon capture and storage on fossil fuel based powerplants

Non-fossil: mix of solar, wind and hydropower

IEA Blue Map: mix according to Shell Blue Map scenario, including fossil fuels as well as renewable energy sources.

This upscaling will therefore lead to an increased demand for metals, and therefore a faster depletion of existing mines.

In the end-of-life stage, impacts could occur via final waste treatment. Metals are emitted to the atmosphere (incineration), to surface water (waste water treatment) and especially end up in landfills, where there is a risk they may leach into the environment. Increasing recycling rates in some cases already can be observed to reduce landfill of metals.

Metals in a Larger Context

Studies to support prioritisation of a materials or resource policy, as summarized in the International Resource Panel's report on "Assessing the Environmental Impacts of Consumption and Production", come to the conclusion that, compared to other materials, metals have a high impact per kg. However, other materials are used in far higher quantities. Agricultural resources, especially of animal origin, and fossil fuels are important contributors to environmental impacts; metals at the moment play a modest role.

In the future, it is possible that metals will become relatively more visible from an environmental impact point of view, for the following reasons:

- The demand for metals is rising rapidly, much more so than the demand for agricultural products.
- A shift towards a renewable energy system implies that the metal intensity of energy production will increase even faster.
- In future, the energy intensity of the production of metals is expected to increase if production, as the current trend suggests, is shifting to lesser grade ores. Lower ore grades lead to exponentially more energy use in the production of metals. For some metals, this trend is already visible and for others it may become apparent over the next decades.

It is difficult to estimate to what extent these events will occur, what the result of this feedback loop will be and to what extent it will be mitigated by increased exploration, cleaner processes, increased secondary production and substitution. Process efficiency increases continually, be it slowly. Recycling rates are increasing, which is a promising development. Technologies to increase those even more are being developed and may substantially reduce the need for primary production, and therefore the potential impacts connected with that.

Developments differ per metal. For metals with a declining use, such as As, Cd, Hg and to some extent Pb, emissions from old stocks dominate, which will decline gradually over time. A complicating factor is that, in as far they are produced as by-products of other metals, their potential supply does not decrease with decreasing demand. This implies we may be entering an era where metals are mined and stored instead of used. For metals with a rising demand, a trend is already visible that recycling rates are increasing. Due to the time delay caused by the residence time in societal stocks, the share of secondary production remains low as long as total demand keeps rising. This means that emissions related to mining, production and use will probably rise as well, although at a lower pace than production itself.

Because both population and welfare are increasing and energy will to a large extent remain dependent on fossil fuels over the next decades, a further rise of the emissions from non-metal sources can be anticipated.

Research Required to Support a Sustainable Metals Management

While there is a large body of knowledge available for metals, there are some gaps that are important to fill in order to make meaningful forecasts and estimate the effectiveness as well as the side-effects of certain changes in management.

- In the area of environmental fate, toxicity and impacts research has progressed most. Nevertheless, it is not complete. Especially the impacts of the presence of a mix of metals/metal compounds is yet unclear, as is stated in Chapter 2 of this report.
- In the area of the anthropogenic cycles and their links to the environment, there are many studies at the national or regional level. Information at the global level is becoming available, but needs to be expanded and linked to all the regional and na-

tional information. A further cooperation and finetuning between the research with regard to anthropogenic cycles and natural cycles is very relevant. If we are to develop measures and policies to reduce impacts of metals while at the same time keeping their functionality, it is essential that we know the origins of metal-related problems, both in general and more specific.

- LCA data and studies on metals and metal containing products are available. They could be improved and added to. LCI data could be improved over the whole chain, but especially on recycling and final waste management processes. The debate around allocation of multi-metal production should be solved somehow. In LCIA, the calculation of toxicity impact factors for metals is still a field under development.

- Combining the life cycle approach with a global level assessment, enabling to include issues of scale as well as enabling to detect side-effects at the global level, is very important to obtain a picture of the overall effectiveness and soundness of certain improvement options, be they technological improvements, substitutions or whole new ways of providing functions. Such a Life Cycle Sustainability Assessment is still in its earliest stages.

- Important knowledge is still missing in the linkages that exist between different types of resources: metals, energy, water, and maybe others. This refers both to the resources needed in the chain of the metals (e. g., energy for refining) and to the fact that metals are in some cases mined as a by-product of other materials (mostly other metals, but sometimes other materials, e. g. mercury production from natural gas). In scenario explorations for the future, this is essential knowledge. It requires an interdisciplinary approach and the cooperation of researchers from different fields to build up this type of knowledge.

- The effectiveness of measures and policies to reduce impacts of metals is also an area of research where there are still many gaps. Effectiveness as well as side-effects of product and process design, of substitution and of new applications, of local remediation, of waste management and of recycling should be investigated further, using a life-cycle approach, both at the micro-level and at the macro-level.

A Sustainable Metals Management

A sustainable metals management has many different aspects. Sustainability includes economic, social and environmental aspects. All these should be included when outlining such a management. In this report, some outlines are sketched based on environmental considerations only. The IRP Global Metal Flows Working Group will develop a report on policy issues in a broader sense. The recommendations formulated here form one of the inputs, other inputs will come from the other reports of the Global Metal Flows Working Group.

Because metals, once in the environment, disappear from it only with geological processes and therefore at a very slow rate, a sustainable metals management should reduce emissions of metals to the biosphere to a level that approaches rates of geological reprocessing. At the same time, a reduction of the metals' potential life cycle impacts could be beneficial for a number of environmental impact categories, most notably GHG emissions related to the high energy requirement of metal production.

Life Cycle

Options to reduce potential impacts over the life cycle are, generally speaking: substitution, dematerialization, and recycling. In addition, metals can reduce impacts in their application in various technologies, for example in renewable energy systems.

- Metals have an important function in new energy systems, thus contributing to a reduction of GHG emissions. It should be kept in mind, however, that implement-

ing these technologies at pages scale will probably lead to a reduced availability of high quality ores. Hence the production of these metals will become more increasingly energy intensive, which in turn reduces resource productivity.

- Substitution of metals by other materials could be an option to consider. However, side-effects must then be considered as well: these substitutes are not without their own environmental and supply issues, and an assessment should be made of the benefits of such a substitution in all cases. Moreover, the use of metals in new technologies is often essential, and therefore substitution will come at the expense of either resource efficiency losses or functionality.

- Dematerialisation, in the context of a sustainable metals management, would mean using less metals in the product to fulfill the same functions. This would reduce potential life cycle impacts accordingly. Again, one has to be aware of potential side-effects.

- Recycling rates for many metals are at present low, but rising. System optimization and design for recycling can help much to further increase recycling rates. Secondary production in general takes much less energy than primary production, therefore, increasing the share of secondary production in the total supply would reduce energy use substantially.

In all cases, information is needed over the whole life-cycle to assess whether or not specific options are preferable over others.

Mining and Production

Mining industries have developed better and more cost-effective approaches to reduce the environmental impacts of metal production. These need to be implemented by all mining companies. They include:

- Reclamation of disturbed land.

- Treatment and stabilisation of metal-bearing soils.

- Prevention and treatment of contaminated water.

- Controls on the amount and character of emissions to the atmosphere.

The energy use of primary production is a major cause of potential impacts. Reducing this is therefore of major importance. Energy efficiency increase can be achieved by the following changes:

- A significant process efficiency increase could yet be made. A potential factor 2 – 20 reduction in energy use per kg produced metal, all else being equal, is mentioned in Chapter 4.

- Increase of secondary production, which generally takes two or more orders of magnitude less energy per kg produced.

- Use of waste streams (fly ash, sludges and suchlike) as sources of metals, especially if a variety of metals can be recovered from them.

Waste Management and Recycling

In many places in the world, waste treatment can be improved greatly. One example is the upgrading of present environmentally harmful informal treatment of electronic waste, another is lengthening the life span of products by repair. Recycling, in addition to reducing energy use, reduces the amount of final waste to be treated. Nevertheless, thermodynamics, in particular the 2nd Law of Thermodynamics, prohibits within a reasonable economic framework the complete closure of the materials cycle. Hence there will always be losses from the production and use of metals, and there will always be a need to make up for these losses by primary production from metallic ores. Old, unwanted stocks of metals no longer used entering the waste stage also can be seen as unavoidable losses from the cycle. Finally, by-product metal reserves no longer demanded but still excavat-

ed must be stored in some way. This implies that a sustainable metals management also should include a final waste treatment. Since metals cannot be destroyed, the only way to prevent them from causing environmental impacts is to remove possible pathways to sensitive receptors so that they do not pose unacceptable risks: immobilize them and landfill or store them.

Non-metal Sources

Non-metal sources of metals to the environment such as fossil fuels or fertilizer are increasing in importance, both relatively and absolutely, and are difficult to address since their use is inherently dissipative. Nevertheless they should be addressed in a sustainable metals management. A reduction of their use is one option. The shift to a renewable energy system, although leading to a higher metal demand, will at the same time lead to a reduction of fossil fuel use. A reduction of phosphate fertilizer use is not likely to occur in the near future. Nevertheless, phosphate rock is a scarce resource in its own right, and solutions may have to be found to solve that problem anyway. A shift to a less animal product-intensive diet will certainly be a step in the right direction.

General

Metals are the ideal type of resource for closing cycles: they do not degrade and can be recycled virtually indefinitely. Approaching a situation where cycles of metals are indeed to a large extent closed is only possible when the demand for metals levels off: a relative de-coupling between economic development and the use of metal resources. Only in that case can secondary production catch up with the demand and will it be possible to substantially reduce primary production and therefore the energy requirement for metals production. This situation is yet far away. Developing economies are now building up their infrastructure, and the approaching energy transition also will lead to a growing demand. Nevertheless, closing cycles as far as possible is essential for a sustainable metals management on the long term.

It is clear that a sustainable metals management cannot be defined in isolation. A global issue like this is linked to many other issues at the global level: population and welfare increase, the concurrent expected rise in demand for food, water and energy, the availability of metals and other non-renewable materials, the shift to a renewable energy system, dietary choices etc. Linkages exist between demand and supply for all major resources, and the present scale of production and consumption is such that constraints are becoming apparent in all corners. A sustainable metals management therefore should be part of an overall effort to steer society towards a more sustainable development.

1. Introduction

Authors: Ester van der Voet, Reijo Salminen, Matthew Eckelman, Terry Norgate, Gavin Mudd, Roland Hischier, Job Spijker, Martina Vijver, Olle Selinus, Leo Posthuma, Dick de Zwart, Dik van de Meent, Markus Reuter, Ladji Tikana, Sonia Valdivia, Patrick Wäger, Michael Hauschild, Arjan de Koning

1.1 Aim and Scope

This report is the third report of UNEP's International Resource Panel's (IRP) Global Metal Flows Working Group, and is published jointly with the Working Group Environmental Impacts. In this report, literature with regard to the environmental impacts of metals and their use is brought together, and conclusions are drawn with regard to the impacts themselves, their causes, and possible options to reduce them. All conclusions are based on existing literature; no new research is conducted for this report. Economic and social aspects of metal use are not treated in this report.

Lately, reports on the potential future scarcity of metals have been published. Scarcity, a subject of significant debate, is not the topic of this report, since it is covered in the other reports of the Global Metal Flows Working Group. The current report treats environmental impacts, based on a large body of literature. The two topics, however, are linked to a certain extent, as will be made apparent in this report. The same is true for potential solutions: recycling, if conducted properly, not only contributes to reduce scarcity problems, but also to a reduction of environmental impacts.

Report 1 – Metal Stocks in Society

Report 2a – Recycling Rates of Metals

Report 2b – Metal Recycling

Report 3 – Environmental Risks and Challenges of Anthropogenic Metals Flows and Cycles

Report 4 – Future Demand Scenarios for Metals

Report 5 – Critical Metals and Metal Policy Options

The first five reports form the necessary basis for the last report.

Metals are an important category of resources. Their unique properties make them invaluable for a number of applications. Their demand, in general, is increasing. Most important developments at the moment are the building up of the infrastructure in rapidly developing economies, leading to steeply rising demand for steel and alloys and other bulk-metals, and the rapid progress in electronics – mobile phones, television screens etc. – conquering the world, leading to an increasing demand of a wide variety of metals. A third development, that has not yet led to large changes but is bound to become important in the future, is the need for new energy technologies to make the transition to a more sustainable and less fossil-fuel-based energy system. These new technologies, too, result in an increase in the demand for metals.

Metals are a specific group of elements from an environmental point of view. As elements, they do not degrade in the environment but accumulate in soils, sediments and seas, and disappear from the biosphere only

via geological processes. Since the mobilization of metals is greatly increased by mining, the biogeochemical cycles of metals have a large anthropogenic contribution. Metals do not just enter the environment via their mining and use as such. Important emissions originate from the involuntary use of metals, as a contaminant in other materials such as phosphate fertilizer and fossil fuels. For some metals, these are presently more important sources of emissions than the metals cycles themselves. On the other hand, the mobilization and use of metals goes hand in hand with a number of environmental impacts related to the use of energy, water and auxiliary materials. If lower grade ores are processed, these impacts can become more important.

All these aspects are covered in this report with the overall objective to present a balanced and complete picture reflecting the current state of knowledge regarding environmental impacts related to metals. The report is meant to provide useful information for policy makers, stakeholders from the metals and mining industry, as well as for scientists.

1.2 Choice of Metals

The number of metals in the periodic table is large. For this report, we focus on a selection of metals.

The selection, starting from the long list of elements as covered in the first report of the Global Metal Flows Working Group on "Metal Stocks in Society" (UNEP 2010b), is based on the following criteria:

- Data availability
- Societal relevance
- Environmental relevance

1.2.1 Data Availability

An important starting point is the list of metals covered in the other reports of the Global Metal Flows Working Group. In their first report (UNEP 2010b), the following metals were included. The report refers to stocks of metals in society, and is relevant for an estimate of emissions:

Ag (silver), Al (aluminium), Au (gold), Cd (cadmium), Co (cobalt), Cr (chromium), Cu (copper), Fe (iron), Hg (mercury), Mg (magnesium), Mn (manganese), Mo (molybdenum), Ni (nickel), Pb (lead), Pd (palladium), Pt (platinum), Rh (rhodium), Sb (antimony), Sn (tin), Ti (titanium), W (tungsten), Zn (zinc).

A next source of information concerns literature on metals in the environment, since this report deals with environmental impacts. A few global inventories have been made of metal concentrations in environmental compartments, but there is an extensive overview of metals in the environment in Europe: the Geochemical Atlas of Europe (Salminen et al., 2005). In this comprehensive publication, all of the above metals are included as well, except for Au, Pd, Pt and Rh. Since Au, Pd, Pt and Rh are very stable, their bio-availabilities are small. In addition, many more are included – in total 67 elements (including a number of non-metals). These data refer to concentrations of metals in soils, surface water and sediments and are relevant for the environmental assessment. It is not possible to narrow down based on this publication.

A third source of information is information about the impacts of the metals. A lot of this information is collected in Life Cycle Impact Assessment (combined fate, exposure and toxicity data) and in Life Cycle Inventory databases (life-cycle wide extractions and emissions of all sorts of substances of the mining, production, use and waste management processes of the metals). In the most comprehensive LCA Impact Assessment list, the CML 2000 list (Guinée et al., 2002) a number of metals have a toxicity potential. This probably implies that for these metals no-effect

level or TDI data are available as well. Out of the list of metals put forward by the Global Metal Flows Working Groups first report, the following metals are covered: Cd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Sb, Sn, Zn. In addition, toxicity potentials for human and ecosystem health are available for Tl (thallium), As (arsenic), Be (beryllium), Se (selenium), and V (vanadium).

Metals are included in various Life Cycle Inventory databases. By far the most complete one is the Ecoinvent database. This database includes mining, refining and production data of a wide array of metals. The list of metals included in the first report of the Global Metal Flows Working Group is included in the Ecoinvent database, except for Sb, Ti and W. In addition, data are available regarding Dy (dysprosium), Nd (neodymium), Pr (praseodymium), Ga (gallium), and In (indium). Ecoinvent also includes some data for secondary production: for Al, Ag, Au, Cu, Ni, Pd, Pt, Rh and steel.

Overall, a narrowing down of the list based on information gaps is not indicated.

1.2.2 Societal Relevance

Societal relevance is related to the availability of metals and the importance of their applications. This criterion is rather difficult, because there is always the possibility of substitution. Nevertheless, we look at two subcriteria here:

- Magnitude of use.
- Reported scarcity on the market.

Fe is the metal that is used in the largest quantities. Al is a good second, followed by a group of Cu, Zn, Pb, Cr, Ni. It is important to include these metals just because of the scale of their use. Not all of them are related to toxicity problems, but they all do have an environmental impact via their life cycle, especially the energy requirement.

Market scarcity is more related to metals that are present in ores in small quantities. It is partly a geological issue, but it is also determined by economics, politics and social factors. Some scarcity assessments have been made, including a number of precious and specialty metals. Not just present, but also future scarcity issues are relevant: new technologies related to solar and wind energy generation, and fast growing products such as cell phones, computers, electric motors for cars etc. contain a high number of such metals. The topic is gaining interest worldwide.

The most extensive scarcity assessment presently available is from Nagasaka (2008). Metals covered in this publication are not directly relevant from an environmental impact point of view, but are interesting because of their societal relevance. Out of the metals selected in the previously mentioned Report on **Metal Stocks in Society**, the following are included: Co, Cr, Cu, Fe, Mn, Mo, Ni, Pb, Pd, Pt, Sn, Zn. In their report on critical materials, the European Commission (European Commission, 2011) has listed Sb, In, Be, Mg, Co, Nb, PGMs (platinum group metals, including Pt, Pd and Rh), Ga, Rare earths (including the lanthanides, Sc (scandium) and Y (yttrium)), Ge (germanium), Ta (tantalum) and W. This list addresses also potential future supply risks.

A third, relevant issue in relation to societal relevance is

- The management of the metals.

To set up a sound management it is important to acknowledge their origins: the thermodynamic link between metals as they occur in ores together. This has environmental implications as well, via the choice of production technology, the choice for application of these metals in products, and the implications this has for recycling technologies. This implies assessing co-product and by-product metals together with the main carrier metals. For our choice of metals, it means we have

to cover both carrier and co-product and by-product metals to obtain a relevant picture.

1.2.3 Environmental Relevance

The environmental relevance is the most important criterion, since this report is about the environmental impacts of metals. Sub-criteria in this criterion are the following:

- Inherent and environmental toxicity of the metals themselves.
- Disruption of natural metal cycles.
- Life-cycle impacts of metals.
- Local impacts related to mining and smelting.

Inherent and Environmental Toxicity

A number of metals are known to have toxic impacts when they are released into the environment. Among those are (compounds of) As, Au, Bi, Cd, Cr, Hg, Ir (iridium), Pb, Pd, Pt, Rh, Sb and Tl (e. g. Wolterbeek and Verburg 2001). If we add information out of the Life Cycle Impact Assessment, we can add Ag, Be, V, Mo, Co and Ni. Toxicity potentials for these metals (human toxicity, problem oriented approach) are relatively high. These toxicity potentials are expressed in relative terms and are related to the emission of 1 kg of a certain metal (Rosenbaum et al., 2008). They include environmental fate, exposure and toxic impacts, and thus they provide a good comparative picture of the environmental toxicity. Many of these metals are not on the list of the Global Metal Flows Working Groups first report.

Disruption of Natural Cycles

Several publications have indicated the magnitude of the anthropogenic metals cycle compared to the natural cycle (Benjamin et al., 1992; Ayres, 1992), or the magnitude of the emissions from society compared to natural flows (Nriagu & Pacyna, 1988; Pacyna et al., 1995; Olendrzinsky et al., 1996). From these publications, we consider Pb, Hg, Ag, Sb, Se, As, Mo, Zn, Cu, and Cd as important metals. All are included in the first report of the Global Metal Flows Working Group, except As.

Life Cycle Impacts of Metals

Significant impacts are related to the use of energy to mine and refine the metals. While it is clear that the impacts per kg are highest for metals that appear in their ore in low concentrations, it has also been shown that due to the sheer magnitude of their cycles the production of bulk metals still has the largest impact. Other impacts refer to the use of water, to emissions of pollutants to air and surface water, and to leaching from landfilled waste. Cradle-to-gate impacts per kg are very large for PGM metals, but impacts of metals worldwide are dominated by iron and steel, followed by Al, Cr, Cu, Ni, Zn etc. From this point of view, the bulkier metals should be selected, maybe supplemented by some metals that have a rapidly rising demand, an especially high energy use, or are associated with declining ore grades. This could be an argument to include metals such as Mg and Ti as well.

Local Impacts Related to Mining

Mining in many cases presents risks of local landscape degradation, loss of ecosystems and pollution. This is hardly a distinguishing criterion. However, Au is a special case – environmental and social problems related to artisanal and small-scale mining are relatively widespread.

1.2.4 Metals Included in the Assessment of this Report

Based on the above, we come to a selection of metals to include in this report. The choice is restricted to the list of metals of the first report of the Global Metal Flows Working Group, mostly for practical reasons, with one exception: the metalloid As, which is highly toxic and very relevant for a discussion on historical contamination.

(1) Bulk metals: Al, Cr, Cu, Fe, Ni, Pb, Sn, Zn

- Data availability good, for both environment and society.
- Important for society, environmental importance also large, via cradle-to-gate impacts.
- A number of their by-products can be included as well (see (4).

(2) Some smaller scale metals specifically associated with environmental problems, often produced as co- or by-products: As, Cd, Hg

- Data availability good, for both environment and society.
- Although their use is decreasing or at least not increasing, they are still environmentally important due to their high toxicity or the problems related with contaminated sites.

(3) Some rare/precious/specialty by-product metals with potential for increase in use: the PGMs (Pt, Pd, Rh), Au, and in addition Co and Mo.

- Data lack may be occurring, but some data is at least available for both environment and society.
- Their use is increasing, per kg cradle-to-gate impacts are often very high, will become more important for society as well as for the environment.
- Their selection allows us to address its issue of co- and by-production and the environmental relevance.

(4) Co- and by-products of bulk metals: in as far they are not covered in the above lists, information about them will be included ad hoc whenever relevant, but they are not assessed systematically. For the ones that do occur in the list above, their link with the carrier metal production should be acknowledged. This is relevant especially for Chapters 4, 5 and 6, where technologies for production and recycling and life cycle impacts come into the picture.

This leaves us with a list of 17 metals: Al, As, Au, Cd, Co, Cr, Cu, Fe, Hg, Mo, Ni, Pb, Pd, Pt, Rh, Sn, Zn. They will be assessed in this report.

1.3 Structure of the Report

In the report, various aspects with regard to environmental impacts of metals are covered.

In Chapter 2, the huge body of literature related to metals in the environment and related risks is reviewed. Natural cycles and the anthropogenic addition to those, concentrations in various environmental compartments, combined with data on acceptable and no-effect levels will give an insight in the extent to which the presence of metals actually poses environment and health problems.

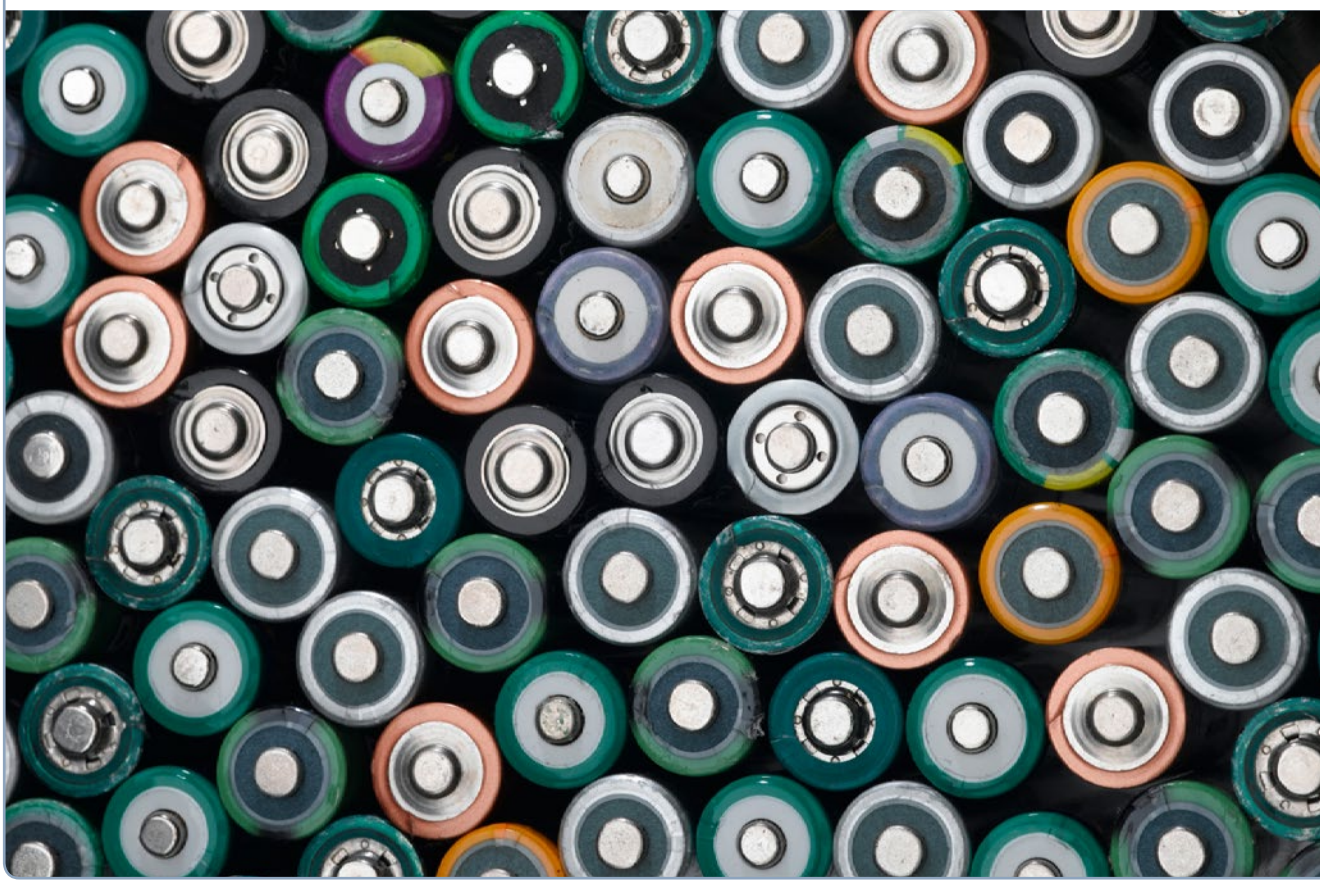
Chapter 3 is dedicated to sources of metal emissions. These can be natural, but mostly they are anthropogenic. The nature of these emissions has changed over time, from mainly industrial point sources to mainly diffusive sources unrelated to the actual mining, refining and use of the metals themselves. Other sources seem to have become more important. Also in this chapter, we treat legacy contamination: the emission of metals from abandoned mining or production sites.

Because this appears to be a very important issue, Chapter 4, is dedicated to the energy requirement of metals cycles. Not so much the emission of the metals themselves but the cradle-to-gate impacts related to the use of energy to mine and refine them seems to be an increasingly important cause of environmental impacts. This is explored in Chapter 4.

In Chapter 5, other impacts related to metals are covered. This covers the whole life cycle: impacts related to mining, to refining, to production, use and waste management. Although the picture is still global, these impacts are relevant especially at the local scale. They cover, among others, land degradation, water use, water quality deterioration, air quality problems. Also, the effects of mitigating measures, including dematerialization, product and process design, substitution and recycling are treated. This enables to comment on options for a more sustainable metals management, at least from the point of view of environmental impacts.

In Chapter 6, all these impacts are brought together and integrated into a view on Life Cycle Impacts related to metals. For this, an important aspect is the Life Cycle Impact Assessment: the translation of all kinds of impacts into a limited number of impact categories at midpoint or endpoint level, and the aggregation of those different impacts into a single score. Also, the availability of Life Cycle Inventory data is investigated and data gaps are identified.

Finally, in Chapter 7, conclusions are drawn and recommendations are made with regard to the environmental impacts of metals and options to reduce those, based on the information from the previous chapters.



2. Metals in the Environment

Reijo Salminen, Job Spijker, Martina Vijver, Matthew Eckelman, Olle Selinus, Leo Posthuma, Dick de Zwart, Dik van de Meent.

2.1 Natural Concentration of Metals in the Environment, Local and Global

2.1.1 Characterization of Metals

Metals are present in various forms: as elements, as alloys and as compounds. The form wherein they occur determines their chemical and physical properties. From a perspective of determining risks for human and ecosystem health, it is important to make that distinction. Elementary metals seldom are harmful for humans or in the environment. Metals in certain oxidation state, some ionic forms, and compounds, such as organo-metallic compounds can be essential (such as proteins) or harmful. Therefore, it should always be carefully defined what we mean when we are talking about harmfulness of metals in the environment. Following chapters characterize metals in a very general level and the harmful speciation of elements is not described separately.

Major metals: Fe, Cu, Zn, Al, Ni, Cr, Pb, Sn

Iron (Fe)

Iron is one of the major metallic elements of the Earth's crust. As a main element it takes part in almost all natural and man-caused geochemical processes. In magmatic differentiation, iron is enriched in ultramafic and mafic rocks; and also in mafic volcanic rocks. Acid and alkaline igneous rocks, limestones, and sandstones have relatively low Fe contents. In oxidizing conditions, iron oxides and hydroxides yield sedimentary iron ores, laterites, and the illuvial zone in podzols. In reducing conditions, iron precipitates as sulfides, carbonates, or phosphates. In the biosphere, Fe abundance is relatively high, and Fe is an essential element for life.

Copper (Cu)

Copper is a common metal found in both natural geogenic and anthropogenic systems. Geochemically it behaves similarly with a big group of elements such as Fe, Ni, Co, Zn, Pd, and Ag. As a chalcophile element it exhibits typically as sulfides. During magmatic and volcanic processes, copper is enriched in late solutions, which give rise to, for example, porphyry copper or volcanic exhalative ores, in which chalcopyrite ($CuFeS_2$) is the most common mineral. In exogenic sedimentary ore processes Cu is also one of the most important elements. Copper is a biologically active trace element and important for life; either a lack or an abundance of Cu may be dangerous for many organisms. Copper is widely used in different industries. In the biosphere and hydrosphere, Cu is relatively mobile. Therefore Cu in biosphere is distributed more evenly than in the lithosphere.

Zinc (Zn)

Zinc is a relatively widely distributed metal in the Earth's crust. In bedrock, it replaces Fe and Mg in the crystal lattices of silicates. In magmatic differentiation, its behaviour is controlled by the crystallization of ferromagnesian minerals and sulfides. In bedrock the distribution of Zn is quite uniform. The highest Zn concentrations are in carbonatites of surficial and mesoabyssal alkaline formations and also in shales. In soils, zinc is very mobile, but it is easily adsorbed on Fe, Mn, and Al hydroxides and organic complexes. In stream waters, elevated Zn concentrations are connected with organic and non-organic colloids. Zinc is an essential element for plants and animals, but it is toxic in excess. Anthropogenic contamination by Zn can be intensive in areas of (abandoned) mine sites and metal production industries.

Aluminum (Al)
Aluminum is one of the most common elements in the Earth's crust. It is a metal with pronounced amphoteric properties, i. e. it can react as an acid as well as a base. Aluminum is one of the main components of numerous rock- and ore-forming minerals. Most rocks have quite high total Al concentrations, with the exception of ultramafic rocks, sandstones, and limestones, in which Al concentrations are low. Mineral dust, both geogenic and anthropogenic, is the most common source of elevated Al concentrations in the sample medias studied. The solubility of Al in soils is highly dependent on pH and on complexing agents such as organic matter. Al-bearing solid phases are relatively insoluble, particularly at neutral pH values, but in acid conditions Al concentrations increase, resulting in adverse effects on both aquatic organisms and terrestrial plants.

Nickel (Ni)
Nickel is a relatively common metallic element. In magmatic processes it tends to behave like Mg and Fe and is removed from the silicate melt at an early stage. In igneous rocks Ni content rapidly decreases from ultramafic to basic and acid rocks being the lowest in alkaline rocks. Nickel may also be abundant in carbonaceous sedimentary rocks and in Fe-Mn sedimentary deposits, owing to its capacity to adsorb onto Fe-Mn hydroxides. In the hydrosphere, the mobility of Ni is high when the pH value of water is low. Nickel is an element that can have toxic and carcinogenic properties in certain forms and compounds.

Chromium (Cr)
Chromium is widely distributed in the Earth's crust. The amount of Cr decreases from the mantle through the lower to the upper crust and from the oceanic crust to the continental crust. Chromium is geochemically close to Fe, Ni, Co, Ti, and Mn and tends to be present in mafic minerals. Common Cr minerals are chromite, chrome mica (fuchsite), and chrome spinel. Cr content decreases rapidly from ultramafic to mafic, acid, and alkaline igneous rocks. Chromium is a common constituent in many minerals and is common in abyssal rocks such as kimberlites. Chromium's hydro- and bioavailability are low. For the most part, Cr migrates in stream water in its solid phase. In the hexavalent state, (Cr(VI)), it is especially toxic. Mobile cationic Cr(VI) is usually formed in the biosphere, by anthropogenic activities.

Lead (Pb)
Lead is not a very common metal in the Earth's crust. It is enriched in the late stage of magmatic differentiation, and Pb ores are crystallized mainly from hydrothermal solutions. In igneous rocks Pb concentration are highest in acid (granites) and alkaline rocks. In the feldspars it replaces K and Sr. In the sedimentary rocks Pb is quite evenly distributed. Lead is poorly soluble in the weathering processes and the Pb compounds formed are quite immobile. Thus a positive correlation exists between lead levels in bedrock and soils. In the biosphere, anthropogenic mobile lead is strongly accumulated in the uppermost organic and the illuvial layers of soils. The use of leaded petrol in the past has been a main source of lead in the atmosphere, but in many places this source now no longer exists. Lead is a very toxic element.

Tin (Sn)
Like Pb, tin is a relatively rare metal, but it is well known as a metallic element, because of its use in household products and the relative ease of its extraction from natural sources. It is one of the seven metals known in antiquity. Tin is a siderophile metallic element forming several minerals, including cassiterite SnO_2 and the rarer stannite Cu_2FeSnS_4, but can also be present as an accessory element in biotite, muscovite, amphibole, sphene and rutile. It is enriched in felsic relative to mafic igneous rocks. The mobility of Sn during weathering is highly pH dependent and, Sn^{2+}, which is a strong reducing agent, is only present in acid and reducing environments. Tin forms soluble and insoluble complexes with organic substances. The occurrence of Sn in soil has not received much study. Many Sn compounds are toxic to lower organisms

Metals specifically associated with environmental problems, often produced as co or by-products: Hg, Cd, As, Au

Mercury (Hg)

Mercury is a mobile but not very widely distributed and not very common metal. Geochemically it behaves similarly to Cd, Zn, Au, Ag, and Tl. In mineral lattices, Hg replaces mainly Zn and Cd, and it may be a constituent in ore deposits, particularly in gold mineralizations. In sulfide mineralizations, cinnabar (HgS) is the most common Hg mineral. Mercury differs from other elements because of its ability to vaporize under natural surface conditions. The volatility of Hg facilitates its migration, and it may reflect the deep structures of the bedrock. Very high accumulations of Hg are known in gas, oil, and coal deposits. High Hg contents are also known to occur in phosphates and manganese ores. Very low levels of Hg characterize igneous rocks. In younger sedimentary rocks, Hg concentrations are on average higher than in the older crystalline rocks. The geochemistry of Hg is characterized by the formation of organo-mercury compounds that are quite stable in aqueous media. The transformation of these compounds, especially methylation, plays an important role in the Hg cycle in the environment. Mercury is a very toxic element, and the methylation processes especially have been associated with environmental catastrophes by Hg poisoning.

Cadmium (Cd)

Cadmium is a rare and widely dispersed metal. Its geochemical properties are close to Zn, In, and Hg. Cadmium is, for the most part, found as an admixture with other elements in different sulfides (especially in Zn ores). Elevated Cd contents are very often found in carbonates, kaolins, phosphorites, and fossil fuels. Although Cd concentrations are low in the Earth's crust, it is very important in exogenic processes, because of its mobility in aquatic and gaseous phases and its capacity to accumulate in different media in the biosphere. Cadmium is a very toxic and carcinogenic element. It is emitted into the air and water by mining and metal smelting, and by industries using cadmium in nickel-cadmium batteries (nicad), alloys, paints, and plastics. The burning of oil and waste produces air-borne Cd. Cadmium is also released from phosphate fertilizers and from sewage sludge.

Arsenic (As)

Arsenic is a trace element with semimetal properties. High As concentrations are typical for sulfide ores, and arsenopyrite is also an indicative mineral for most gold mineralizations. Its content in different igneous rocks is quite low and stable. Variation of As concentrations is higher in sedimentary rocks. The highest As concentrations are found in schists and shales (black shales and coals). It is a toxic element and it is more abundant in surficial deposits than in the bedrock. The main sources of anthropogenic As are processing of ores, non-ferrous metallurgy, heat energy production, and agriculture.

Gold (Au)

Gold is very scarce in the earth, but it occurs in many different kinds of rocks and in many different geological environments. It is found as the free metal and in tellurides. Gold is almost always associated with pyrite (and some other sulfides) hiding in their mineral lattice or as native metal in quartz veins. Gold is found also in alluvial deposits as nuggets of Au alloys. Though it is extremely resistant to weathering it occurs in sea water in the amount of 0.1 to 2 mg/ton, depending on the location of the sample. Gold is one of the metals less active and it is not absorbed well by the body and its compounds are not normally particularly toxic.

By-product metals with potentially increasing use: Pt, Pd, Rh, Co, Mo.

Platinum Group Metals (Pt, Pd, Rh)
Platinum group metals occur together and often natively in small quantities in ultramafic and mafic rocks. Platinum is a silvery-white metal, when pure, and is malleable and ductile. The metal does not oxidize in air at any temperature, but is corroded by halogens, cyanides, sulfur, and caustic alkalis. It is insoluble in hydrochloric and nitric acid, but dissolves when they are mixed as aqua regia, forming chloroplatinic acid. In the finely divided state platinum is an excellent catalyst, used much in fuel cells and in antipollution devices for automobiles. Platinum group metals do not normally cause problems to biota as they are unreactive, however, some PGMs compounds should be regarded as toxic. The main anthropogenic source at present corresponds to the use of catalytic convertors in the exhaust systems of automobiles.

Cobalt (Co)
Cobalt belongs to the Fe group and it is closely related to Ni and PGMs. It is common as accessory element in many minerals. Most common host minerals are pyrite, pyrrhotite, magnetite and femic silicates (such as amphiboles and pyroxenes). Cobalt values decrease from ultramafic and mafic rocks towards acid and alkaline rocks. In sedimentary rocks, Co contents are higher in claystones than in limestones. High Co values are typical for poly-metallic sulfide ores, and also for caustobioliths and carbon-bearing rocks. In the biosphere, Co is common, but the values are rather low in the hydrosphere. Cobalt is an essential element for vital function, but at the same time it is a toxic one; both its abundance and deficiency are equally harmful.

Molybdenum (Mo)
Molybdenum is a metallic element that occurs in small amounts in the Earth's crust. In magmatic differentiation it is enriched in late stages in granites, pegmatites, and hydrothermal formations, and in alkaline rocks. Geochemically Mo resembles Cu, W, U, and rare earth elements. Molybdenum is a common constituent in sedimentary sulphur-rich carbonaceous rocks, clays, and caustobioliths. It plays a very important biological role because of its high mobility in the biosphere. Metal-organic Mo compounds are especially mobile in the hydrosphere. Molybdenum is widely used in the metal industries and is important in surficial deposits. Mo plays a vital role in the biological process of nitrogen fixation. It is an essential element also for the human metabolism. Both deficiency and abundance can cause health problems.

2.1.2 Natural Background Concentrations

There are no exact data about the abundances of metals in the Earth's crust, but estimates are available in the geochemical literature (Reiman & Garrett, 2005). Estimates which look today most reliable are compiled in Table 2.1. In some cases several values are given (min-max), showing the variation of estimates. In most cases the recent estimates do not differ too much. Table 2.2 shows measured median values and the ranges of metal abundances from Europe and the USA. In waters, metal concentrations in solution depend very much on pH, Eh, presence of other elements, dissolved organic particles and colloidal particles. In all media, natural variation of metals is large and depends on the matrix as can be seen in Table 2.2.

Table 2.1

Average values of the metal concentrations in different constituents of Earth's crust and some surficial deposits.

Metal	Lithosphere %	Soil %	Stream water µg/L	Sea water µg/L	Biota %
Fe	3.09 w[1] – 5.33[2]	0.4[2]	40[2]	5[2]	2.2[2]
Al	7.74[1]	7.10[2]	160[2]	1[2]	6.1[2]
Metal	**Lithosphere mg/kg**	**Soil mg/kg**	**Stream water µg/L**	**Sea water µg/L**	**Biota mg/kg**
Zn	52[1]	60[7]	20[2]	1[2] – 4.9[4]	46[2]
Cu	14.3[1] – 53[2]	15[7]	7[2]	0.25[2]	30[2]
Ni	18.6[1] – 56[2]	5[2]	2.5[2]	0.5[2]	10[2]
Cr	35[1] – 93[2]	70[2]	1[2]	0.25[2]	50[2]
Pb	12[2] – 20[5]	12[2]	0.03[2]	1.0[2]	0.008[2]
Sn	2.1[6]	3[7]	< 0.5[8]		1.1[9]
Hg	0.04[2]	0.02[2]	0.07[2]	0.03[2]	0.2[2]
Cd	0.10[1]	0.35[2]	0.02[3]	0.07[2]	16[2]
As	1.8[1]	6[2]	4[3]	2[2]	3[2]
Au	< 0.001	< 0.001		0.001[10]	
Pt	< 0.001	< 0.001			
Pd	< 0.001	< 0.001			
Rh	< 0.001	< 0.001			
Co	10[5] – 23[1]	8[2]	0.3[2]	0.02[4]	22[2]
Mo	1.4[1]	1.2[2]	0.5[3]	10[4]	1[2]

[1] Wedepohl, 1995
[2] Ivanov, 1996
[3] Koljonen, 1992
[4] Lide, 1996
[5] Taylor&McLennan, 1995
[6] Rudnick & Gao, 2003
[7] Salminen, 2005
[8] Neal and Robson, 2000
[9] Kabata-Pendias, 2001

Table 2.2

Median values (% or mg/kg) and the range of metal concentrations of soils from some international geochemical mapping projects

Metal	1.	2.		3.
		topsoil	subsoil	
Fe	1.71 % 0.18 – 8.97 %	3.51 % 0.16 – 22.3	3.75 % 0.11 – 5.6	1.95 %
Cu	11 < 10 – 243	13.0 0.81 – 256	13.9 0.86 – 125	18.2
Zn	43 < 10 – 264	52.0 < 3.0 – 2900	47.0 < 3.0 – 3060	51.7
Al	4.73 % 0.16 – 9.74	11.0 % 0.37 – 26.7	11.7 % 0.21 – 27.1	5.14 %
Ni	7 < 3.39	18.0 < 2.0 – 2690	21.8 < 2.0 – 2400	15
Cr	32 < 3 – 614	60 < 3.0 – 6230	62 3 – 2140	40
Pb	15 < 4 – 85	22.6 5.32 – 970	17.2 < 3.0 – 938	16.5
Sn	< 2 < 2 – 20	3 < 2.0 – 106	3.0 < 2 – 106	n. a.
Hg	n. a.	0.037 0.005 – 1.35	0.022 0.002 – 0.93	0.05
Cd	n. a.	0.15 < 0.01 – 14.1	0.09 < 0.01 – 14.2	n. a.
As	4.0 < 2 – 30	7.03 0.32 – 282	6.02 0.22 – 593	5.57
Au4	n. a.	1.69 0.3 – 61.0	1.29 0.3 – 10.2	n. a.
PGM	n. a.	n. a.	n. a.	n. a.
Co	< 3 – < 3 – 38	7.78 < 3.0 – 249	8.97 < 3.0 – 170	n. a.
Mo	< 2 < 2 – 83	0.62 v0.1 – 21.3	0.52 < 0.1 – 17.2	n. a.

2.1.3 Regional Variation

In geochemical mappings of large continental scale areas (e. g. Reimann 1995, Xie et al. 2008, Gustavsson et al. 2001, Salminen et al. 2004, Salminen 2005), anthropogenic influences on metal concentrations have not been detected, or rather it has been impossible to differentiate anthropogenic impact from geological variation. This means that in most cases the geological variation is so large that it fully hides the diffuse anthropogenic contamination. Fig 2.1 shows Ni concentrations

of top soils in Europe. Low Ni values in northern Europe are due to the presence of glaciogenic deposits as soil parent material. Soil is often sandy and during glaciation processes the soil parent material was depleted in metals. In the rest of Europe, soil parent material is most often composed of weathering products of the crust, and the exogenic geological processes have not had such a strong influence on metal concentrations. High Ni concentrations in SE Europe are due to mafic and ultramafic intrusions. Fig. 2.2 shows the large variation of As ion top soils in the USA. This is aloso strongly controlled by the geological formations of different age.

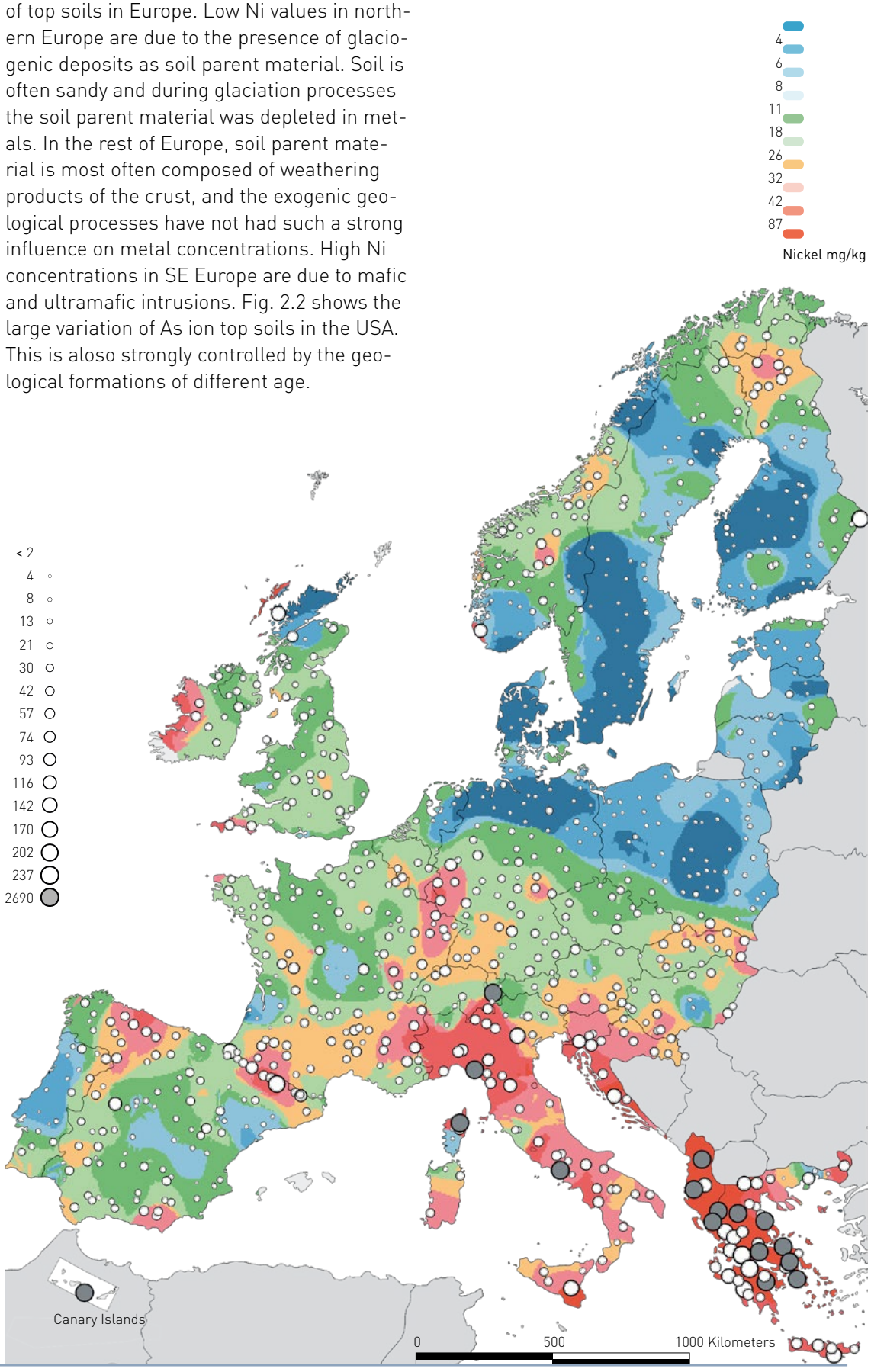


Figure 2.1

Ni concentration in the uppermost 25 cm minrogenic soil layer in Europe according to the Geochemical Atlas of Europe (Salminen, 2005).

In contrast to the regional scale, the influence of emissions from point sources is often strong and easily detectable at a short distance (up to tens of kilometres) from the source. The Ni smelters of the Kola Peninsula are a good example. However, in some cases geological variation can also lead to values as high as those resulting from very strong anthropogenic contamination (see Annex 1).

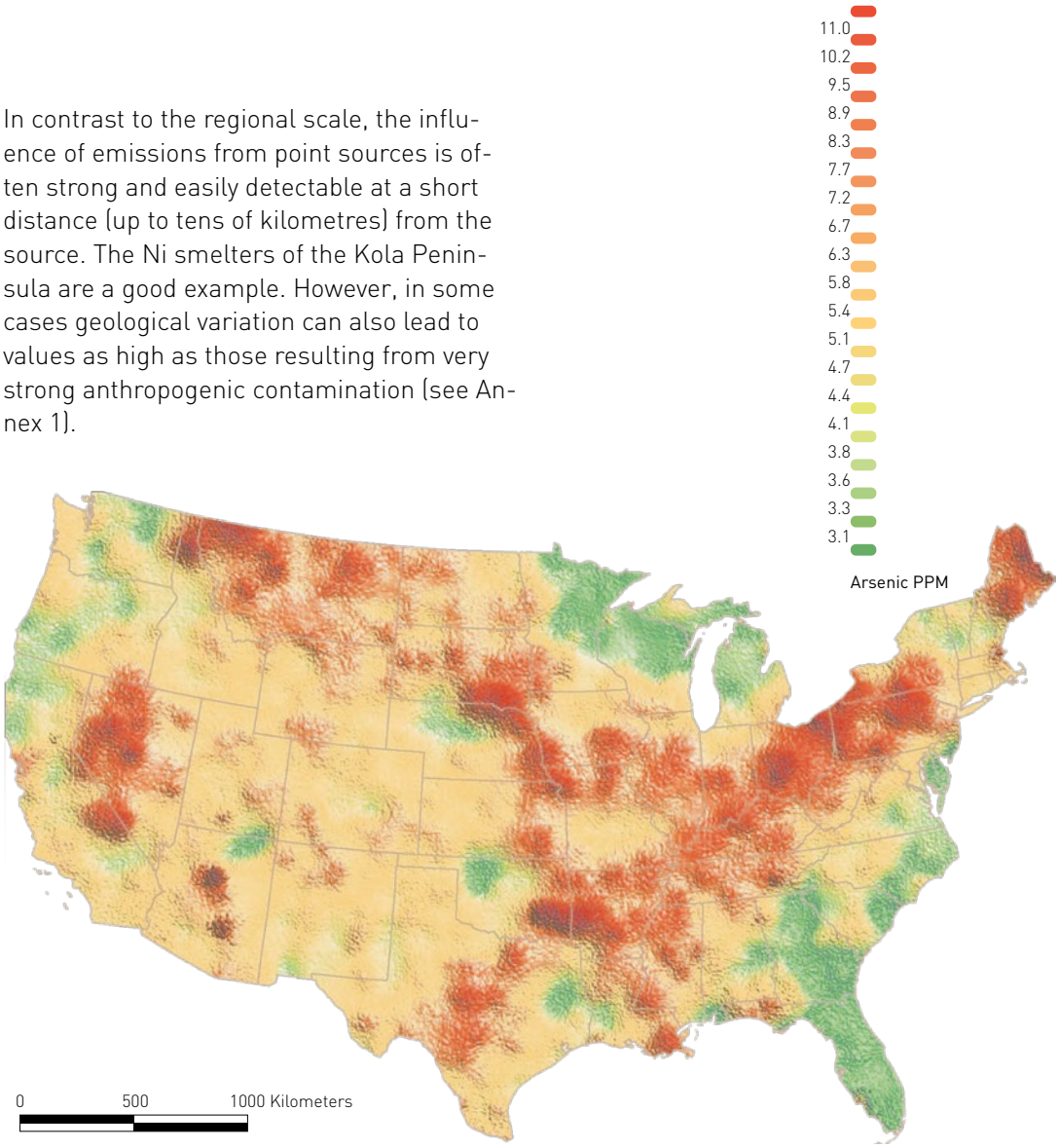


Figure 2.2

Total As concentration of top soil samples in the USA (Gustavsson et al., 2001). Number of samples is 1323 representing sampling density 1 sample per 6000 km2.

In many cases only a part of the metals in soils and bedrock are in the chemical form which make them biologically active. The amounts of metal that can be leached from mineral grains in soils and rocks are often measured by strong acid extraction (e.g. aqua regia or 7M nitric acid). The actual bioavailable concentration is sometime estimated using extraction by weak acids such as acid ammonium acetate. Table 2.3 shows the percentage of metal that was leached from agricultural soil samples by aqua regia and by acid ammonium acetate extraction in the Baltic Sea region. In many cases less than one percent of metal was in extractable form. Differences between topsoil and bottom soil were small but in most cases metal extractability in top soil was a little bit higher. Arsenic was an exception: the bioavailable concentrations of top soil were not available, but in subsoil some 20 % was in extractable form.

Table 2.3

Percentage of metals extracted by aqua regia (AR) and acid ammonium acetate (potentially bioavailable) in agricultural top soil in Northern Europe. (Data from Reimann et al., 2003).

Metal	AR	Bioavailable
Fe	62.12	0.26
Cu	78.79	4.65
Zn	76.74	3.49
Al	14.29	0.18
Ni	80.81	1.01
Cr	37.50	0.41
Pb	49.41	3.88
Co	77.36	3.40

2.2 Natural Cycling of Metals

2.2.1 Biogeochemical Cycling

Human society uses many chemical compounds for the production of goods, health care and agriculture. These chemical compounds can be either synthetically produced or be of natural origin. The latter group is mostly comprised of metals (including metalloids like arsenic and antimony). These metals are a part of a natural biogeochemical cycle of elements. Within this cycle the metals are exchanged between the geosphere, hydrosphere and biosphere.

In this section we will give a short overview of the concepts of the biogeochemical cycle and how this cycle is altered by human activity. It will present common geochemical knowledge, rather than a complete scientific review.

Figure 2.3 depicts a conceptual overview of the cyclic processes in the earth's crust and on its surface. Earth's inner magma, containing many elements including metals, is brought to the surface as rocks by upheaval, outcropping and volcanic activity. Weathering of these rocks releases the metals into the surface environment. The metals are transported in and between compartments, like the ocean, the atmosphere, soils and groundwater. Finally they are deposited and buried again. Subsidence of these sediments to the Earth's inner sphere completes the cycle.

When metals are part of the surface compartments, they interact with the hydrosphere and biosphere. It is during this stage of the cycle that metals are part of the human environment and biota in which they can have their beneficial and adverse effects.

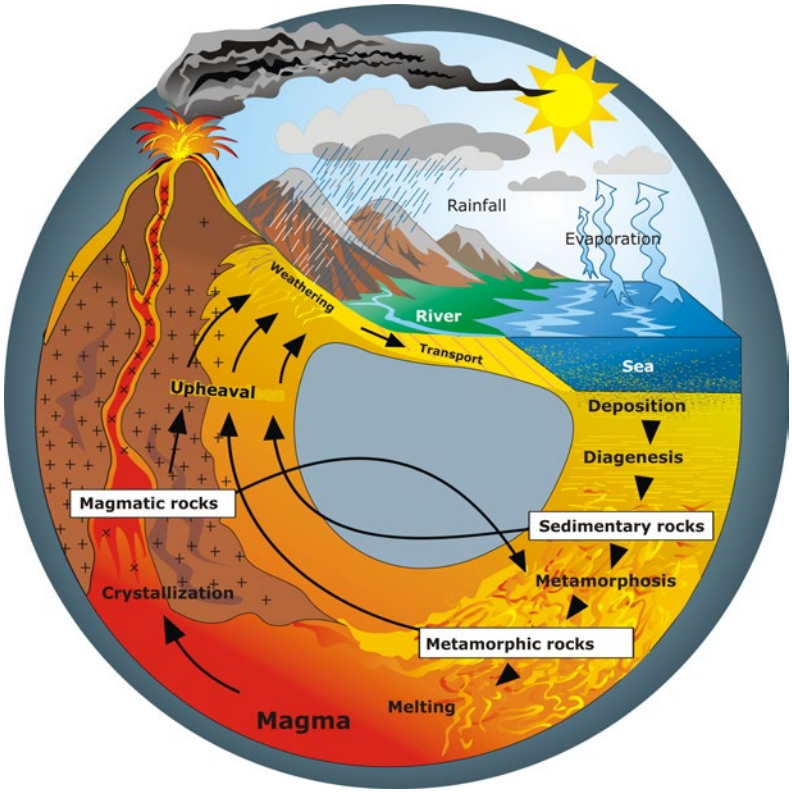


Figure 2.3

The geological part of the biogeochemical cycle (De Vos and Tarvainen, 2006)

2.2.2 Processes

Metals can be mobilized when the geochemical character of their environment changes. During the weathering metals are released by chemical, mechanical or biological processes. For example, the rocks exposed to rainwater, which is slightly acid by nature, are slowly chemically "dissolved". Another example is the weathering as caused by plants. Their roots are mechanically "breaking" rocks and by excreting acids and metal chelators they slowly "dissolve" the rock matrix. Another mechanism of mobilization involves volatilization during volcanic activity. The hot vapours emitted from these volcanoes release metals to the atmosphere.

When metals are mobilized they are exposed to chemical processes such as oxidation and reduction, complexation and sorption. The oxidation state determines the fate and biological significance of the metal. The form of a metal depends on the oxidation potential, the pH and the chemical composition of the environment in which the metal occurs. Altering this environment can also alter the oxidation potential and as consequence the stable form, or speciation, of the metal. For instance, the reduction of organic litter can lower the oxidation potential, with the result that free metal ions are deposited as sulfides. Free metal ions can form complexes with other substances within the environment, for example complexes with dissolved organic matter which enhance the solubility of the metals. Furthermore, metals can be adsorbed to particles, either as part of the solid phase or suspended in air or water. These complexation and adsorption reactions are two interacting processes.

When metals are part of the water phase, either in solution or adsorbed to suspended particles, or when they are volatilized or suspended in the atmosphere, they will be transported over large distances and between the different reservoirs of the earth system.

2.2.3 Biological Interaction

For biotic systems the understanding of metal speciation is important if one wants to look at the effects of the present metal concentrations. For Zn, Cu and Cd we know that the bioavailability of metals is strongly related to the presence of the free metal ions in aqueous solution. Metals adsorbed or complexed are in general not directly available for biological uptake. Additionally, changes in the oxidation state (e. g. Cr (VI)) and interaction with micro-organisms (methylation of mercury $(CH_3Hg)^+$) are processes which have a profound influence on bioavailability.

However, organisms have the ability to change the redox state of the metals. By changing the redox state, the speciation of the metals is changed as well. Hence, if organisms can alter the speciation of the metals in their immediate environment, they additionally alter the extent in which this metal is bioavailable. Many metals are required for the proper function of enzyme systems. However, they will be toxic when concentrations exceed the range for optimal function of these enzymes.

Another way biota can alter metal speciation, thus altering availability, is by changing their local environment. For example, bacteria have the ability to reduce the local environment and change its redox state. This reduction can lead to the formation of precipitates, e. g. sulfides, which decrease the concentration of free metal ions. Bacteria can also reduce the pH of solutions. The acidification enhances the dissolution rate of rock and liberates metal ions in solution.

2.2.4 Human Influence

As shown in the previous paragraph, metals are part of the natural biogeochemical cycle. That this cycle is significantly altered by human interaction is no longer the subject of debate but is more or less regarded as fact. The uncertainty of this alteration lies in the extent of the human influence. Due to our limited understanding of the complex natural processes, as mentioned above, and how they interact with anthropogenic alteration, and also the lack of a good global inventory for metals, it is difficult to make good predictions of the magnitude by which humans have changed the biogeochemical cycle.

Human activity alters this biogeochemical cycle in two ways, both interrelated. First we alter the rate at which metals become available, and second, we change the form in which the metals occur in our environment, i. e. their speciation. Humans isolate metals by mining and extraction from the earth crust. During the smelting and refining of these metals, many trace elements are collected in deposited waste and landfilled, suspended as dust in air, or volatilized in the vapor phase. The final product is also 'released' to the environment. Almost every metal will degrade by corrosion when it is exposed to air and water, albeit at very slow rates. Therefore, many final products will very slowly degrade to a less useful form until they are disposed as waste, if not upgraded by, for example, recycling.

The form, or speciation, of metals is also altered by refining and producing metal based, or metal containing, products. For example, the use of tetraethyl lead as an anti-knock agent in gasoline was a source of lead to the environment. Another example is the release of copper-ions to soils as part of the Bordeaux Mixture, a fungicide used during the growing of grapes. On the other hand, the alloying of metals by humans greatly reduces their mobility. Changes in the environment, as a result of human activity, can also alter the speciation of metals. For example groundwater extraction, for drinking water or agricultural purpose, can lower the groundwater table. This results in a change of the redox environment. Subsequently elements, which were otherwise not available, can be released to ground- and surface water. For instance, the release of the metalloid arsenic as a result of groundwater extraction is a great threat for human health in India, Bangladesh and Mongolia.

Another example is acidification of the environment especially via acid precipitation. Watershed acidification can change the pH of soil and water and affect their speciation in aqueous solution (see e. g. Nelson and Campbell 1991).

Table 2.4

Ratio human cycle vs. natural cycle according to various authors.

Metal	Ayres (1996), from Galloway (1982)	Azar (1996)	Klee & Graedel, (2004)
Fe		1.4	8.9
Cu	14	24	5.9
Zn	23	8.3	0.9
Al		0.048	0.4
Ni	4	4.8	2.3
Cr	2	4.6	139
Pb	333	12	5.2
Sn		11	3.5
Hg		6.5	18.5
Cd	20	3.9	0.2
As	4	0.33	1.7
Au			504
Pt			1049
Pd			108
Rh			555
Co			0.1
Mo		8.5	0.3

The numbers in the Table 2.4 represent the ratio between human and natural mobilization of metals. Human cycling mainly is determined by the mining and fixing of the metals in societal stocks, but also by the mining of fossil fuels and other resources wherein metals occur as contaminants. The numbers are different, sometimes widely different, among the three sources. Possibly this is due to very large uncertainties in the data of the natural cycle, since the amount of mining is quite well documented over the years. Differences may also be found in the definition of "mobilization". Another reason for the differences may be the time – the investigations span over two decades, and mining of metals has significantly changed in that period. Different use patterns are also a likely reason since for most metals human extraction has increased over that period, while some of the ratios are considerably lower for the later years.

Differences aside, it can be concluded that for all metals in the list the human cycle is significant compared to the natural cycle, and in many cases the human transfer of metals is orders of magnitude larger. Especially for the precious metals, Au and the PGMs, the natural cycle is negligible compared to the human cycle.

The presence of a large human cycle does not necessarily imply large emissions to the environment, and certainly not equally large ones. As is concluded in the report on "Metal Stocks in Society" by the Global Metal Flows Working Group, most of the mined metals accumulate in stocks in society. For the most part, these stocks are rather immobile, similar to geological stocks. Nevertheless some dissipative applications and waste streams can represent large emissions of metals relative to their natural cycles. Emissions of metals will be treated in Chapter 3.

2.3 Behaviour of Anthropogenically released metals

2.3.1 Anthropogenic Contribution

Whereas metals exist naturally in waters, soils, and sediments, emissions and accumulation from anthropogenic sources can vastly alter the concentrations of metals in the environment, relative to the natural background.

This is particularly true for metals where the scale of anthropogenic mobilization is much higher than that of natural mobilization of metal. Klee and Graedel (2004) developed an index to compare these two rates. This global level assessment was extended to local conditions by Rauch (Rauch 2010), who mapped the level of anthropogenic or natural dominance for several base metals, for the entire globe (Figure 2.4).

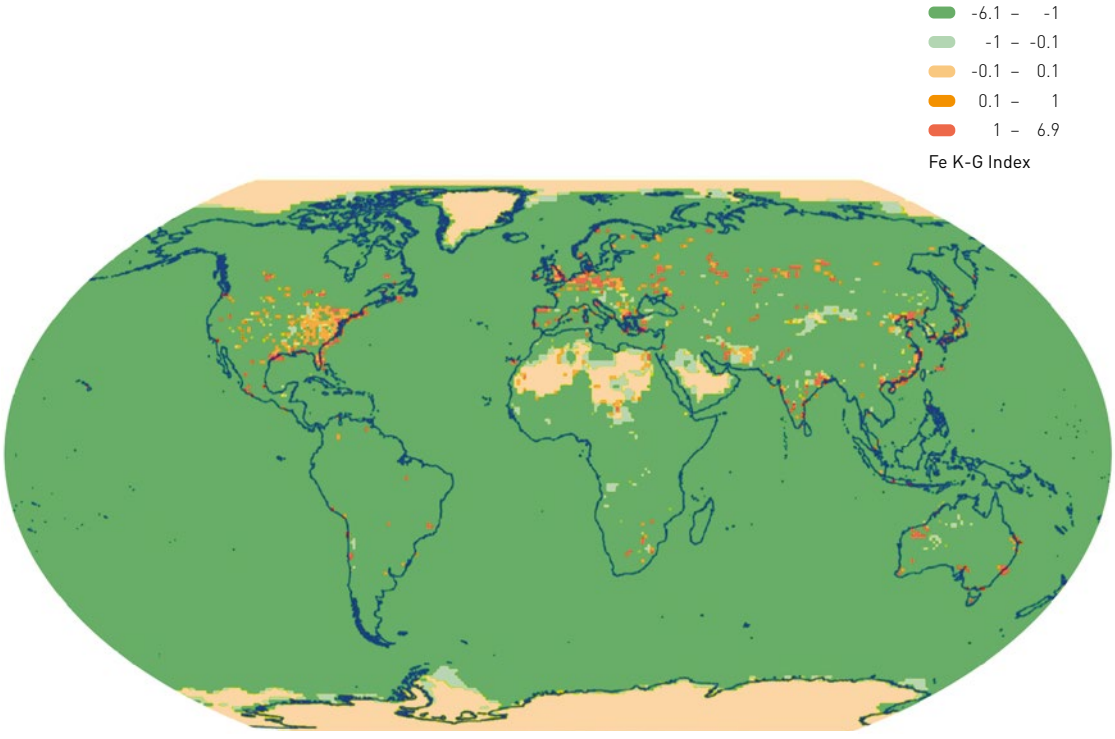


Figure 2.4

Dominance of anthropogenic (red) versus natural (green) mobilization globally for iron on a 1° x 1° grid (Rauch, 2010).

One line of research on anthropogenic metal concentrations in the environment is based on substance flow analysis, or tracking a particular metal as it flows through the economy and eventually into the environment. This research starts with an inventory of emissions from metal sources (Pacyna and Pacyna 2001, Nriagu 1979) and models how these metals will move through air, water, and soils, where metals will be deposited, and how this deposition will alter the baseline concentration of metals in the local environment (see e. g. Guinée et al. 1999, Eckelman and Graedel 2007). Tracking metals in this way allows researchers to establish scenarios about future economic activities and estimate how much metal pollution may occur, but this method also requires a large amount of information, particularly in creating an inventory of all anthropogenic sources of emissions. This line of research is followed up in Chapter 3.

The other, much larger and well-established field of scientific analysis of anthropogenic metal concentrations has worked in the opposite direction: from sink to source. Samples are taken in different locations where metal concentrations are particularly high relative to background levels, such as sediments near coastal cities, and then modeling is used to try to discover the time and place that the original metal emissions took place

(Förstner et al. 1979). In examining historical emissions of metal, researchers have looked at the concentrations of metals in ice cores, peat bogs, and aquatic sediments as a historical record of anthropogenic emissions of metal (Nriagu 1996). A famous study of lead looked at concentrations in ice cores from Greenland to show that during the times of the Roman Empire, smelters producing the metal emitted enough lead to increase concentrations in the Northern Hemisphere to more than four times background levels. Lead levels in ice collapsed with the empire, rising again markedly with the dawn of industrialization and peaking in the 1970s, then declining as lead was phased out of gasoline/petrol and other products (Murozomi et al. 1969; Nriagu 1996).

More recent research has made use of complex fate and transport computer models, starting with measurements of metal deposition or concentrations, and running the model backwards to determine the original sources of the emissions. This method has been used in particular to study the atmospheric emissions of mercury (Jaffe and Strode 2008, Selin and Jacob 2008).

In summary, metals are part of the natural biogeochemical cycle and play an important role in the industrialized human society. Human activity alters this biogeochemical cycle by increasing the rate in which some metals become available together with processes which alter the form in which metals are present in the environment. That human activity has its influence on the biogeochemical cycle is generally accepted. However, the uncertainties in the extent to which the cycle is influenced are still under scrutiny.

2.3.2 Environmental Properties of Metals

The initial measurements of contaminants during site investigations are usually total concentrations of contaminants. Results from daily practice show that a certain level of metal contamination can be toxic and present a significant risk, while at the same total level but under different conditions, metal contamination may prove to be harmless (Sauvé et al. 2000). This shows that bioavailability cannot simply be defined in one term, because it is a composite concept. In 2002 the United States of America National Research Council published a report on bioavailability on soils (National Research Council, 2002) which was usefully summarized by Ehlers and Luthy (2003). The report notes that the term bioavailability has been defined by various disciplines and goes on to state that this has led to some confusion over the term and that therefore further definitions will be avoided. Instead the report focuses on bioavailability processes, which are the biological, chemical and physical processes that result in an organism being exposed to a contaminant present in the soil. These processes are: release of the contaminant from the solid phase, transport of the contaminant to and across a biological membrane and, incorporation into a living organism. To create an unequivocal understanding of metal bioavailability, it is separated into three specified processes (Dickson et al. 1994): chemical, biological and toxicological availability. This is elaborated further in Annex 2. In all three steps of the metal bioavailability process, metals can occur in available and non-available forms. The partitioning of metals among the different phases, solid versus soluble, is specific for each metal species and dependent on many soil and pore water properties and organism-specific characteristics (e. g. abilities of uptake, uptake routes, detoxification and excretion strategies).

2.4 ERA, No-effect Levels, Optimal Levels, Deficiency Levels, and Acceptable Levels.

2.4.1 Environmental Risk Assessment

The standard for Environmental Risk Assessment in the EU is based on a number of EU regulations, brought together within the framework of REACH (European Commission, 2006). Commission Regulation (EC) 1488/94 (EC, 1994a) which is supported by a Technical Guidance Document-TGD (part 2, European Commission, 2003) sets out the methods for carrying out an EU risk assessment. In short, the Technical Guidance Document describes how ecotoxicological (effect) data and measured and/or modeled exposure concentrations should be derived. This approach yields the so-called PEC/PNEC-ratio in which PEC = Predicted Environmental Concentration and PNEC = Predicted No Effect Concentration. If the PEC/PNEC-ratio is larger than 1, it is assumed that there is a potential risk of adverse effects. PNECs are primarily derived on the basis of laboratory generated toxicity data. Depending on the number of species and the number of trophic levels for which experimental data are available, variable safety factors are used to derive PNECs (see Table 2.5).

The table shows that the magnitude of the safety factor takes into consideration the quantity of data available for a substance. Safety factors are a tool to deal with uncertainty that exists when extrapolating from a limited data set to potential effect levels in an ecosystem. The table follows the general principle that availability of more and high quality data reduces uncertainty, and thus allows for a lowering of the safety factor. Within the EU Water Framework Directive (WFD), in its Annex V section 1.2.6. "Procedure for the setting of chemical quality standards by Member States", the same approach is given to obtain safety assessment factors for setting environmental quality standards for the surface waters.

Within the EU-framework much effort is put into the preparation of Risk Assessment Reports (RARs) for individual priority substances. Basically, the procedures described in the TGD for the preparation of the RARs are designed to assess (hydrophobic) organic compounds. Polar organic, ionized organic acids and bases, polymers, as well as metals and metalloids require case by case considerations to optimize the risk assessment of these compounds and to ensure that the basic philosophy behind the procedures de-

Table 2.5

Proposed safety factors to correct for a lack of sufficient toxicity data to derive PNECs. The safety factors are intended to compensate for the uncertainty in the PNEC-assessment generated by a lack of reliable experimental toxicity data (modified from TGD) (Data from European Commission, 2006).

Available data	Safety factor
≥ 1 acute EC50 from each of 3 trophic levels	1000
1 chronic NOEC (either fish, daphnid, or representative organisms for saline waters), additional to the 3 acute EC50	100
2 chronic NOECs from species representing 2 trophic levels, additional to the 3 acute EC50	50
Chronic NOECs from ≥ 3 species representing 3 trophic levels, additional to the 3 acute EC50	10
Other cases, which allow more precise safety factors to be calculated and applied	1 – 5

scribed in the TGD, and meant to protect man and the environment, are met with sufficient certainty. This requires amongst other considerations the application of compound-specific models to predict adverse effects and actual exposure of man and biota. In the case of metals, one of the promising models for use in the risk assessment procedures is the Biotic Ligand Model (BLM). The Biotic Ligand Model can be used to predict metal toxicity on the basis of metal speciation in aquatic systems. Binding constants on the epithelial surface of the organisms are derived, and related to acute or chronic effects.

BLMs have been used in the metal risk assessment reports to derive PEC/PNEC ratios that are corrected for bioavailability on either the PEC-side or the PNEC-side. As a matter of course, information on the water characteristics of the specific water body, as well as well-documented information on the media in which aquatic toxicity testing was conducted, need to be available to enable proper implementation of the bioavailability correction by means of BLMs. BLM-normalized toxicity data can then be used further to construct the Species Sensitivity distribution (SSD) and to derive the site-specific effect concentrations. BLMs thus allow comparison of the PEC-bioavailable directly to the PNEC-bioavailable, normalized to the same geochemical conditions. Following the TGD (2003), the PNEC is taken as the HC5 (Hazardous Concentration at which 95 % of the species in an ecosystem are assumed to be protected against the adverse effects of the chemical) divided by the safety factor. As this HC5 is based on a limited number of toxicity data, a number of additional uncertainties may exist.

2.4.2 Natural Concentrations versus Acceptable Levels

Defined action limits of metal concentrations in soils and waters are needed for practical operations. However, these limit values of metal concentrations defined in the legislation vary greatly from country to country. For certain single elements, the difference may by even an order of magnitude. The legis-

lation is evolving all the time, as more relevant information becomes available. Thus comparison between natural concentrations of metals and acceptable levels defined by the authorities is difficult. One of the newest legislations comes from Finland where a new Decree was accepted in 2007 (the Government Decree on the Assessment of Soil Contamination and Remediation Needs, 214/2007). It was preceded by a twenty years discussion among the authorities, scientists and different interest groups. Finally, in addition to strict action limits, a risk assessment plays a very strong role in defining the contamination degree of soil. The threshold and guideline values are based on a risk assessment carried out on a general level, in which various reference values for soil concentrations are derived, describing both negligible and maximum acceptable risks to the environment and human health. Furthermore, a register of local natural background values should be created to support local risk assessment, and especially to determine whether cleaning up a site makes sense (Reinikainen 2007).

As an example, in Table 2.6 the action limits for metals included in the Finnish Decree are compared with the data from Geochemical Atlas of Europe (Salminen et al. 2005). On a European scale, the most problematic element is arsenic, for which half of the observed natural values are higher than the threshold value. Additionally, there are rather large regions with too high As values in many countries. It has been estimated that about 60 – 100 million people in India and Bangladesh are currently at risk as a result of drinking arsenic-contaminated waters. Arsenicosis is also prevalent in certain areas of PR China (Xinjiang, Inner Mongolia and Taiwan Province of China), Vietnam and recently Nepal. For these endemic areas, the major arsenic exposure pathway is believed to be from drinking contaminated groundwater whereas the contribution of arsenic from food is relatively low (Ng et al., 2003).

For the other elements, natural concentration values higher than the given action levels represent scattered single sites. In soils, the least problematic metal is mercury, although in aquatic environment it is ranked as one of the most problematic metals. However, the maximum observed natural values for each element are much higher than the given action limits.

Table 2.6

Threshold and guide values (mg/kg) from the Finnish legislation for contaminated soil (Decree 214/2007) and aqua regia extractable (recommended analytical method by the Decree) median, 90th percentile and maximum values of European top soil (Salminen et al., 2005). Values of Sb, As and Hg are total concentrations

Element	Threshold value	Lower guide value	Higher guide value	Topsoil Europe		
				Median	Value of the 90th percentile	Maximum
Arsenic (As)	5	50	100	5.0	20	562
Mercury (Hg)	0.5	2	5	0.04	0.1	**1.35**
Cadmium (Cd)	1	10	20	0.15	0.48	**14.1**
Cobalt (Co)	20	100	250	7.0	17.0	**255**
Chromium (Cr)	100	200	300	22	53	**2340**
Copper (Cu)	100	150	200	12	33	**239**
Lead (Pb)	60	200	750	15	38	**886**
Nickel (Ni)	50	100	150	14	41	**2560**
Zinc (Zn)	200	250	400	48	96	**2270**

2.4.3 Essentiality

Many metals and metalloids are required for biological life, and therefore their presence in the ambient environment has actually shaped the natural ecosystem. The metals that are classified as being essential to flora and fauna are given in table 2.7.

Table 2.7

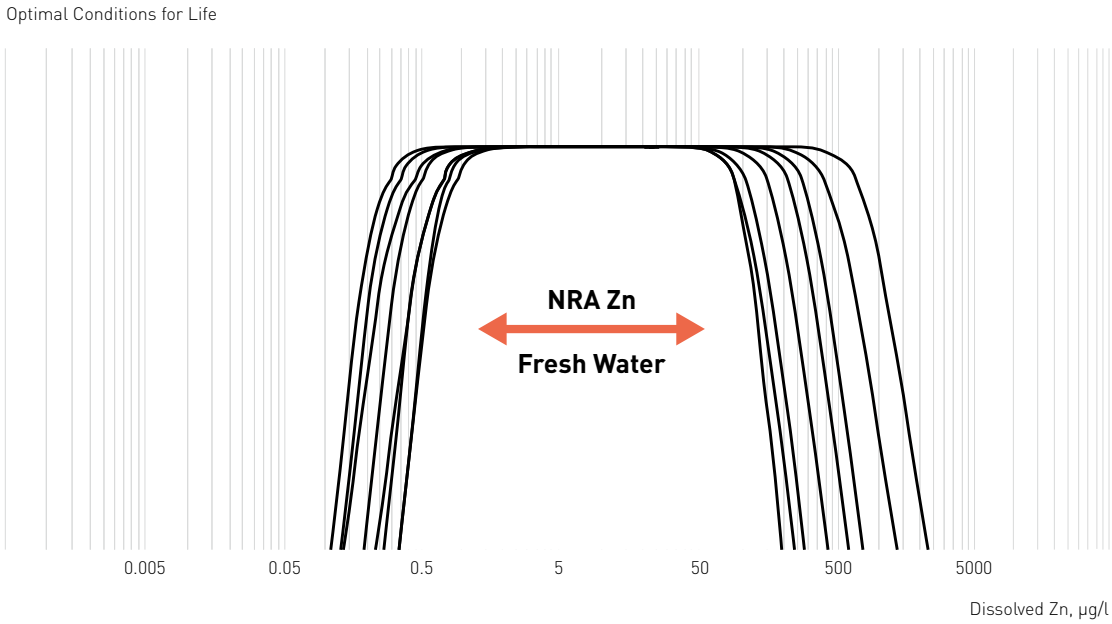
Classification of metals by their status as essential element (Adapted from EPA, 2007).

Metal	Essential (known requirement for health and function)		Beneficial (but not known to be essential)		Nonessential (and not known to be beneficial)
	Plants	Animals	Plants	Animals	
Al					X
As				X	
Ba					X
Cd					X
Cr		X			
Co		X	X		
Cu	X	X			
Pb					X
Mn	X	X			
Hg					X
Mo	X	X			
Ni	X	X			
Se		X	X		
Ag					X
V				X	
Zn	X	X			

Bioaccumulation of essential metals is a natural process required by living organisms for metabolism and growth. Many organisms have developed effective means of regulating internal essential metal concentrations within quite narrow ranges (homeostasis). Homeostatic mechanisms (such as induction of stress proteins) can even play a role in the detoxification of non-essential metals such as Cd, Pb, or Hg. In terms of adverse effects, it is accepted that essentiality should be viewed as part of the overall dose-response relationship, recognizing that the shape of this relationship can vary among organisms and for given subpopulations. In this respect, the principle of optimal concentration range of essential elements (OCEE) is advocated, as graphically shown in Figure 2.5.

Figure 2.5

Hypothetical presentation of the OCEE curves of all individual organisms in a given environment (adapted from Waeterschoot et al. 2003).



The inner envelope of these curves represents the No Risk Area (NRA) for that given environment in which all organisms are protected from both toxicity and deficiency.

This principle states that ecosystem functioning is impaired both below and above the OCEE. Impairment of ecosystem functioning is further complicated by evolutionary processes, which may shift the OCEE. Evolution is contingent upon genetic variability and environmental conditions, and as populations are not genetically homogeneous across their distribution ranges, they can locally undergo evolutionary processes that result in modified dose-response relationships (Morgan and Morgan 1988). Two generic mechanisms may be identified by which organisms cope with excessive metal burdens in their native (non-disturbed) habitat: adaptation and acclimation. Adaptation involves heritable, genetically determined, induced resistance resulting from directional selection during multigenerational exposure histories. Acclimation results from stress responses during the lifetime of an individual, the traits of which may be lost if the stressor is withdrawn. To further complicate and complete the picture, it should be kept in mind that the toxicity of certain metal elements is associated with deficiency of other elements. For example, increased Zn, Cu, and Ni toxicity can be associated with Fe deficiency (Saxe et al. 2001), and increased Pb and Zn toxicity can be related to P deficiency (Jager et al. 2003, Vijver et al. 2003; Didden 2003). Also, the behavior of plant species in response to nutrient deficiencies varies, and this behavior can affect the uptake of metal elements (Løkke and Van Gestel 1998). All these factors need to be taken into consideration when assessing the impact of chemical interactions of metals at background levels with biotic species.

2.5 Effects of Metals in the Environment

There are two main sources of metals in the environment: (i) natural (geologic, biologic) and (ii) anthropogenic. The natural factors, also called diffuse dispersion of metals, influence everywhere varying much from place to place. High impacts of anthropogenic metal pollution on local environments have been detected in restricted areas surrounding sources such as abandoned mine sites, the refining industry and other human activities which produce metal emissions.

2.5.1 Effects of Metals on Ecosystems

Calculation of Toxic Pressure on Ecosystems

Toxic effects of chemical substances on ecosystems are commonly expressed in terms of their combined toxic pressure, which measures the fraction of species that is exposed to harmful concentrations. As explained in the standard work by Posthuma et al. (2002), toxic pressure calculation makes use of SSD of toxic chemicals. Not all biological species are equally sensitive to a chemical, so that the toxic impact of a chemical on different species can be represented by a statistical (cumulative) distribution function of ecotoxicity test results: the Species Sensitivity Distribution (SSD), generally assumed log-normal.

Log-normal SSDs are characterized by the average toxicity (expressed as log(NOEC) or log(EC50)) of all tested species and the standard deviation. Cumulative SSDs express the fraction of species $\mathbf{F_c}$ with a sensitivity to the chemical greater than a certain concentration value c, and can be used to find the fraction of species for which a given concentration in the environment exceeds a critical effect level (Figure 2.6). This is the so-called Potentially Affected Fraction of species. **PAF** is referred to as the toxic pressure that the concentration of the chemical in the environment exerts on the ecosystem. A higher PAF implies a higher fraction of potentially affected species.

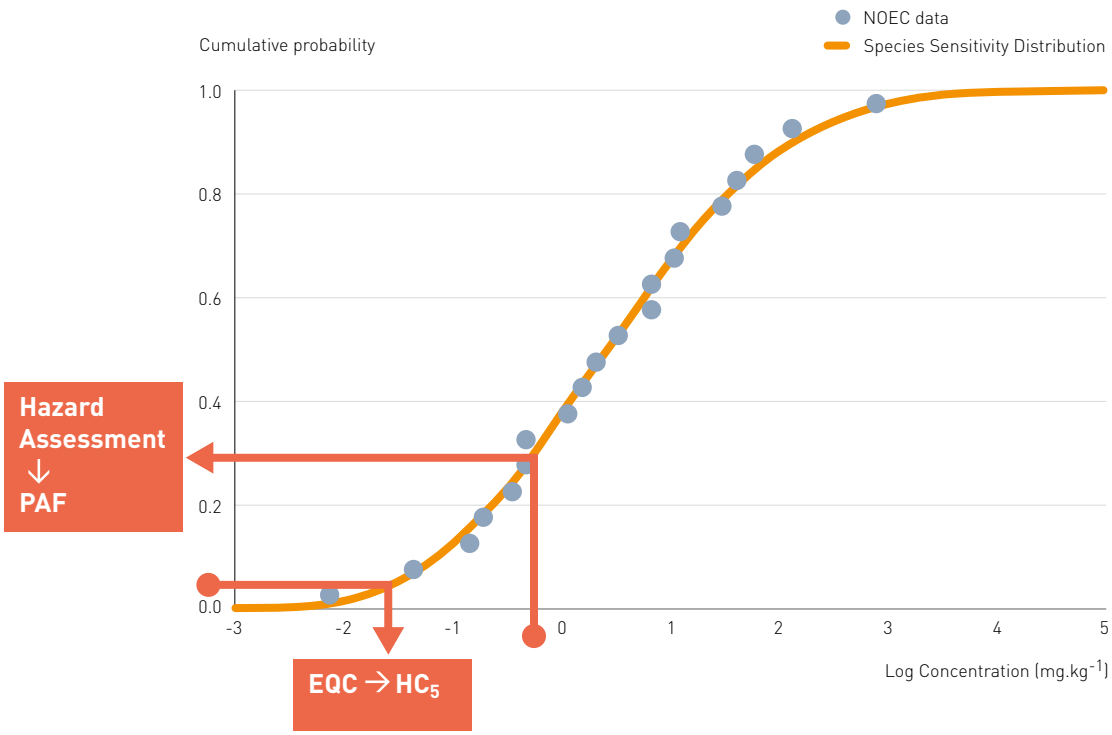


Figure 2.6

Use of a cumulative Species Sensitivity Distribution function to derive the toxic pressure PAF for a given concentration C of a certain metal (Posthuma et al., 2002).

The other use, to set Environmental Quality Criteria (EQC) for toxic compounds is also given, yielding the Hazardous Concentration for 5% of the species (HC5). Note that the acute SSD of a compound is positioned to the right of the chronic SSD of the same compound. Though compound-specific shifts can be determined, a gross pattern is that the acute SSD is shifted one log-unit to the right (a factor of 10).

Toxic pressure has been demonstrated to relate closely to biodiversity. Posthuma and De Zwart (2006) studied the association between predicted acute toxic pressures and species loss in surface water samples, and found that mixture-associated species loss was associated with predicted acute toxic pressures. The same authors (Posthuma et al., 2011) further studied the direct association between predicted and observed fractions of affected species in differently contaminated sediment sites. Predicted and observed fractions of species appeared to co-vary closely. Hence, toxic pressure values provide insight into the fraction of species being affected in the field.

SSDs can be based on chronic NOECs (often used for setting environmental quality standards e. g. in the Netherlands) or on acute EC50s (proposed use for e. g. calculating Ecotoxicity Effect Factors in Life Cycle Impact Assessment) or other test endpoints, expressing different levels of ecotoxic impact. By virtue of choice, SSDs can thus be tailored to the risk assessment context. Acute toxic pressures show the clearest association between toxic pressure and fractions of species affected. Toxic pressure data can be used for ranking and mapping of expected impact levels, e. g. on the European or national scale (Figures 2.7 and 2.8).

Toxic pressure can be determined per chemical (for one chemical compound; single-substance PAF or ssPAF), or for a number of chemicals combined (multiple chemicals, e. g. all metals in soil; multi-substance PAF or msPAF). Aggregation of toxic pressures over compounds is obtained using classical mixture toxicity models, related to modes of action of the chemicals (De Zwart and Posthuma, 2006).

Toxic pressure calculation is informative in terms of risks or expected impacts when the toxic pressure is derived not from total concentrations, but from reactive or even bioavailable concentrations in the environment. Spijker et al. (2011a) and Mol et al. (2010, in prep.) have shown that the man-made "enrichment" can be directly estimated using the 0.43 M HNO_3-extractable fraction of metals in top soils. Toxic pressures derived with this fraction reflect the upper estimate of the man-induced increase of local toxic pressure. De Vries et al. (2007) and Posch and De Vries (2009) have demonstrated how relevant concentrations of metals in top soil can be related to rates of atmospheric deposition, which, in turn, can be related to release rates of metals to the environment.

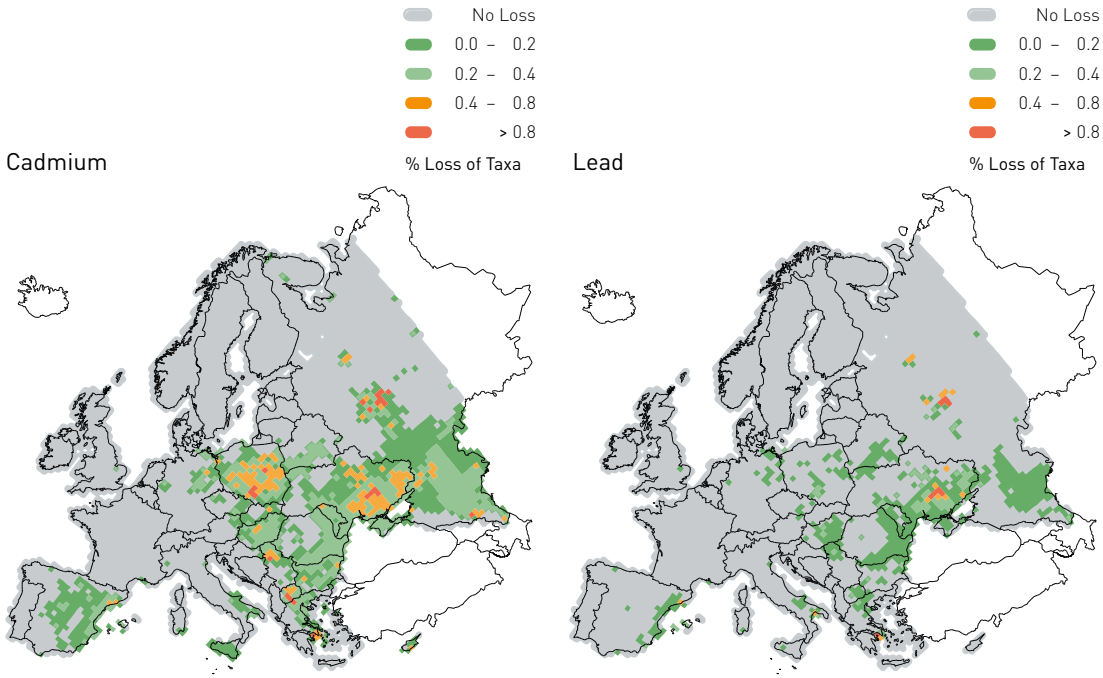
Below, an example is provided to show the spatial variability and variance of risks and impacts of man-induced metal exposures in soils resulting from diffuse emissions. Similar assessments can be made for aquatic and sediment systems. Note that toxic pressures calculated for point sources and dump sites are substantially higher, and are not presented here. Note further, that one of the uncertainties in the methodology is the exposure assessment of metals. Major differences in exposure level at the same total concentration may occur due to substrate characteristics. Given these uncertainties, toxic pressures provide an indication of relative hazard differences amongst compounds or amongst contaminated environmental samples.

Predicted Steady State Metals Concentrations and Loss of Species in Europe

Toxic pressure calculation has been used to evaluate the effects of emission reduction measures on risks and impacts of metals on soil organisms in the framework of the UN-ECE Convention on Long-range Transboundary Air Pollution (CLRTAP) of metals. Predicted metal exposure data, resulting from alternative long-term emission and immission scenario's of CLRTAP, were used to calculate local acute toxic pressures, assuming that biological species are exposed through the pore water.

Figure 2.7

Spatial variance in acute toxic pressures of cadmium and lead at steady state soil concentrations with current depositions, resulting from CLRTAP emission and deposition scenario's, assuming that acute toxic pressures are 1:1 related to species loss (De Zwart et al., 2010).



Each grid cell consists of a large subset of site toxic pressure data. The graphs show the 99th percentiles of acute toxic pressures within grid cells. Left for Cadmium and right for Lead.

Potential acute toxic pressure and associated predicted loss of biodiversity due to deposition of cadmium and lead was reported by De Zwart et al. (2010). Given the atmospheric depositions as reported under the CLRTAP convention, free metal concentrations in soil pore water have been calculated. Note again that there are large uncertainties involved in these calculations, up to a factor 1000 (Unsworth et al., 2006). Toxic pressures were calculated using acute EC50-based SSDs for aquatic organisms, in view of the pore-water mediated exposure, both for the metals individually (ssPAF, Figures 2.7 a,b) and for the two metals combined (msPAF, Figure 2.8). The thus-calculated toxic pressures can be interpreted as potential loss of species, signifying at least relative hazard differences amongst areas. The results demonstrate that there is variation in the net toxic pressure in top soils across Europe. Assuming a 1:1 association between toxic pressure and species loss, a loss of biodiversity from Cd- and Pb-deposition beyond 0.8 % of the species is expected to occur only in certain areas in Southern and Eastern Europe. Throughout Europe, the predicted loss of species due the expected metal loads at steady state soil concentrations with current depositions is lower than 1 %. Note that species experience sublethal impacts before they are lost. That is, maps of NOEC-exceedances show higher fractions of species chronically affected.

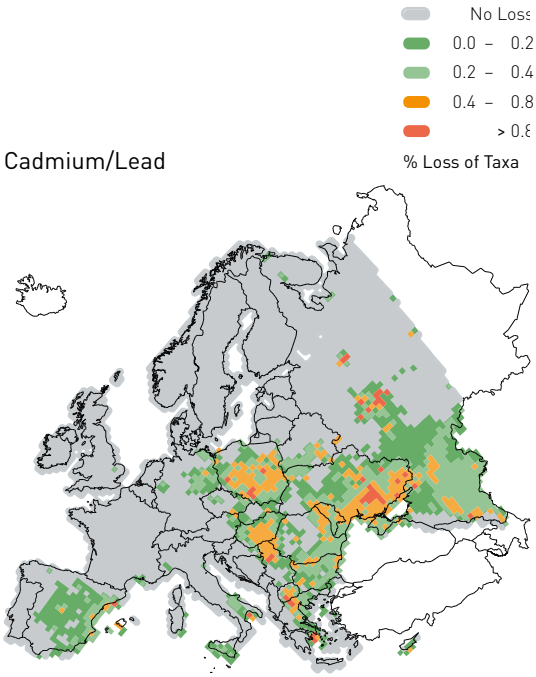


Figure 2.8

Similar to Figure 2.7, but now with the 99th percentile of predicted loss of species at steady state with current depositions for the combined effect of cadmium and lead (De Zwart et al., 2010).

2.5.2 Potential Impacts of Metals on Health and Environment, Local and Global

The impacts of metals on health differ greatly depending on the metal and also the region or country. Perhaps the most important factor is the natural environment or local and regional geology (bedrock, soils and water). This is often referred to as the forgotten half of environmental medicine affecting almost all people on the globe. Therefore a discipline named medical geology has developed in recent years involving geoscientists, toxicologists, epidemiologists, pathologists, biologists and others. Medical geology involves the study of the relationship between natural geological factors and health problems in man and animals, and of the influence of ordinary environmental factors on the geographical distribution of such health problems. Medical geology is therefore a broad and complicated subject, which requires interdisciplinary contributions from different scientific fields if the problems are to be understood, mitigated or resolved.

Metals are naturally present in the environment, and most of them are essential to biological function. Living organisms get the metals needed for their biological functions in the diet and drinking water. Sometimes there is a lack of some essential metal, e. g. iron, and we need to add it for maintaining full health. Sometimes metals in the environment constitute one category of threats to human or ecosystem health. Sometimes one finds places were metals naturally are so abundant that they reach toxic levels and the places themselves are dangerous for humans. As potentially toxic we understand metals whose effects are harmful to living organisms and, of course, to people. Metals appear in several forms often with vastly different biological effects, as will be stressed below under lead. Metals in organo-metallic compounds are often even more toxic than dissolved inorganic metal ions. Metals, since they are chemical elements, never degrade, which means they cannot be broken down or metabolized and in this way disappear. They can be washed out, be part of waste, stored in landfills or incorporated into harmless mineral forms, but they still remain in the environment.

Most of the metals discussed in the current report are essential in different amounts for biological functions of organisms (e. g., cobalt, copper, manganese, molybdenum, zinc, nickel, and vanadium). They are so called micronutrients. At high concentrations, however, all metals negatively influence organisms. The large scale introduction of metals in society, the technosphere, and eventually into the biosphere, has in some cases given rise to toxic effects. Cadmium, mercury, lead, copper, and other metals have all been connected to various toxic effects in living organisms. Of these, arsenic, mercury, cadmium and lead do not seem to serve any biological functions in living organisms (this is however a matter of discussion). Table 2.8 illustrates the fact that most elements can cause diseases either they are too low or too high in concentrations.

Table 2.8

Diseases at state of deficiency respectively toxicity caused by the same element (selected elements) (Data from Selinus et al., 2005).

Element	Deficiency	Toxicity
Iron	Anaemia	Haemochromatosis
Copper	Anaemia, "Sway back"	Chronic copper poisoning, Wilson-, Bedlington-disease
Zinc	Dwarf growth, Retarded development of gonads, Akrodermatitis entero pathica	Metallic fever, Diarrhoea
Cobalt	Anaemia, "White liver disease"	Heart failure, Polycythaemia
Magnesium	Dysfunction of gonads, Convulsions, Malformations of the skeleton, Urolithiasis	Ataxia
Chromium	Disturbances in the glucose metabolism	Kidney damage(Nephritis)
Selenium	Liver nechrosis, Muscular dystrophy ("White muscle disease")	"Alkali disease", "Blind staggers"

In the living cells metals are bound to proteins, where they serve specific functions as components in e. g. enzymes. The copper and iron atoms in proteins give the cells their capacity e. g. to bind and transport oxygen and to oxidize the food, and thus serve key functions in the energy metabolism of the cells. Zinc serves as catalyst in enzymes that are active in the buildup of the hereditary material, DNA. Special metals such as molybdenum and manganese have key tasks in photosynthesis and nitrogen metabolism. In all cases metal ions bind to oxygen, nitrogen or sulphur atoms. When metals are causing toxic effects they also then bind to proteins but in ways that block the function of the target proteins. It is again their affinity for the oxygen, nitrogen or sulphur atoms in proteins that explains the toxicity.

In Annex 3, effects of both deficiencies and overdoses of metals on human health are described in more detail.

2.6 Conclusions

Metals enter the environment via natural, geological processes and human activities. Once in the environment, their rate of sequestration is very low. Metals tend to accumulate in soils and sediments, they can percolate in surface and underground waters, finally they can enter also animals and human beings trough drinking water.

Concentrations of metals in the environment show large variations, both regionally and locally. These variations occur both as a result of natural processes and of anthropogenic sources. Human activity has increased the magnitude of above-ground metal cycles. Most of the metals mobilized by mining accumulate in the technosphere. However, environmental metal concentrations generally are higher now than some centuries back. On the continental scale it has been impossible to differentiate anthropogenic impact from geological variation. However, at a local scale, increased environmental metal concentrations due to emissions of metals from point sources have been demonstrated.

Metals enter the food web via plant uptake and through bio-accumulation, which may lead to a high intake in animals, including humans, at the top of the food chain. Many metals are essential for life, but their intake has an optimum. Below that, deficiency symptoms occur, and on the other side, adverse impacts of too high intakes can be detected. Impacts on human health occur mostly at the local scale. Ecosystem impacts occur more widely. Although there are still many unknown variables, it is becoming likely that metals in the environment could be having an impact on biodiversity.

Although this field of research has generated a lot of knowledge, there are still gaps concerning the dispersion as well as toxicological impacts of metals. Among these gaps are the impacts of exposure to a metals mix, and the global distribution and ultimate fate of metals in the global environment.

3. Metals in society: sources of metals emissions

Authors: Ester van der Voet, Gavin Mudd, Reijo Salminen

3.1 Applications of metals

Metals have a wide variety of applications, related to their unique properties. Among others, their electrical and thermal conductivity, their malleability, their luster and density are properties that make them valuable and suitable for certain applications. An overview is given in Annex 4. These applications are crucial for the functioning of our present society. When considering possibilities to reduce the use of metals in general, and specific metals in particular, substitutability is an important issue. In some of the applications, metals can be replaced by other materials easily, but in many, substitution is difficult, or the substitute will be another metal. This puts some boundaries on options to reduce emissions (see Section 3.6).

The applications themselves, as well as the upstream processes of mining, refining and manufacturing, and the downstream processes of waste management, cause emissions of metals to the environment. These emissions are the subject of Chapter 3. In Section 3.2, investigations of stocks and flows of metals will be discussed. In Section 3.3, the emissions related to those stocks and flows are treated. Section 3.4 describes emissions from legacy contaminations. Section 3.5 discusses some expectations for future developments in metal emissions. In Section 3.6 options to reduce emissions are treated. Emissions of other substances in the life cycle, such as GHG emissions, particulate matter (PM, SOx, NOx and many others), as well as impacts on land, water and biodiversity are discussed in Chapter 5.

3.2 Stocks and flows of metals in society

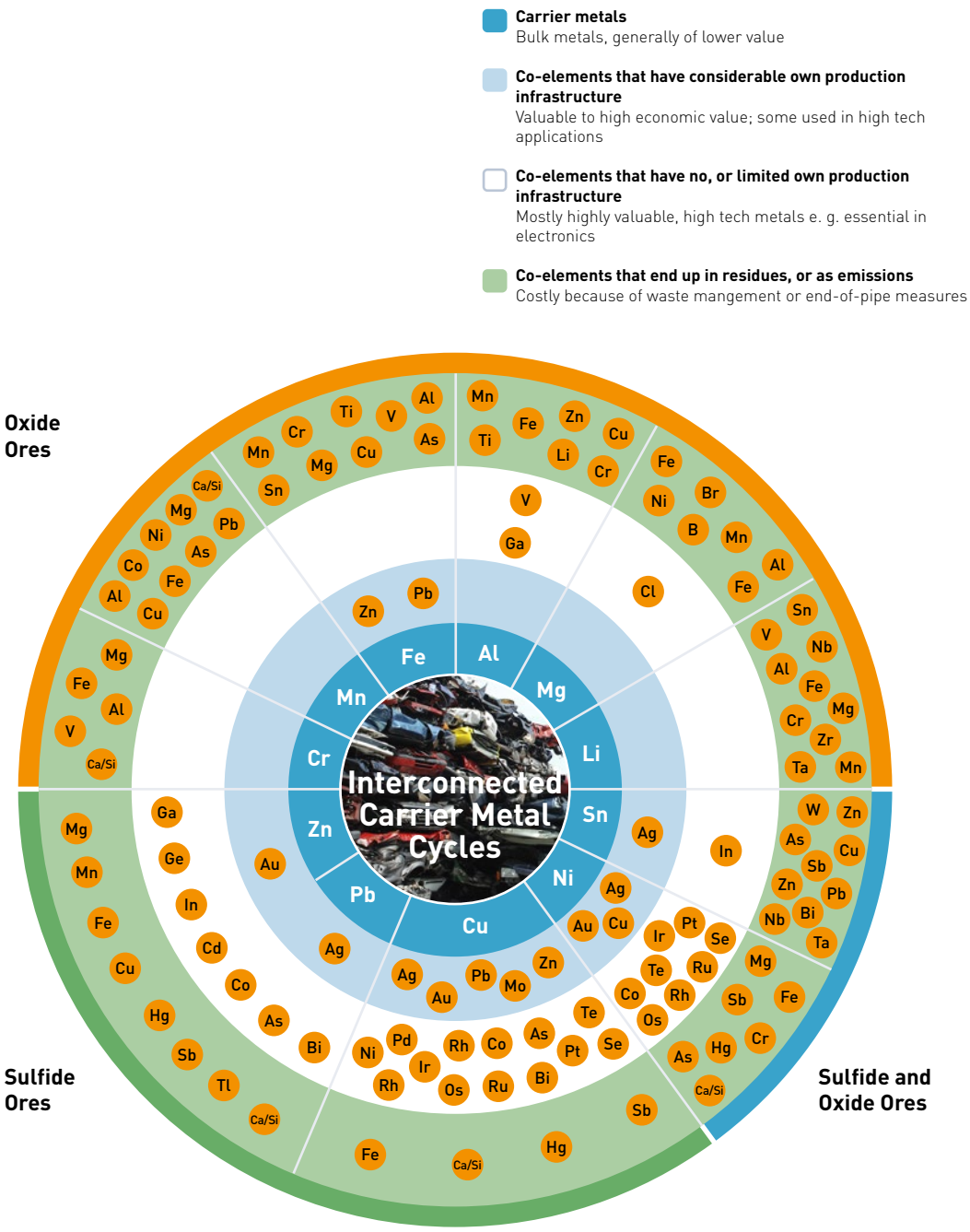
As established in Chapter 2, humans mobilize metals in large quantities. The natural cycles in many cases are dwarfed by the anthropogenic flows. This is not necessarily related to large emissions and environmental problems. In this chapter, the relation between anthropogenic metal cycles and the environmental flows of metals is explored. Other impacts related to the anthropogenic metals cycles, for example due to the use of energy or the landscape impacts of mining, are treated in Chapters 4 and 5.

The various main minerals are described by the Metal Wheel as depicted in Figure 3.1, presented by the inner circle. These main minerals are always associated with a suite of minor elements as shown. Some of these have high value and some (presently) little, but due to evolving technology this is constantly changing. The metallurgical industry is in a constant process of optimizing the extractive metallurgy of the elements considering thermodynamics, technology and economics. The metallurgical infrastructure and this deep knowledge reflected by the Metal Wheel makes the recovery of these elements possible. The outside ring shows those elements that ultimately report to the low value benign residues that are an inevitable product of any metal production. While many of the valuable metals are recovered in suitable systems if Best Available Technology is used, the residues deport some of these elements as is dictated by thermodynamics, physics and the applied technological limitations. If the containment of the residues of the green ring is not done well, this has an impact on the environment and is a main topic of discussion in this document. Therefore succinctly this diagram shows that if one needs indium, germanium, gallium, PGMs for sustainability enabling products one has to mine certain base metals represented by the inner carrier circle. This obviously has environmental impacts if the deportment of elements to the green circle is not well controlled. This shows clearly that the linkages are complex

and have to be well understood to optimize the complete system and hence to drive Resource Efficiency.

Figure 3.1

The Metal Wheel, showing carrier metals and their co-elements as they occur in ores naturally (Reuter et al, 2005)



A large number of publications exists with regard to individual anthropogenic metals cycles, in the tradition of material flow analysis (MFA) or rather substance flow analysis (SFA). Metals covered in those assessments are Fe, Al, Cu, Zn, Pb, Cr, Ni, Cd, Hg, Sb, Ag, Mo, Mn, W and PGMs (Graedel et al., 2004; Chen et al., 2001; Daigo et al., 2007; Daigo et al., 2009; Daigo et al., 2010; DeMarco et al., 2005; Elshkaki, 2007; Geyer et al., 2007; Gordon et al., 2003; Gordon et al., 2004; Graedel et al., 2002; Graedel et al., 2005; Guo et al., 2010; Guo & Song, 2008; Harpel & Graedel, 2008; Hatayama et al., 2010; Igarashi et al., 2007; Izard & Müller, 2007; Johnson et al., 2005; Kapur, 2006; Kapur et al., 2003; Lanzano et al., 2006; Mao et al., 2008; Nakajima

et al., 2007; Nakajima et al., 2008; Oda et al., 2010; Reck et al., 2006; Saurat & Bringezu, 2008;, Spatari et al., 2002; Spatari et al., 2003; Spatari et al., 2005; Tanimoto et al., 2010; van Beers et al., 2004; Wang et al., 2008; Yellishetty et al., 2010). This includes most of the target metals in this report. Mostly, these studies cover one country, but some include continents or even global estimates. Several of these publications originate from the STAF-project conducted at Yale University, covering global flows of metal cycles for a number of metals.

Most of these publications are drafted from a point of view of resource conservation and management. Underlying questions are: where do the mined metals end up, how can we improve the efficiency of metal cycles, is it possible to improve resource availability by recycling or mining urban stocks, and suchlike. Emissions are often not specified, and the relation with the environmental flows is not established. Nevertheless, data from these studies could be used as a starting point to specify emissions, especially related to industrial production and to corrosion from metal stocks-in-use, combined with emission factors.

Another group of SFA-studies is motivated from environmental problems. These have different underlying questions: what is the source of metal pollution in agricultural soils, what is the origin of metals in sediments, how can it be explained that the environmental concentrations do not go down while the metals cycles become more efficient? The scope of metals covered in these publications is somewhat smaller: Cu, Zn, Pb, Cr, Ni, Cd and Hg (Annema et al., 1995; Bergback et al., 1994; Bergback et al., 2000; Boehme & Panero, 2003; Cain et al., 2007; De Cerreno et al., 2002; Elshkaki et al., 2004; Guinée et al., 1999; Hansen & Lassen, 2003; Hawkins et al., 2006; Hendriks et al., 2010; Kwonpongsagoon et al., 2007; Lindqvist & Eklund, 2001; Ma et al., 2007; Sörme et al., 2001(a) Sörme et al., 2001(b); van der Voet et al., 1994; van der Voet et al. (eds.), 2000). The very large scale metals Fe and Al are not included in these studies – no doubt due to the fact that these metals are present in the environment in large quantities and their presence in the environment is generally not associated with environmental impacts. Also, some smaller scale metals are not included. For those as well, supply constraints will be more urgent than impacts related to flows of these metals in the environment.

While the first group of studies focuses on the major flows of metals, we can observe that the second group include minor flows as well, and include other materials such as fossil fuels, phosphate fertiliser, cement, sewage sludge and sometimes (ores of) other metals, wherein the target metal occurs as a contaminant. Early studies, focusing on river basins, conclude that the importance of industrial point sources for emissions to surface water declines, while on the other hand, diffusive "dissipative" sources become more important (Ayres & Rod, 1986; Stigliani et al., 1993). This is confirmed by later studies (e. g., van der Voet et al. (eds.), 2000). "Diffusive sources" is a wide area of metal applications. It may refer to applications of the metal that are inherently dissipative, such as metals in paints, pesticides or wood preservatives, directly entering the environment. It may also refer to applications of other materials, wherein the metal occurs as a contaminant. Some fertilisers appear to be an important source for rising concentrations of metals in agricultural soils. Fossil fuels are the source of a variety of metal emissions to the atmosphere. In a series of studies in the 1990s, the importance of stocks in society is signaled, not just as a potential secondary source of the material, but also as a source of emissions: copper and zinc roofs, lead sheet, fences and all kinds of metal structures exposed to the weather are contributors to the emissions to the environment (Sörme et al., 2001; Elshkaki et al., 2004), especially to the surface water.

In Section 3.3, the different sources of environmental flows are investigated and compared.

3.3 Emissions of metals

3.3.1 Natural sources

Metals are essential constituents of every natural material in lithosphere, hydrosphere and biosphere. The concentration level of most metals in natural media is very low (in the order of mg/kg or even µg/kg). Exceptions are major elements such as Al and Fe (measured in g/kg or even %). In some places metals are enriched in geological formations such as ore deposits or rock types including naturally anomalous abundances of metals. The order of magnitude of the enrichment factor, compared to the average of the Earth's crust, is around 1000 in ore deposits. Normally the dimension of ore deposits is small and the volume of emissions from them is small and local, although contrast to the surrounding areas may be high. Certain rock types such as ultramafic rocks or some shales which normally include high Ni, Co, Cr, (enrichment factor around 100) and Fe may cover large areas and thus cause relatively high concentrations of metals in rather large areas.

Metals are mostly tightly bound in the lattices of minerals that were formed under higher pressure and temperature conditions than those now prevailing at the Earth's surface. Thus there is a tendency for minerals to change to forms that are stable under the prevailing conditions. This takes place via weathering processes when the lattice structures break down and the metal ions are liberated. Weathering takes place in solid bedrock and mineral soils. In soils, the soil-forming processes are the major factors to move metal ions tightly bound in mineral lattices into soil water solution. Minerals have different susceptibilities to weathering and thus knowledge of the original mineral is essential when the liberation of metals, for example into bioavailable forms, is estimated.

In addition to chemical weathering, metals are distributed from solid rock and soil as minerogenic dust into air. This is a part of diffuse distribution of metals, but in the dust metals are normally inert and still bound in mineral lattices. On the other hand, small grain size of dust particles enhances much chemical weathering and metals will change to chemically active form rather quickly. Metal concentrations of terrestrial moss are often erroneously considered to indicate only anthropogenic airborne contamination, but part of the metals in moss samples comes from the dust derived from the local geogenic sources, as is discussed in Chapter 2.

Finally, metal ions liberated from originally inert minerals migrate towards groundwater and surface water, and are transported to oceans. On their way to oceans metal ions can be freely available for biological processes.

Changes in oxidizing and/or pH conditions, whether due to natural processes (flooding, erosion) or anthropogenic can mobilize metal ions which are in an inert form. A good example refers to the problems in Bangladesh related to As in the groundwater. The high concentrations of As, from natural sources, cause health problems. Although the exact mechanism by which the arsenic is transferred to the water is not yet fully understood, one explanation may be that drilling wells through As bearing geological strata and following lowering of groundwater caused oxidizing conditions and got As to dissolve from mineral lattices to the water.

Probably all metals are necessary to some biological processes, although no role has yet been identified for some metals such as Pb, Cd and As. The change of metals to bioavailable form can be a result of natural geogenic process or some anthropogenic factor. However, differentiation between natural and anthropogenic influences is often difficult; both components may be present at the same time in the same place. In some cases, a natural source may become an anthropogenic source. In the case of mining it is quite clear that the material in the tailings area is a result of anthropogenic process, despite the fact that the metal concentration is much lowered during the processes leading to tail-

ings production. In the ore deposit before mining started, the source is natural. However, the problem is much more complicated in areas where soils naturally have metal concentrations higher than action limits defined by the authorities (e.g., the case of arsenic).

3.3.2 Emissions from point sources

Emissions from mining and smelting

Mining can cause major land disturbances through clearing, excavation and placement of mine waste (tailings, waste rock, smelter slags), truck and vehicle emissions, contaminated water releases (direct and indirect), and process plant emissions. Most of these emissions refer to other pollutants, but part of these are emissions of the metals themselves. Metal emissions are most prominently to air and water, with mine wastes to land commonly excluded unless it generates airborne dust or allows escape of leachate or seepage to adjacent ecosystems. In Chapter 5, this is addressed more extensively. Metal emissions may also occur in case of accidents. Especially tailings dam failure results in emissions of metals and other substances used in the mining industry, such as cyanide (IIED and WBCSD, 2002).

pollutant emissions annually to government. In Australia this is called the National Pollutant Inventory (NPI), while in Canada it is the National Pollutant Release Inventory (NPRI) or the Toxic Release Inventory (TRI) in the USA. In Europe there is the Industrial Emissions Directive (IED) and the European Pollutant Release and Transfer Register (E-PRTR). Pollutant release inventory systems have been in operation for almost a decade (or more in some cases), and provide a data rich source of emissions data from mining – although such studies are surprisingly relatively rare to date. A nice example can be found at http://www.cec.org/Page.asp?PageID=751&SiteNodeID=1097 which was developed by the Taking Stock Initiative of the Commission for Environmental Cooperation (CEC) to assess emissions for the North American continent.

Two metals are briefly reviewed, namely copper and uranium, using mines and data from Australia and Chile. All copper projects include the four stages of primary copper metal production (mining, milling, smelting and refining), while both uranium projects produce relatively pure uranium oxide. The primary metrics adopted are total and unit pollutant emissions per year or per metal produced,

Table 3.1

Average total and unit pollutant emissions per year for copper projects in Australia and Chile (Data from Mudd, 2009a; NPI, 2010; Chilean corporate report, var.).

Project	Tonnes per year				Kilograms per tonne copper		
	Cu	SO_2	PM_{10}	As	SO_2	PM_{10}	As
Project 1	893,952	101,199	524	498	115.2	0.62	0.57
Project 2	386,639	184,094	1,263	332	490.7	1.08	0.91
Project 3 #	175,216	1,988	976	0.52	12.9	5.30	0.003
Project 4	71,967	84,543	1,234	498	1,220.5	16.65	6.81

Project 3 refers to a copper-uranium-gold-silver producer, but given that copper is the dominant metal at ~75% of revenue, all emissions have been allocated to copper for this example.

In countries such as the United States of America, Canada and Australia, as well as many across Europe, there are now statutory protocols that require major industry facilities to monitor, estimate and report their

shown in Tables 3.1 and 3.2. The tables show other emissions besides metals as well.

Table 3.2

Average total and unit pollutant emissions to air per year for uranium projects in Australia (Data from Mudd 2009a; NPI, 2010)

Note: Metals includes As, Cr^{3+}, Cr^{6+}, Cu, Pb, Ni, Be, Cd, Co, Mn, Zn and Hg; Organics includes PAHs, VOCs, cumene, benzene, toluene, ethylbenzene and xylene.

Project	Tonnes per year							Kilograms per tonne uranium oxide					
	U_3O_8	SO_2	PM_{10}	NO_x	CO	Metals	Organics	SO_2	PM_{10}	NO_x	CO	Metals	Organics
Project 5	4,854	133	500	958	349	1.28	82.92	27.9	101.7	202.0	72.6	0.26	18.1
Project 6	812	0.64	195	76	47	0.122	10.4	0.8	242.8	94.3	58.9	0.15	12.9

For the copper projects chosen, both the production scale and the total and unit emissions vary significantly. This is largely related to the extent of pollution control and environmental management at each site, especially for the smelter and refinery stages. For example, Project 3 in South Australia captures sulfur dioxide and produces sulfuric acid which is used elsewhere on site (mainly in the hydrometallurgical sections of the project). Project 1, 2 and 4 sites are also old, amongst the oldest continually operating copper mines in the world, and hence the community expectations, environmental regulation and pollution controls are still evolving. For example, SO_2 capture has historically been a lower priority in Australia due to its relative isolation and lower concentration of processing industries.

At numerous old and operating mining projects around the world, the legacy of point source pollutant emissions has sometimes led to impacts such as elevated metal exposures to adjacent mining communities. The Mt Isa mining complex in western Queensland, Australia, has mined and smelted lead-zinc-silver ore since 1931, as well as parallel copper mining and smelting since 1953. After considerable debate and studies, recent research has shown that the elevated blood lead concentrations in young children of Mt Isa is clearly related to historic and ongoing emissions from the Mt Isa mining and smelter complex (Taylor et al., 2010). The Mt Isa smelting complex, viewed from the downtown region, is shown in Figure 3.2.

Figure 3.2

The lead (left) and copper (right) smelters at Mt Isa, Queensland, Australia, viewed from the downtown area (Photo courtesy Gavin M. Mudd, April 2010)

Emissions from industrial processes

Point sources from industry related to metals are often unrelated to the life cycle of the metals themselves. Primary metal production causes emissions to surface water, but generally in small amounts. Moreover, Industry emissions have often reduced drastically over the last 20 years due to emission reduction management systems, induced voluntarily or by governments.

For a number of metals, the phosphate rock industry is a significant source of emissions to surface water. Phosphate rock contains metals, such as Cd, Cr, Cu, Ni and Pb, as trace contaminants. Other industries causing metal emissions to surface water are diverse – petrochemical industry, ceramics industry, fabrication of pesticides and pharmaceuticals, alloy production, coating, food processing, pigment production and many others. Very specific sources refer to shipyards (copper) or chlor-alkali production (mercury) who are users rather than producers of metals.

Emissions to air are mainly caused by the use of fossil fuels, especially coal. Fossil fuels, as fossilized biomass, contain trace amounts of metals that are emitted at incineration. Power plants are therefore an important source of emissions of metals, in addition to other industrial users. Again, emissions to air are mainly due to sources unrelated to the production and use of the metals themselves.

Emissions from waste management processes

A substantial fraction of the metals used ends up as waste. This can be recycled, but most of it still ends up in landfills. The landfilling of waste causes leaching of metals to the groundwater. Incineration of metals may lead to emissions to the atmosphere. Incineration takes place in waste incinerators, but also in less controlled circumstances, such as in the informal treatment of electronic waste (e. g., Wong et al., 2007).

A significant source of emissions of metals to the environment is waste water treatment. Metals end up in waste water via all kinds of sources, industrial as well as domestic, and tend to get concentrated in waste water treatment (Chang et al., 1984; Dai et al., 2007). Their origins can be traced back to specific industrial sources, or to diffusive sources such as corrosion from pipes, the human metabolism, and rainwater containing metals corroded from construction elements (Lundqvist & Eklund, 2001, Sörme et al., 2001, Annema et al., 1995). Since metals cannot be degraded, they either end up in the effluent or in the sewage sludge. Effluent is added to surface water, while the sludge generally ends up on landfills or soils. Sludge incineration can create an interesting closed-loop cycle of metals when the waste water from the incineration process is treated again with the sewage water (van der Voet et al., 1989).

3.3.3 Emissions from diffusive sources

Emissions from use processes
As in industrial production processes, emissions of metals from fossil fuels take also place in use processes. The main source in the use phase is traffic. Trace contaminants of metals are still present in transportation fuels.

Other emissions from products in use refer to corrosion of metals from metal surfaces exposed to the environment: roofs, fences, gutters etc. The use of metals in paints, sprays and pesticides also leads to emissions to the environment: the so-called dissipative applications, where the use of the product equals the emission to the environment.

Finally, a group of applications related to agriculture cause emissions to the environment: the use of phosphate fertilizer wherein metals occur as trace contaminants, and the use of metals such as copper and zinc in animal feed. These emissions lead to cycles in agriculture: metals being taken up by plants used as animal feed, ending up in manure which is used on the land, leading to increasing concentrations in agricultural soil. Even relatively small additions to the cycle thus may lead to high concentrations (e. g. Van der Voet et al., 2000). Figure 3.3 shows the effect of "closed loop accumulation" on Dutch agricultural soils: the steady state represents the situation when the 1990 metals management is continued indefinitely. These calculations, however, do not specify the amount of time involved in reaching such a steady state – for that, a more elaborate dynamic model would be required. Due to the large uncertainty related with "steady-state calculations" and the importance of bio-availability, recent risk assessment practices have assessed accumulations after 100 years accumulation and include bio-availability. The resulting refined predicted exposure levels are similar to the measured exposures levels.

Note that for zinc, the PNEC value has been revised recently (ECB 2008). With the revised PNEC, no exceedance of MPC would be predicted even in the steady state.

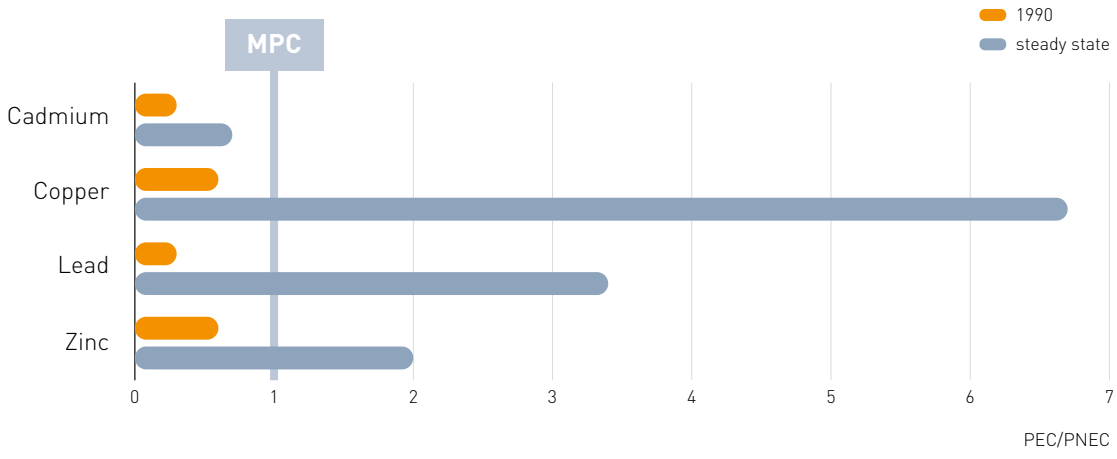


Figure 3.3

PEC/PNEC for four metals in Dutch agricultural soil, based on the Maximum Permissible Concentration for soils (van der Voet et al., 2000).

3.3.4 Quantifying global emissions from natural and anthropogenic sources

A survey from some time ago was made by Nriagu & Pacyna (1988) to estimate metal emissions at the global level. This can be compared with the addition of metals to the environment by natural sources. In this table, the median values have been taken.

Table 3.3

Global emissions of metals to the environment, ca. 1988, in 10^6 kg/year (Data from Reimann et al., 2003)

Metal	Weathering & volcanic (Azar, 1996, from Nriagu, 1990)	Total emissions (ex landfill)	Total chain losses (emissions + landfill)[a]	Emissions to air (Nriagu & Pacyna, 1988)	Emissions to surface water (Nriagu & Pacyna, 1988)	Emission to soil (Nriagu & Pacyna, 1988, landfill excluded)	Landfill mining/smelter waste (Nriagu & Pacyna, 1988)	Other landfill	Ratio natural/societal ex landfill	Ratio natural/societal inc landfill
As	110.0	67.3	157.7	18.8	41.0	7.5	15.9	74.6	0.6	1.4
Cd	5.3	20.4	44.8	7.6	9.4	3.5	5.8	18.6	3.9	8.4
Cr	830.0	264.8	1068.5	30.5	142.0	92.4	–	803.7	0.3	1.3
Cu	380.0	242.5	2218.4	35.4	112.0	95.2	1117.0	858.9	0.6	5.8
Hg	1.4	10.1	18.3	3.6	4.6	2.0	1.9	6.4	7.2	13.1
Mo	15.0	34.4	116.2	3.3	11.0	20.2	13.9	67.9	2.3	7.7
Ni	300.0	227.7	585.2	55.7	113.0	59.1	91.5	266.0	0.8	2.0
Pb	290.0	505.1	1768.9	332.4	138.0	34.8	502.5	761.3	1.7	6.1
Sb	9.9	29.2	79.5	3.5	18.0	7.7	32.0	18.4	2.9	8.0
Zn	910.0	713.6	2601.9	131.9	226.0	355.7	872.0	1016.3	0.8	2.9

a) including mining/smelter waste

The numbers vary, of course, per metal, and it should be noted that the estimates have high uncertainty margins. Nevertheless, it can be concluded that the emissions are roughly in the same order of magnitude as the natural sources, excluding landfill. If landfill is included, this is more – almost one order of magnitude. One can debate whether or not landfilled metals count as emissions to the environment – that may depend on the quality and management of the landfills. Certainly they represent losses from the anthropogenic metals cycles. Mining and smelter waste is a significant post in total landfill, and ranges from about one quarter to two thirds.

Another comparison that can be made, is that between emissions and the annual production of metals. This can be seen in Table 3.4 below.

Table 3.4

Emissions and losses compared to annual production of metals, ca. 1988, in 10^6 kg/year

Metal	Total emissions ex landfill (Reimann et al., 2003)	Total emission inc landfill (Reimann et al., 2003)	Primary production (USGS, data for 1988)	Emissions over primary production (Reimann et al., 2003)	Total losses over primary production (Reimann et al., 2003)
As	67.3	157.8	61	1.1	2.6
Cd	20.4	44.4	20	1.0	2.2
Cr	264.8	620.5	3870	0.1	0.2
Cu	242.5	2218.4	8720	0.0	0.3
Hg	10.1	18.3	6.8	1.5	2.7
Mo	34.4	115.8	113	0.3	1.0
Ni	227.7	585.2	952	0.2	0.6
Pb	505.1	1820.9	3420	0.1	0.5
Sb	29.2	79.5	105	0.3	0.8
Zn	713.6	2601.4	6770	0.1	0.4

For As, Cd and Hg, annual emissions and losses are actually higher than annual production. These three metals were already in decline in 1988 – emissions from old stocks probably dominate, in addition to emissions from non-metal sources. Also for the other metals, emissions are surprisingly high compared to annual production. This is most probably due to the contribution of non-metal sources. Van der Voet (1996) has shown that for both copper and cadmium in the Netherlands in 1990, over 90% of emissions comes from non-intentional and trace applications. For total losses from the chain, including landfill, this is different. It can be concluded from Table 3.4 that losses are high compared to production: the combined result of emissions from non-metal sources and the very low recycling rates at that time.

These numbers are from 1988 publication, quite some time ago. There have been significant changes since that time. In the first place, many industries have reduced emissions to air and surface water. In the second place, changes have taken place in the demand for metals. Some have increased, others – notably As, Cd and Hg – have decreased. Some sources, nowadays recognized as important, are not included, such as corrosion and dissipative applications. Some sources have dwindled, such as tetraethyl lead as an additive to gasoline, leading to substantially lower Pb emissions to the atmosphere. In the third place, certain types of emissions were not included in the 1988 inventory, such as corrosion losses from metal stocks-in-use. Finally, landfill has decreased for a number of metals because recycling has increased, leading to a reduction of total losses from the chains. Reck et al. (2008) show that for Ni primary production has increased significantly, while landfill had been reduced somewhat at the same time. For Cr, the amount of landfill (excluding mining, for which there is no 1988 estimate) has decreased while production has increased (Johnson et al., 2006).

Two more recent studies are relevant in this respect. The first is by Pacyna & Pacyna (2001). They give estimates for anthropogenic metal emissions at the global level for the mid-1990s and compare those to emissions from natural sources. Their summary table is presented below, as Table 3.5

Table 3.5

A comparison of estimated global anthropogenic emissions of trace metals in the mid-1990s with emissions from natural sources (emissions in 10^3 tonnes/year) (Nriagu, 1998; Pacyna and Pacyna, 2001

Trace metal	Anthropogenic emissions	Natural emissions (median values)	Ratio anthropogenic/ natural emissions
As	5.0	12.0	0.42
Cd	3.0	1.3	2.3
Cr	14.7	44.0	0.33
Cu	25.9	28.0	0.93
Hg	2.2	2.5	0.88
Mn	11.0	317.0	0.03
Mo	2.6	3.0	0.87
Ni	95.3	30.0	3.2
Pb	119.3	12.0	9.9
Sb	1.6	2.4	0.67
Se	4.6	9.3	0.49
V	240.0	28.0	8.6
Zn	57.0	45.0	1.3

These numbers are lower, but they are not comparable to the 1988 overview, since they include less sources of emissions and are limited to emissions to the atmosphere. The conclusion however that anthropogenic and natural sources of emissions are roughly of the same order of magnitude does not change. A more direct comparison between the two studies can be made by considering only emissions to the atmosphere, as is shown in Table 3.6

Table 3.6

A comparison of global emissions to the atmosphere as calculated by Nriagu & Pacyna (1988) and Pacyna & Pacyna (2001)

Metal	Emissions to air (Nriagu & Pacyna, 1988)	Emissions to air (Pacyna & Pacyna, 2001)
As	18.8	5.0
Cd	7.6	3.0
Cr	30.5	14.7
Cu	35.4	25.9
Hg	3.6	2.2
Mo	3.3	2.6
Ni	55.7	95.3
Pb	332.4	119.3
Sb	3.5	1.6
Zn	131.9	57.0

In almost all cases, the mid-1990s estimate of Pacyna & Pacyna is lower, indicating that emissions to the atmosphere have been reduced in that decade.

A relevant second later study is the study by Richardson et al. (2001) on emissions of a great many metals to the atmosphere shows considerably higher estimates for natural emissions than the estimates of Nriagu & Pacyna. Table 3.7 shows this.

Table 3.7

Global emissions to the atmosphere from natural sources, Richardson et al. (2001) compared to Nriagu & Pacyna (1988).

Metal	Global mean natural emission to atmosphere, 10^6 kg/year, Richardson et al. (2001).	Global median natural emission to atmosphere, 10^6 kg/year, Nriagu & Pacyna (1988).
Cd	41	1.1
Cu	2000	27.7
Pb	1800	12
Hg	58	2.5
Ni	1800	30
Zn	5900	45

The difference is not caused by changes in metal fluxes over the years, but seems to be due to certain flows that were not taken into account by Nriagu and Pacyna. It would imply that anthropogenic emissions are relatively unimportant compared to natural ones. However, the most important flow seems to be the flow of metals in soil particles being blown into the atmosphere. This dominates the numbers for copper, lead and nickel and contributes about half to cadmium and zinc. For mercury, the main source is volcanic activity and evasion from soils. The metal emissions in soil particles are calculated from the amount of particles emitted and the concentration of metals in soils. Metals in soils originate from natural sources, but also from anthropogenic ones. Although arising from a natural process, this flow therefore cannot be counted as of natural origins.

A complete, "anthrobiogeochemical" picture of stocks of metals in various environmental compartments, and the flows of metals among them, was compiled for lead in a series of recent papers (Rauch and Graedel 2007, Rauch and Pacyna 2009). This research provides a clear view of the importance of anthropogenic sources in the loading of metals into air, waters, and soils (Figure 3.4).

Assessments like these enable quantifying the link between the societal flows and stocks of metals and the flows and stocks in the environment at the global level. They also show, in very general terms, what could be done to isolate the societal cycle further from the natural cycle – a de-coupling at the elemental level.

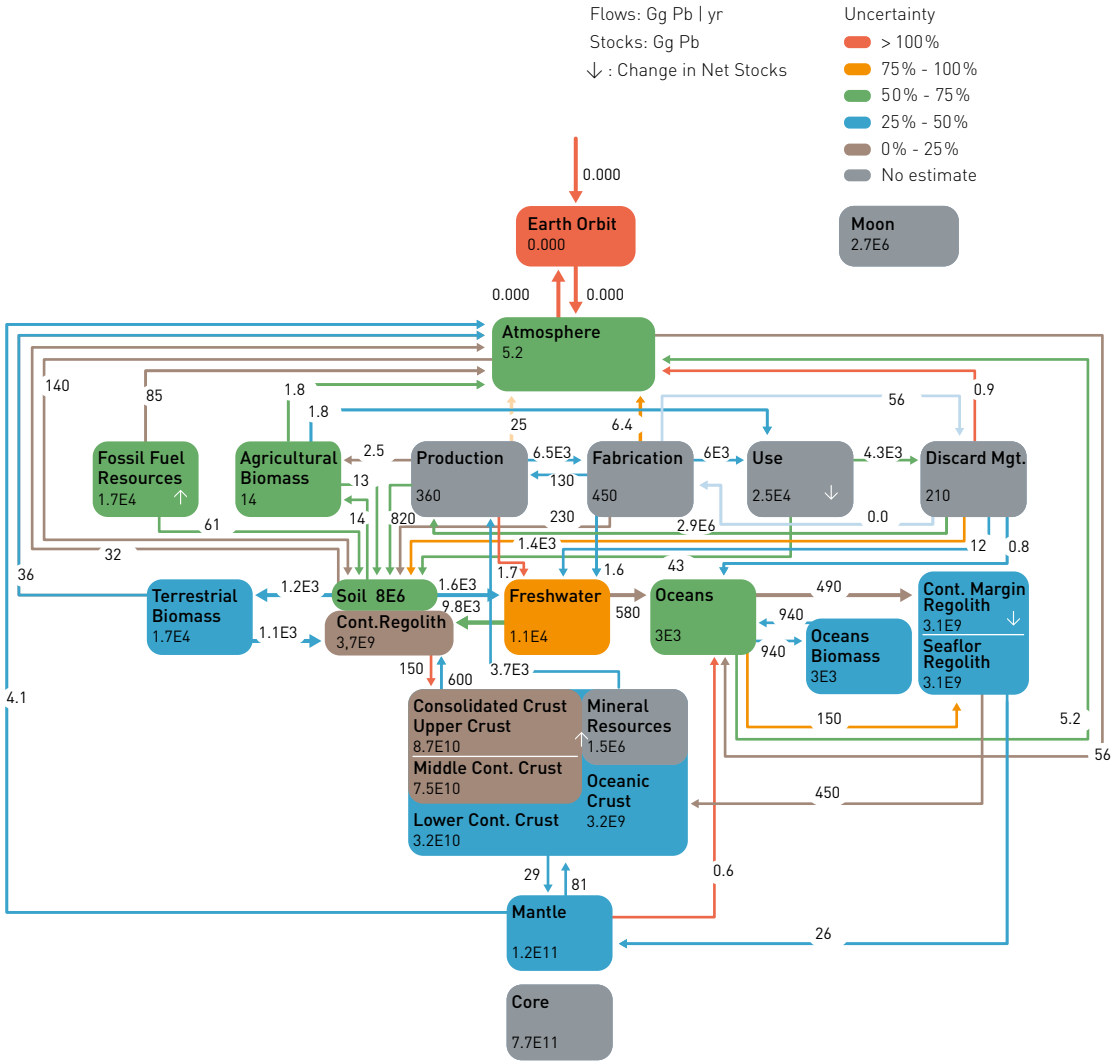


Figure 3.4

Stocks and flows of lead in natural and human reservoirs, and the global flows of metal among reservoirs (Rauch and Graedel 2007, Rauch and Pacyna 2009).

3.4 Legacy Contamination

The primary purpose of mining has always been (and remains) to produce metals useful for society. Historically, there was virtually no environmental management in practice, since production was foremost. From the late 1960s an awareness began to emerge that there was a need for environmental regulation of mining (as well as all major industry). However, by this time there were numerous sites across the world which had closed and left a serious legacy of ongoing environmental contamination (e.g., Chilean Copper Commission & UNEP-DTIE, 2001).

The legacy problems of mining were most famously articulated by scholar Georgius Agricola in his seminal work 'De Re Metallica', published in 1556 shortly after his passing. Although Agricola (1556) was a passionate advocate of mining's benefit to society, he readily acknowledged pollution problems from old mine sites:

"... the strongest argument of the detractors is that **the fields are devastated by mining operations** ... Also they argue that **the woods and groves are cut down**, for there is need of an endless amount of wood for timbers, machines, and the smelting of metals. And when the woods and groves are felled, then are exterminated the beasts and birds, very many of which furnish a pleasant and agreeable food for man. Further, when the ores are washed, **the water which has been used poisons the brooks and streams, and either destroys the fish or drives them away**. Therefore the inhabitants of these regions, on account of the devastation of their fields, woods, groves, brooks and rivers, **find great difficulty in procuring the necessaries of life** ... Thus it is said, it is clear to all that there is greater detriment from mining than the value of the metals which the mining produces."

There are a variety of important mechanisms for pollutant emissions from legacy or abandoned mine sites, including air (dust), soil, surface water, groundwater or through uptake by biota. Soil and wind erosion issues are important, depending on climatic conditions (dry, alpine, temperate or tropical). However, perhaps the greatest issue from legacy mines is acid and metalliferous drainage or acid minedrainage (AMD) (see Da Rosa, 1997; Taylor & Pape, 2007). When sulfidic rock is exposed to water and oxygen, a bioprocess may take place and the sulfide is oxidized and produces acidity. This acid in turn reacts with the rock and puts metals in solution. The leachate can cause extensive impacts if it reaches aquatic ecosystems. These impacts were particularly noted by Agricola and others in central European mines of the Middle Ages, with some regions like the Tinto region of southern Spain famous for such pollution lasting centuries.

Given the exponential growth in mining over the past two centuries, the cumulative scale of the environmental legacies from old and abandoned mine sites has also grown rapidly. An important example of the problems of legacy mines can be found in the former gold fields around Johannesburg, where gold was mined for almost a century without major environmental management and regulation. The ore often contained low grade uranium, and hence the mining activities effectively generated low level radioactive waste also as well as gold tailings. The various suburbs of Johannesburg, especially informal settlements, are built around these large tailings piles – many of which need urgent remediation to address wind-blown dust problems as well as major AMD problems, shown in Figure 3.5.

Around the world there are countless former mines which closed long ago but are still leaching AMD into adjacent surface waters or infiltrating into groundwater. For example:

- Witwatersrand Basin, South Africa (McCarthy, 2010; Winde and Sandham, 2004) – over 120 years of intensive gold mining (including uranium by-products) has left a massive legacy of AMD, closely interspersed with the large population centre of Johannesburg and surrounding settlements. The impacts on water resources will be long-lasting and extremely difficult to remediate.

- Mt Lyell, Tasmania, Australia (Koehnken, 1997) – over a century of copper-gold-silver mining, including local smelting for some 75 years, has led to extreme AMD impacts around the mine area, as well as AMD associated with decades of tailings disposal to the Queen and King Rivers (the tailings delta on Macquarie Harbour is readily visible in Google Earth).

- United States (Da Rosa et al., 1997) – by the 1990s, major regions of the USA were suffering from AMD impacts, including the extensive mining along the full extent of the Rocky Mountains (from New Mexico to Montana), the coal mining in Appalachian Mountains of the east, and numerous other mines which are so polluting they are listed by the SuperFund for large scale remediation (e. g. Summitville, Butte, etc.).

Presently, there are many examples of good practice around the world: sites that are remediated and where the landscape has been restored after the closure of the mine. New ways for remediation are debated in the mining sector and become part of public policy (for example, US-EPA, 2005). Examples on restoration of abandoned mines are provided in Figure 3.6.

Nevertheless, legacy contamination remains an issue that needs attention in many places in the world.

Figure 3.5

Sand dump 20, West Rand gold field, Johannesburg – note the dust from the tailings and large flow of AMD-rich water in the front pipe (Photo courtesy Gavin M. Mudd, October 2010)

3.5 Future Emissions of Metals

What is to be expected for the future development of metal emissions? Various trends, going in various directions, will contribute. Since developments differ for the different metals, the outcome of these combined trends may also be different per metal.

For most of the bulkier metals such as aluminium, copper, iron, nickel, chromium and zinc, demand is still increasing, especially through the rapid growth of large developing economies (Wang et al., 2008; Reck et al., 2010). The demand for some of the smaller-scale metals, for example PGM related to new technologies, is rising very rapidly, and for others it may do so in the future. Ceteris paribus, emissions related to their mining and production can be expected to increase accordingly.

On the other hand, industrial processes have become substantially cleaner and more resource-efficient over the past decades. This ongoing process will have a reducing effect on the level of emissions.

An increase in recycling rates can be expected as well – trends for a number of metals are in the right direction, and new technologies are becoming available to enable a higher recycling rate (see Chapter 5). This implies the increase in primary production, with its concurrent emissions, will be lower. Landfill of metal containing waste may be expected to decline further. Legacy contamination is a problem that will be around for some time: leaching from old polluted sites can go on for a long time if they are not addressed.

Some uses of metals are being phased out. As is shown by Elshkaki et al. (2004) for lead, van der Voet et al. (1994) for cadmium and Maxson (2004) for mercury, this may have unintended consequences. Metals produced as a by-product have an inelastic supply: their mining will not automatically follow the demand but depends on the demand for the "main" material. A declining demand com-

Figure 3.6

Closed and rehabilitated mine site in Keretti, Finland. Today a golf course (Photo courtesy, Outokumpu Mining Museum, August 2003)

bined with a steady supply leads to lower market prices, which in turn may lead to a collapse of recycling activities. In practice, this is more subtle – as the Metals Wheel from section 3.2 shows, metals are co-produced from almost all ores and sometimes the total production of metals for which there is a sufficient demand is what makes the activity economically viable. Which metal is the main product and which the by-products may vary, and may also change over time. In most cases, if there is no demand for the by-product, it will not be extracted from the ore. Still, it is mined with the ore and if not used it ends up in a waste stream. For lead, which is not a by-product but is already recycled to a large extent, a reduction in demand may have a similar effect: the supply from secondary sources may become larger than the demand. Due to the slow discarding of old stocks in society, the supply from secondary material will eventually, over a period of years to decades, become larger than the demand, having the same effect. This may lead to increasing landfill of metal waste. This phenomenon may be observed for more metals when the demand goes down and recycling increases.

With regard to the emissions from non-metal sources, no decreasing trend is to be expected in the near future. Since both population and welfare is still rising and the penetration of renewable energy technology is slow, the use of fossil fuels and of fertilizer is not expected to decrease. Since these diffusive sources are presently very important, it is not to be expected that metal emissions will be reduced in an overall sense.

3.6 Measures to Combat Metal Emissions

Most of the metal cycles are already quite efficient in their production and use stage. Cleaner production, an ongoing process in industry, may reduce emissions in the production phase even further, while reducing dissipative applications of metals will reduce emissions in the use phase. With regards to mining, the principal sources of emissions of metals are dust (mine and mill), vehicle exhaust fumes as well as those indirectly caused by consumption of electricity, fuels and chemicals.

In the waste stage, however, a lot of progress still can be made. Preventing metals from entering the waste stage is a first possibility: increased recycling. This is discussed further in Chapter 5. Two reports of the Global Metal Flows Working Group are dedicated to that (UNEP, 2011; UNEP, 2013). A second step is preventing metals in waste from being emitted to the surface water or the air. Filters on waste incinerators catch metals before they are emitted into the atmosphere. The resulting ash then can be landfilled. In sewage treatment, metals can be taken out of the effluent – they will then end up in the sewage sludge which is mostly landfilled.

The abovementioned measures shift the problem from emissions into surface water and the atmosphere to landfill. Landfills can be controlled to a large extent, preventing the metals from leaching into the groundwater. The main issue remains, however, that every atom of metals mined has to end up somewhere. Recycling for 100 % is a physical as well as economic impossibility. Metals, as elements, cannot be degraded and once they enter the biosphere they disappear from it only via geological processes. Therefore, in a sound metals management the search for a sound sink is an essential part (e. g., Scoullos et al, 2001; van der Voet et al., 1994), such as putting metal waste back into the mines, or store waste metals somewhere as a stock for future use.

High priority should be given to addressing the emissions from non-metal sources. This is also the most challenging aspect. Fossil fuels and fertilizer are used widely and by definition diffusively. Point sources such as coal fired power plants are the least difficult to address – converting air emissions to a solid waste stream of fly ash containing metals. A shift towards renewable energy sources, also desirable because of other reasons, will make a big difference here. Reducing fertilizer use, although effective (Kwonpongsagoon et al., 2007) is even more difficult, as is finding other less polluted sources of phosphate, which also is desirable because of other reasons (Cordell, 2010).

3.7 Conclusions

This chapter has dealt with metal emissions: their extent, their sources and their development. Emissions of other substances related to the metals' life cycle are discussed in Chapter 5.

Emissions of metals from society to the environment, including emissions to atmosphere, emissions to water and diffusive emissions to soil, have been estimated to be roughly in the same order of magnitude as the natural sources, weathering and volcanic activity.

These emissions are increasingly dominated by non-metal sources, especially fossil fuels and phosphate rock, because (1) industrial point source emissions from the metals industry have been addressed in many places and (2) non-metal sources continue to increase. Since both population and welfare are increasing and energy will to a large extent remain dependent of fossil fuels over the next decades, a further rise of these emissions can be anticipated.

Landfill of metal containing waste is a larger flow, but overall it is not increasing so much. Partly this may be due to a better metals management in mining and refining, but mostly this can be attributed to the increased recycling. In the future, a further reduction

can be expected when recycling rates increase.

Developments differ a lot per metal. For metals with a declining use (As, Cd, Hg and to some extent Pb), emissions from old stocks dominate. An end-of-life management for metals like these is indicated, focusing not only on closing cycles but also on a final sink to store unretrievable and unwanted waste streams. For metals with a growing demand, a trend is already visible that recycling rates are increasing. Due to time lag, the share of secondary production remains low as long as total demand keeps rising. This means that emissions related to mining, production and use will probably rise as well, although at a lower pace than production itself.

4. Metals Production and Energy Use

Authors: Matthew Eckelman, Gavin Mudd, Terry Norgate

4.1 Introduction

While metals are a technologically invaluable class of materials, they can require significant amounts of energy to produce. Energy use occurs throughout the life cycle of metals (figure 4.1) and is generally much higher for primary (or virgin) production than for secondary (recycled) production.

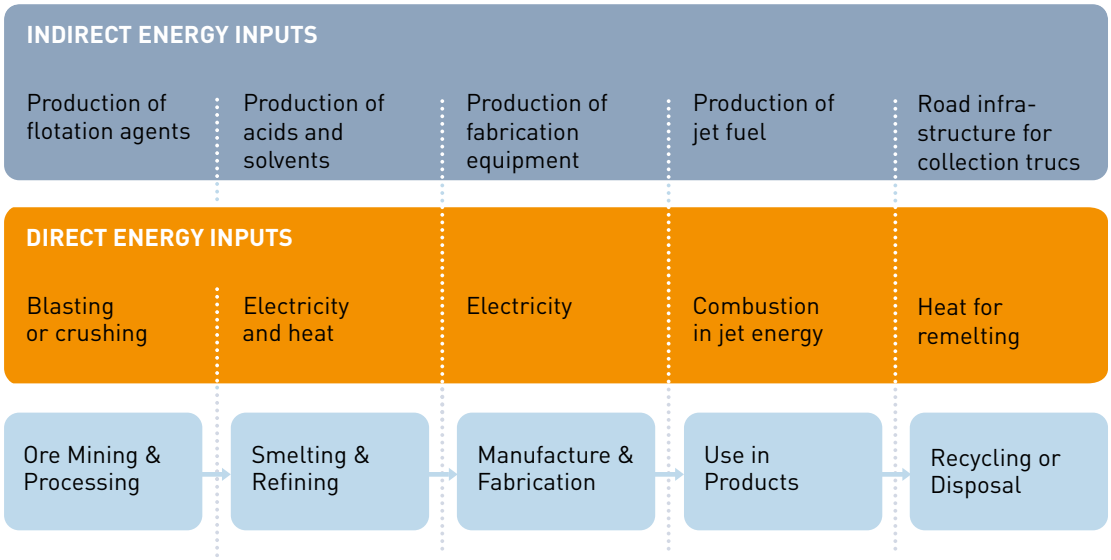


Figure 4.1

Examples of direct and indirect energy inputs during the life cycle of a generic metal

The production of metals from their associated ores typically involves several stages, including mining, mineral processing/concentrating, metal extraction and refining. In each stage, impurities are separated and removed and the concentration of metal in the final product increases. Platinum that starts out at an ore grade (or geologic concentration) of 0.1 % may be processed into metal with a final purity of 99.9 %. For some applications, such as cast iron piping, the required purity of these final products is not stringent, while for others, such as electronic components or high-performance aerospace parts, purity requirements can reach 99.9999 %. Refining metals to this level of purity requires repeated, precisely controlled melting and high levels of energy use, which is an important reason for the high cost of these materials.

Energy use in the metals sector occurs through direct use of fuels, such as combustion of coal to produce heat, or through the use of electricity, which is itself largely produced through fossil fuel combustion. In order to evaluate both of these forms of energy use together, one must consider primary energy use, or the total amount of raw fuel (including renewable sources) used over the entire production chain, which then accounts for the loss of energy during the production and distribution of electricity.

Energy use has long been a crucial factor in the mining and production of metals. Ancient mines relied on wood and charcoal to separate metal from its associated ore, resulting in local deforestation. With the tremendous rise in metal production that accompanied the industrial revolution and later the post-WWII economic boom, the scale of energy use required to fuel that production also increased and is now global in nature. The ferrous and non-ferrous metals industry is responsible for approximately 20 % of all industrial energy use worldwide (IEA, 2009)

There are important physical and chemical reasons for the high energy consumption associated with metal production. Physical parameters such as the ore grade and the depth of a metal deposit dictate how much ore must be mined and how far it must travel to produce a unit of metal, both of which have significant energy use implications. Chemically, nearly all metals found in nature are bound in chemically stable minerals as opposed to existing in a purely metallic state. This means that there is a minimum amount of energy needed to produce each metal, and that no amount of innovation or technological progress will allow humans to pass this thermodynamic limit. The chemical property of Gibbs free energy is the ultimate measure of chemical stability, but the heat of formation normally dictates the minimum energy requirements for a process. For example, the thermodynamic energy required for the production of 1 kg of aluminium from alumina is 31.2 MJ/kg compared to 7.3 MJ/kg for the reduction of iron oxide to iron. This difference partly explains the higher energy consumption required for the production of aluminium compared to iron and steel. Exergy is another important concept for analyzing metal production processes, which tracks flows and losses but also accounts for the inherent quality of the energy being used, as 1 MJ of electricity can do more physical work than 1 MJ of heat (Dewulf et al., 2008).

4.2 Sources of Energy Use for Primary Metal Production

4.2.1 Mining and Mineral Processing

Metal energy use begins with mining, and takes many forms. Mining is carried out through open cut or underground extraction techniques. In open cut (or open pit) mines where ores are relatively close to the surface, such as the Bingham Canyon copper mine (the world's largest in physical size, see Figure 4.2), the overburden (soil layers) are removed using heavy machinery, energy dense explosives and huge excavation machines are used to loosen rock, and a large fleet of haul trucks is used to bring the ores to the surface, thereby requiring large inputs of diesel and relatively minor amounts of electricity. A compilation of data on diesel consumption in open cut mining is given in Table 4.1.

§ Includes the Goldstrike, Cortez, Yanacocha, Newmont-Nevada, Porgera, Dome, Granny Smith, Kalgoorlie West, St Ives, Agnew, SuperPit, Jundee, Tarkwa, Damang, Inti Raymi, Bald Mountain, Misima and Kidston Au mines.

‡ Only includes Codelco Norte (most large Cu mines are Cu-Au; or alternately underground mines only, e. g. Mt Isa, El Teniente). Other large Cu only mines, such as those in Arizona, do not report site specific data (e. g. formerly Phelps Dodge, now part of Freeport-McMoRan Copper and Gold Inc).

Includes the Freeport-Grasberg, Escondida, Alumbrera, Batu Hijau and Highland Valley Cu-Au mines.

Table 4.1

Average diesel consumption in open large cut mines around the world (Mudd, 2009a)

	Years of Data	Mt rock/year			L diesel/t rock		
		average	min.	max.	average	min.	max.
Gold mines§	62	56.7	13.0	199	0.68	0.33	1.18
Copper mines‡	3	394	321.1	432	0.88	0.81	1.00
Copper-Gold mines#	15	202	40.0	360	0.64	0.38	1.18
Overall average	80	96.6	13.0	432	0.68	0.33	1.18

Figure 4.2

Open pit copper mine, Bingham Canyon, Utah, USA (Photo courtesy Wikipedia, 2005 (right) and Jon Bower, 2010 (left))

Underground mines require even more energy to bring ore to the surface because of their greater depth. The TuaTona gold mine in South Africa reaches nearly four kilometers down – miners must descend in a cage for an hour to reach the mining site. Underground mining can be done through shafts, declines or adits, depending on scale, topography, ore geometry, geotechnical and economic considerations. Digging a hole this deep requires large quantities of diesel and electricity to run lifts, conveyers, and some times pumps to pull water out of deep mines.

To bring one tonne of rock up from a deep mine 1 km below the surface requires a theoretical minimum of nearly 10 MJ, equivalent to the gross energy content of 0.25 L of diesel fuel, and this number is directly proportional to the depth of the mine and the mass of the ore hauled to the surface. In practice, the amount of energy use is many times more than the theoretical minimum, with the exact amount of fuel and electricity required depending on the mine depth, the scale of the operation, and the mining methods employed.

Figure 4.3

Underground mining (Photo courtesy www.barrick.com)

Once ore reaches the surface, it can undergo several processing or beneficiation steps to remove the non-metallic waste rock, or gangue, each of which requires energy. Initial screening of ore to remove unusable boulders uses only moderate amounts of electricity to run conveyors and diesel fuel for heavy machinery. Much more significant is the energy (electricity) used for crushing and grinding large chunks of ore into smaller, more easily processed grains, a process generally known as milling. Ore is milled down to the liberation size, which is the particle size necessary to produce separate particles of either valuable mineral or gangue that can be removed from the ore (as tailings) with an acceptable efficiency by a commercial unit process. Crushing produces material typically coarser than 5 mm and consumes relatively low levels of energy, while grinding (or milling) produces very fine products (often below 0.1 mm) and is very energy intensive. Liberation size does not imply pure mineral species, but rather an economic trade-off between grade and recovery. Obviously the finer the liberation size for a particular mineral, the finer the ore must be ground, resulting in higher energy consumption. Figure 4.9 shows how energy requirements increase as the liberation size decreases for the milling of copper ores. It should be noted that fine-grained ores are not necessarily low grade. On the contrary, some high grade ores are fine-grained, such as the McArthur River lead-zinc deposit in the Northern Territory of Australia.

Lastly, particles of some metal ores, such as iron or zinc, may be further concentrated through flotation, where the non-metallic grains are separated out through settling while metallic grains are carried to the water surface through foams or other flotation agents. This process is water-intensive but does not require much direct energy but rather requires energy indirectly in pumping water to the site.

4.2.2 Metal Extraction and Refining

Once metal ores have been mined and suitably processed or beneficiated, the minerals they contain are physically or chemically transformed with the goal of extracting the metal contained within. There are two main classes of technology for metal extraction. The choice as to which processing route is used is invariably based on economic considerations, which are strongly influenced by issues such as ore grade and mineral type.

Pyrometallurgy involves heating of metal concentrates at high temperatures, in order to strip the metal from its associated mineral constituents; this process requires combusting fossil fuels for heating furnaces or electricity to power an electric arc furnace. There are several types of pyrometallurgy, which have different energy considerations. Calcination, a thermal treatment process, can be used for example to drive off water from ore or to break down carbonate minerals. Roasting, which involves chemical reactions between the ore and hot air, is often done to oxidize sulfidic ores. Pyrometallurgy that results in a molten product is called smelting, which typically takes place at higher temperatures than simple roasting or calcining. For some ores, the chemical reactions induced by pyrometallurgy are exothermic, that is, they release energy stored up in the chemical bonds as heat, and thus can be accomplished with little to no external energy. Oxidation of sulfide ores is a common example. Endothermic reactions, on the other hand, require energy inputs in order to proceed, and thus heat must be provided, generally from fossil fuel combustion. For some ores, reducing agents must also be added to help remove impurities from the metal. If the reductant is carbon, usually in the form of coal or coke, this will further add to the fossil energy burden of pyrometallurgy.

Hydrometallurgy consists of treating ores or concentrates with liquid solutions in order to separate metals from other mineral constituents. This is generally done by leaching, for example by piling the ore into large mounds or heaps, or feeding the ore into tanks, and dissolving the metal out of the ores using strongly reactive solutions such as cyanide, ammonia, or sulfuric acid. For heap leaching of copper ores, this step is completed in the open air in large engineered piles, while for other ores, such as gold ores, the process can take place within a hydrometallurgical plant. Leaching does not generally take place at high temperature, but can require high pressures, such as the high-pressure acid leaching (HPAL) process for nickel laterite ores, which requires energy to maintain. For some ores, pyrometallurgical processes such as calcining or roasting may be performed prior to leaching.

Refining of the metal may be necessary after smelting or leaching steps, depending on the intended application. Many refining processes are electrochemical in nature, and so consume electricity, though some diesel and other fuels may also be used. The most common refining process is solvent extraction/electrowinning, where the metal of interest is further separated by extraction with solvents in an aqueous solution, which is then subjected to an electric field and the metal ions are deposited on the cathode of the electrolytic cell. This can also take place in a molten salt solution, as for aluminium and magnesium. Electro-refining is a related process where an impure metallic anode is dissolved in the electrolyte and then plated onto the cathode again using strong electric fields. For some metals, the amount of electricity needed to run a modern-scale refinery is quite large, and for this reason, many refineries are situated close to cheap and abundant sources of hydropower.

The ratios of actual energy consumption during the metal extraction stage to theoretical energy consumption (derived from the heat of formation) for various metals, derived from various published sources, are shown in Figure 4.4. This figure shows that there is considerable scope for reducing the energy consumption for primary metal production by focusing on the metal extraction stage of the metal production life cycle.

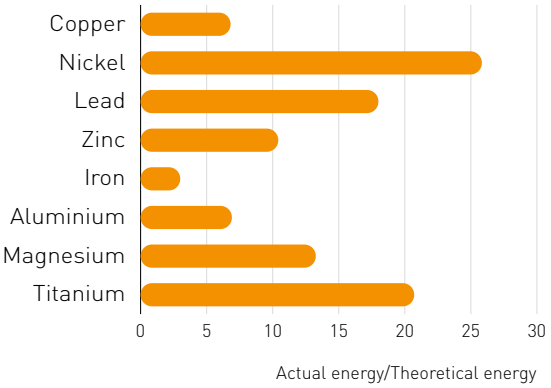


Figure 4.4

Ratio of actual to theoretical energy consumption for metal extraction (Norgate and Jahanshahi, 2010).

Note that the ratio's in Figure 4.4 represent potential improvements compared to the theoretical heat needed for formation of metals, and are not related to actual technologies.

4.2.3 Fabrication and Manufacturing

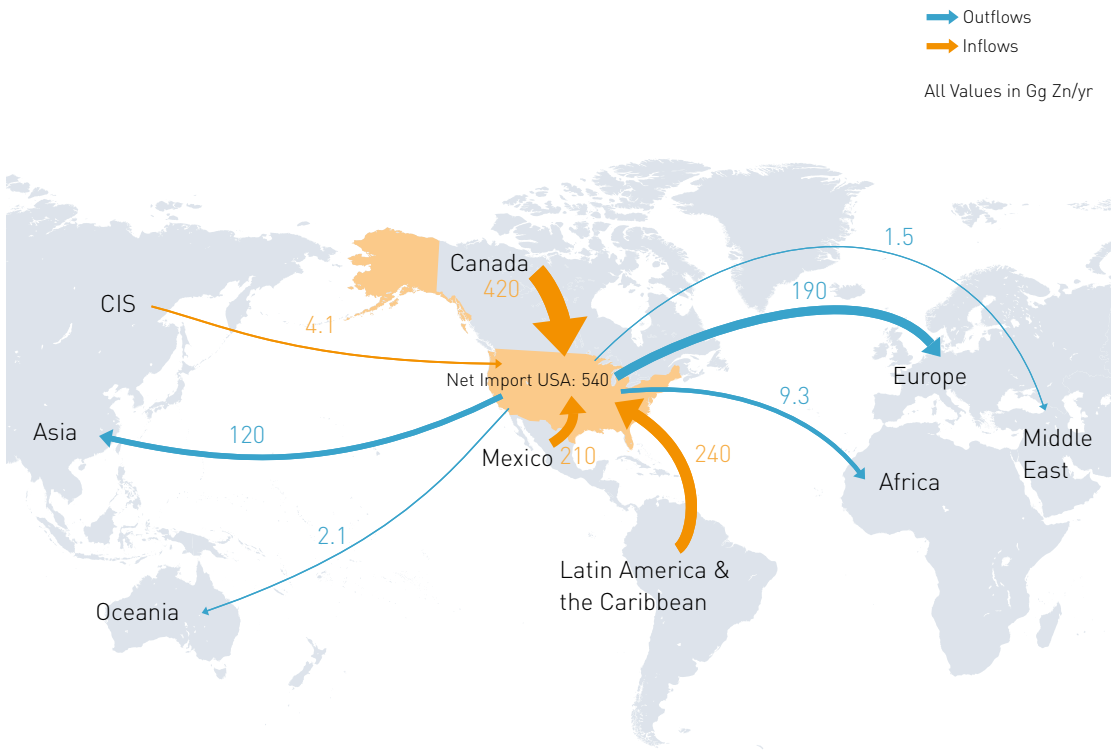
After metal has been refined, it is melted and cast into some kind of shape, commonly an ingot or a billet. These forms are convenient for transport but are often not the actual shapes of metal that are needed for final products. Metal that requires shaping is then sent to a fabrication plant, where it is turned into semi-products such as sheets, coils, bars, or pipes. These are then sent out to manufacturers, who further shape the metal into a final product, such as a washing machine. All of these fabrication and manufacturing steps require energy, mostly in the form of electricity.

4.2.4 Transportation

The chain of production of metals can require significant amounts of transportation. Ores and concentrates are dense materials that are processed at significant scales. At the mine site, energy is required to transport material using trucks or conveyor systems. Metal production facilities are distributed all over the world, and ores, concentrates, and intermediate products are frequently shipped internationally. In some cases, metal mines, smelters, and refineries are all located in a single place, bringing external transportation energy costs to a minimum. In many instances, however, metal is mined in one country or region, transported by train to the coast, if necessary, loaded onto barges, and shipped on to another location. Per unit of contained metal, transport energy use is highest for moving raw ore, as this requires moving the waste rock portion of the ore as well, and for this reason it is rarely done. Transport also applies to metals once they are incorporated into final products and shipped to consumers (figure 4.5).

Figure 4.5

Flows of zinc into and out of the United States (Johnson and Graedel, 2008)



4.2.5 Life Cycle Energy Use for Primary Production

Over the past several decades, many researchers and companies have carried out environmental assessments of the full production chain for various metals. This research has largely focused on energy use, but other environmental impacts such as water use or emissions of greenhouse gases are also commonly considered.

Primary data on life cycle energy use for virgin metal production have been compiled in various life cycle inventory databases, which ensure that each value has transparent assumptions and consistent system boundaries. All of the metals considered in this report have been investigated (table 4.2) but for many metals, including elements being increasingly used in high-tech applications, no robust analyses of primary energy use exist. Various methods have been proposed for extrapolating energy use for one metal to other metals, based on patterns of co-production, enthalpies of formation, ore grades, or prices (Ashby, 2009). Most primary metal operations produce multiple co-products; in this case, it is most common to allocate energy use to individual products according to their relative prices.

Table 4.2

Average primary energy needed for virgin metal production cradle-to-gate

Metal/Product	Primary Energy MJ/kg	Notes	References
Aluminium	190 – 230		EAA; ecoinvent v2.2; Bath ICE v2.0
Antimony	140		ecoinvent v2.2
Cadmium	17		ecoinvent v2.2
Cerium	350	Bayan Obo, China	Koltun and Tharumarajah, 2010
Chromium	83		Bath ICE v2.0
Cobalt	130		ecoinvent v2.2
Copper	30 – 90	Multiple routes	Kupfer Institute; ecoinvent v2.2; Bath ICE v2.0
Ferrochromium	37	68 % Cr	ecoinvent v2.2
Ferromanganese	23	75 % Mn	ecoinvent v2.2
Ferronickel	160	25 % Ni	ecoinvent v2.2
Gadolinium	2,200	Bayan Obo, China	Koltun and Tharumarajah, 2010
Gallium	3,000	Semiconductor grade	ecoinvent v2.2
Gold	310,000		ecoinvent v2.2
Indium	2,600		ecoinvent v2.2
Iron/Steel	20 – 25	Low-alloyed	worldsteel, ecoinvent v2.2; Ashby, 2009
Lanthanum	220	Bayan Obo, China	Koltun and Tharumarajah, 2010

Table 4.2 _b

Average primary energy needed for virgin metal production cradle-to-gate

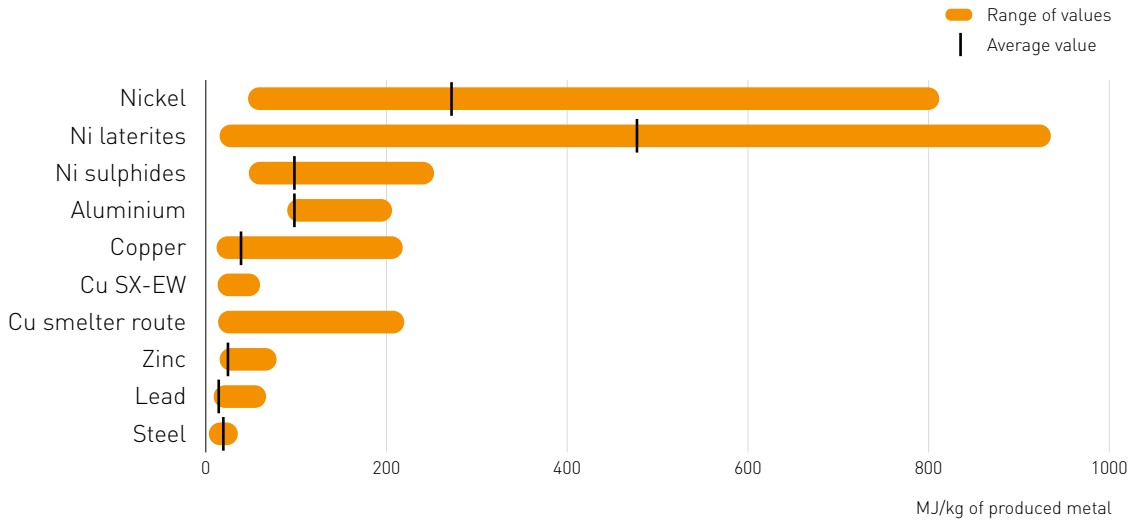
Metal/Product	Primary Energy MJ/kg	Notes	References
Lead	25 – 50		ecoinvent v2.2; Bath ICE v2.0; GaBi
Lithium	380 – 850		ecoinvent v2.2
Magnesium	270 – 350		ecoinvent v2.2; Ashby, 2009
Manganese	52 – 59		ecoinvent v2.2; Bath ICE v2.0
Mercury	90 – 180	Liquid	ecoinvent v2.2; Bath ICE v2.0
Molybdenum	15 – 380		ecoinvent v2.2; Bath ICE v2.0
Neodymium	390	Bayan Obo, China	Koltun and Tharumarajah, 2010
Nickel	180 – 200	Class I	ecoinvent v2.2, Eckelman 2010
Palladium	180,000		ecoinvent v2.2
Platinum	190,000		ecoinvent v2.2
Praseodymium	220	Bayan Obo, China	Koltun and Tharumarajah, 2010
Rhodium	560,000		ecoinvent v2.2
Silicon	1,000 – 1,500	Electronics-grade	ecoinvent v2.2
Silver	1,500		ecoinvent v2.2
Stainless (304)	57 – 68		ISSF ecoinvent v2.2
Tantalum	4,400	Capacitor-grade	ecoinvent v2.2
Tellurium	160	Semiconductor-grade	ecoinvent v2.2
Tin	250 – 320		ecoinvent v2.2; Bath ICE v2.0
Titanium	360 – 750		Norgate et al., 2007; Bath ICE v2.0
Vanadium	3,700		Bath ICE v2.0
Yttrium	760 – 1,500	Bayan Obo, China	Koltun and Tharumarajah, 2010; Bath ICE v2.0
Zinc	49 – 55		IZA; ecoinvent v2.2
Zirconium	1,600		Bath ICE v2.0

Energy use in metal production is also highly variable. Different plants use different process designs, have different efficiencies, and use different sources of electricity, and each of these factors greatly alters the amount of primary energy needed to produce a unit of metal. Figure 4.6 shows global variation in the production of base metals.

The results in this figure have been broken down to show the contributions of the mining/mineral processing and metal extraction/refining stages. It can be seen that for nearly all the metals shown, the metal extraction/refining stages make the greatest contribution to these impacts for the current average ore grades considered, with the exception of

Figure 4.6

Life cycle energy required for primary production, selected metals (Adapted from Barkas (2009) as reported in Eckelman (2010)).

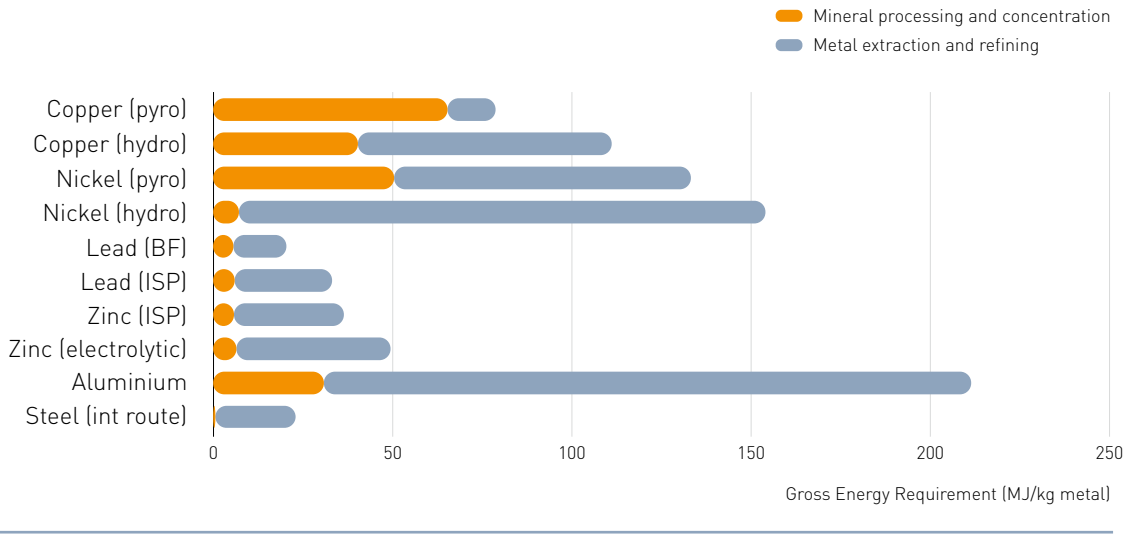


Life cycle assessments have been carried out for various primary metal production processes, in part to identify which processes dominate overall energy use. Norgate et al. (2007) examined all base metals for typical Australian ore grades and updated the analysis to reflect current world average grades (Norgate and Jahanshahi, 2010) and the embodied energy results are shown in Figure 4.7.

pyrometallurgical processing of copper. Combining the results given in Figure 4.7 with current world metal production rates gives the global annual energy results shown in Figure 4.8. This amounts to a total of roughly 30,000 PJ/y, or 30 EJ/y, or 7 – 8 % of the world total energy consumption.

Figure 4.7

Embodied energy for primary metal production (Norgate and Jahanshahi, 2010).



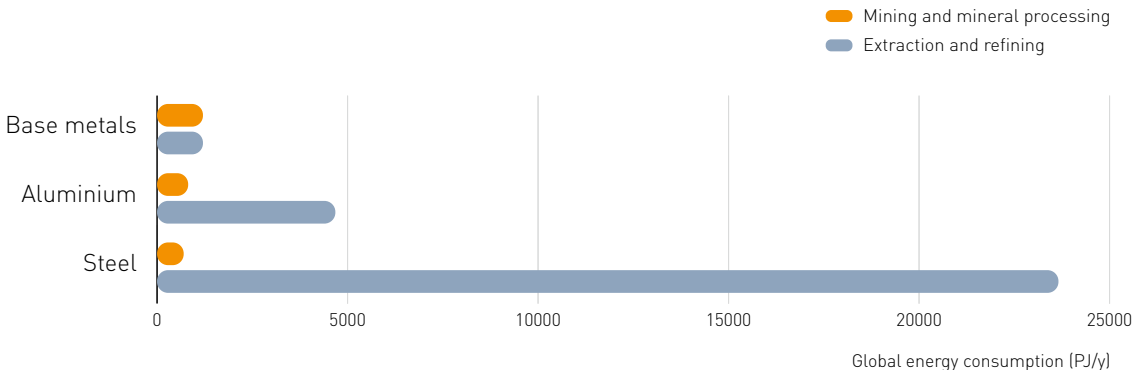


Figure 4.8

Global energy consumption for primary metal production (Norgate and Jahanshahi, 2010).

The results presented above indicate that efforts to reduce the energy consumption of primary metal production should mainly focus on the metal extraction stage of the metal life cycle, and that there is considerable scope to make significant reductions here, particularly for steel and aluminium. While the contribution of the mining and mineral processing stages to energy consumption and GHG emissions can be expected to increase in the future as outlined above, and will present opportunities for reducing these impacts by improving the energy efficiency of comminution (that is, breaking up the ore, primarily through crushing and grinding), these opportunities will still be appreciably less than those from the metal extraction and refining stages.

4.3 Energy Required for Secondary Production

The production of metal from scrap material, or secondary production, generally requires much less energy than for primary production, as many fewer steps are involved. Secondary metal must be re-melted into ingots or other metal products, and is usually mixed with virgin material in an electric arc furnace to control key composition parameters. As the scrap material portion is already in metallic form, much less energy is needed to reduce the metal. All of the energy used in mining, milling, concentrating, and transporting ore to a smelter is also avoided when recycling metals. The energy benefits of recycling are thus particularly significant for metals with a high heat of formation (such as aluminium) or for low ore-grade metals (such as platinum) where large quantities of ore must be excavated and processed to produce one unit of metal.

There are also added energy costs: metal scrap must be collected, sorted, and separated from any potential sources of contamination. Fabrication and manufacturing facilities produce "new scrap" that is fairly homogeneous and does not require any energy-intensive separation processes. End-of-life scrap, on the other hand, is heterogeneous and dispersed and must be collected, shredded, and sorted from other material waste streams. Both operations have energy costs: diesel fuel to run the collection trucks and trains, and electricity to run large-scale sorting machinery. What is collected and sorted from end-of-life scrap can be contaminated in various ways, through surface treatment, alloying, or adhesion to other materials for example. Depending on the metal and the contaminant, additional energy can be expended to purify the scrap, through pyrolysis or incineration. Materials that are not separated during remelting become incorporated as tramp elements. Primary energy costs for different recycling processes are shown in Table 4.3.

Table 4.3

Energy use for common metal recycling processes (adapted and expanded from Norgate, 2004)

Recycling Stage	Metal/Product	Primary Energy MJ/kg product	References
Deconstruction	Steel	0.9	ecoinvent v2.2
Collection	Al packaging	0.3	Quinterz et al. (2001)
	Ni-Cd batteries	7.4	Lankey & McMichael (1999)
Sorting	Al packaging	0.4	Quinterz et al. (2001)
Collection and Sorting	Ni-Cd batteries	1.8	Rydh & Karlstrom (2002)
	Iron scrap old	0.7	ecoinvent (2010)
Shredding	Steel/tinplate	0.8	Grant et al. (2001)
	Misc. scrap	0.5	Woldt et al. (2002), Chapman and Roberts (1983)
	Misc. scrap	0.6	Jackel et al. (2002)
	E-scrap	0.9	ecoinvent v2.2
Mechanical Processing	Al packaging	2.7	Quinterz et al. (2001)
Magnetic Separation	Ferrous scrap	20	Chapman and Roberts (1983)
Sink-float	Al packaging	2.9	Quinterz et al. (2001)
Wire Separation	Cu wire	3	Chapman and Roberts (1983)
Drying	Misc. scrap	0.2 – 1.5	Chapman and Roberts (1983)
Pyrolysis/Incineration	Al packaging	2.4	Quinterz et al. (2001)
Sweating Furnace	Misc. scrap	2 – 10	Chapman and Roberts (1983)
Remelting	Al packaging	9.3	Quinterz et al. (2001)
	Al	5.0	Das et al. (2004)
	Fe	6.3	Schifo & Radia (2004)
All processes	Al scrap new	5.6	EAA (2008)
	Al scrap mixed	7.7	EAA (2008)
	Li-ion batteries	12	ecoinvent v2.2
	Ni-Cd batteries	4.9	Rydh & Karlstrom (2002)

The energy benefits of recycling depend on the metal and the technological context, and research into this topic has been conducted for several decades. Early studies were done in 1970s by Kellogg (1977) and Kusik and Kenehan (1978), which examined aluminium, copper, iron and steel, lead, nickel, stainless steel, tin, titanium, and zinc. At this time, many companies, industry groups, and local governments also started publishing figures on energy savings. These figures were generally quite close to those reported by independent analysts, as compiled by Powell (1983).

Since then, improvements in energy efficiency and development of new technology, as well as changes in prices, have shifted results. Researchers and industry analysts have continuously updated and expanded our understanding of the energy benefits of metal recycling, with a summary of results compiled in Table 4.4. Other environmental considerations related to metal recycling are discussed in Chapter 5.

Table 4.4

Ranges of energy savings of recycling for various ferrous and non-ferrous metals (adapted from Norgate, 2004).

Metal/Product	% Savings	References
Aluminium	90 – 97	Norgate & Rankin (2002), Gaballah and Kanari (2001), Quinkert et al. (2001), International Aluminium Institute (2011), Chapman and Roberts (1983)
Copper	84 – 88	Norgate and Rankin (2002), Gaballah and Kanari (2001)
Gold	98	ecoinvent v2.2
Lead	55 – 65	Norgate and Rankin (2002), Gaballah and Kanari (2001)
Magnesium	97	USEPA (1994)
Nickel	90	Norgate and Rankin (2002)
Palladium	92 – 98	ecoinvent v2.2
Platinum	95	ecoinvent v2.2
Rhodium	98	ecoinvent v2.2
Silver	96	ecoinvent v2.2
Steel	60 – 75	Norgate and Rankin (2002), Gaballah and Kanari (2001)
Stainless Steel (304)	68	Johnson et al. (2008), Eckelman (2010)
Titanium	67	Chapman and Roberts (1983)
Zinc	60 – 75	Norgate and Rankin (2002), Gaballah and Kanari (2001)

4.4 Future Developments of Metals-related Energy Use

Future energy requirements for primary metal production from ores will mainly be dependent on the following factors:

- Processing of lower ore grades will increase energy requirements.
- Smaller metal seams and higher overburden layers will increase energy requirements.
- Ores with higher chemical energy will increase energy for metal extraction.
- Remote deposits will require more transportation energy.
- Improvement of technology will decrease energy requirements.

Most of these factors serve to increase the energy required to produce a unit of metal, but it is not clear at the present time how strong the countervailing effect of increased exploration and technological improvement will be. With new technologies, will metal extraction in 100 years be more energy intensive than it is today?

4.4.1 Ore Grades and Energy Requirements

Ore grades, which specify the metal content in the ores, are an important factor for the energy requirement of some processes in the metal production chain. For most base metal ores, such as copper, a concentrate is produced at the end of the mineral processing stage with a relatively constant grade independent of the initial ore grade. As a result, the subsequent metal extraction and refining stages are essentially unaffected by ore grade. However, the energy for mining and mineral processing is inversely proportional to ore grade, due to the additional energy that must be consumed in the mining and mineral processing stages to move and treat the additional gangue (waste) material. This is illustrated in Figures 4.9 and 4.10 using modeled data for copper production, and in Figure 4.11 using actual data for nickel production. This latter Figure also shows the high degree of variability among mining circumstances in different locations, with the energy required to mine one tonne of contained nickel ranging over two orders of magnitude.

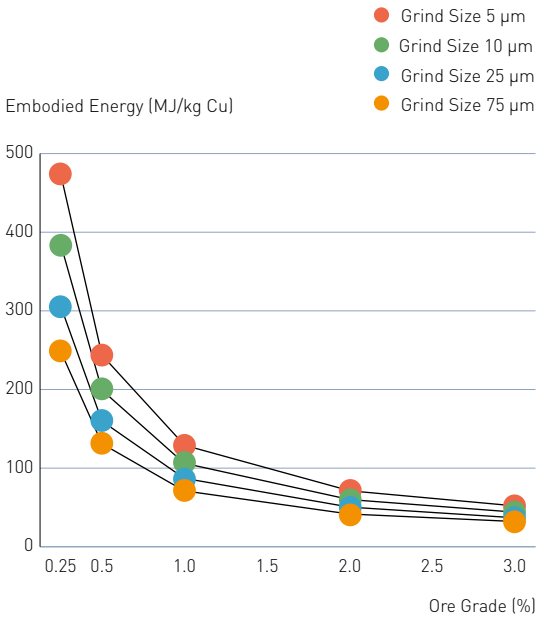


Figure 4.9

Effect of ore grade and liberation size on embodied energy for copper production (Norgate and Haque, 2010).

Figure 4.10

Effect of ore grade on stage-by stage energy consumption for copper production (Norgate and Jahanshahi, 2006).

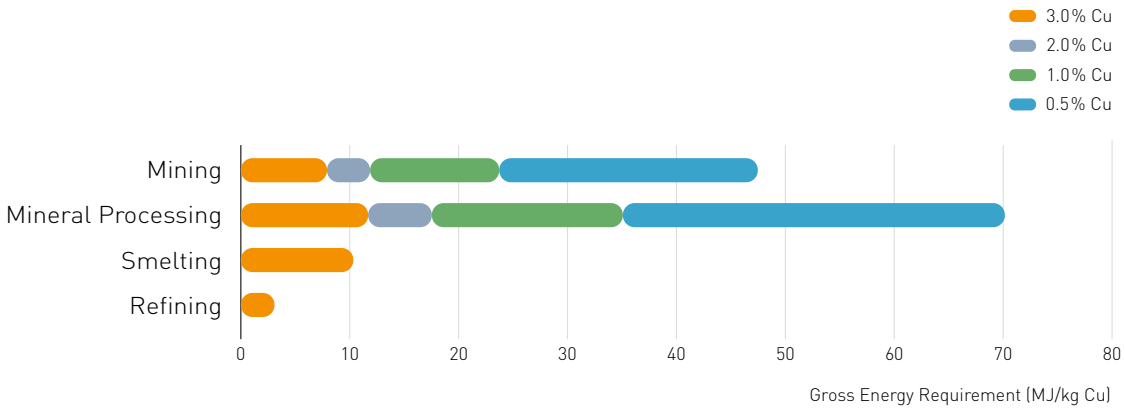
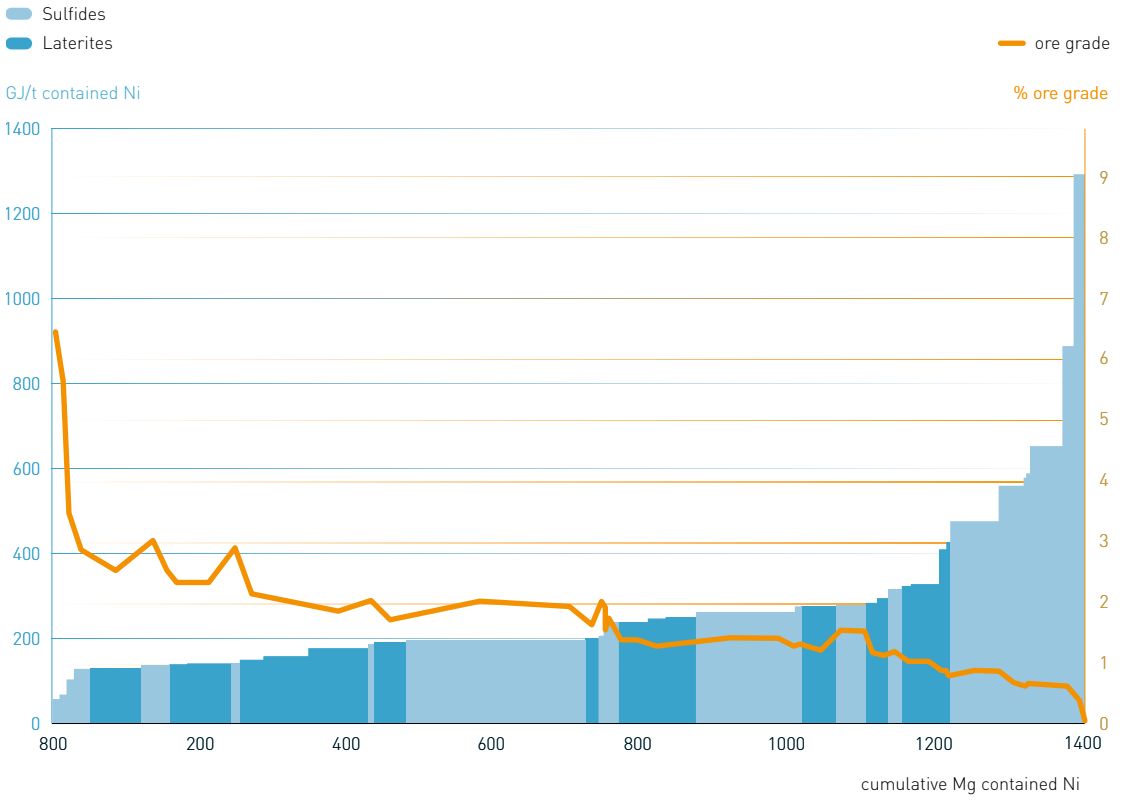


Figure 4.11

Effect of ore grade on energy expended for mining, milling and concentration at global nickel mines (Eckelman, 2010)



4.4.2 Ore Grade Reductions

Historically, the long-term trend in the grades of ores processed has declined for numerous metals, often substantially in the first half of the twentieth century and more slowly in recent decades, depending on the metal. In general, the synthesis of extensive production statistics remains relatively uncommon, although a range of recent papers have published data on trends for copper, uranium, gold, nickel and platinum group metals of varying historical lengths. There are a range of factors which need to be considered in understanding the drivers behind ore grade reductions, as these are crucial in any projection of the likely future trends in ore grades.

The ore grades processed at any given time are a complex function of available technology, prevailing prices, demand-supply balances, ore types, ongoing exploration success or sometimes even social or environmental constraints. In general, growing demand, improving technology and exploration success has continued to ensure reliable and relatively cheap supply (in real terms). This has allowed the gradual lowering of cut-off grades, the grade at which it is economic to process ore, and a substantial expansion of annual global production.

In Annex 5, examples are shown of declining ore grades for a number of metals, including a discussion on the specific reasons for that.

For copper, a recent paper by Crowson (Crowson, 2012) includes a remarkable range of data on Cu mining and ore grades for select mines and fields around the world. Some century-old Chilean and USA Cu mines are shown in Figure 4.12, with relative trends in ore grades over 30 years from initial production for several large Cu mines shown in Figure 4.13.

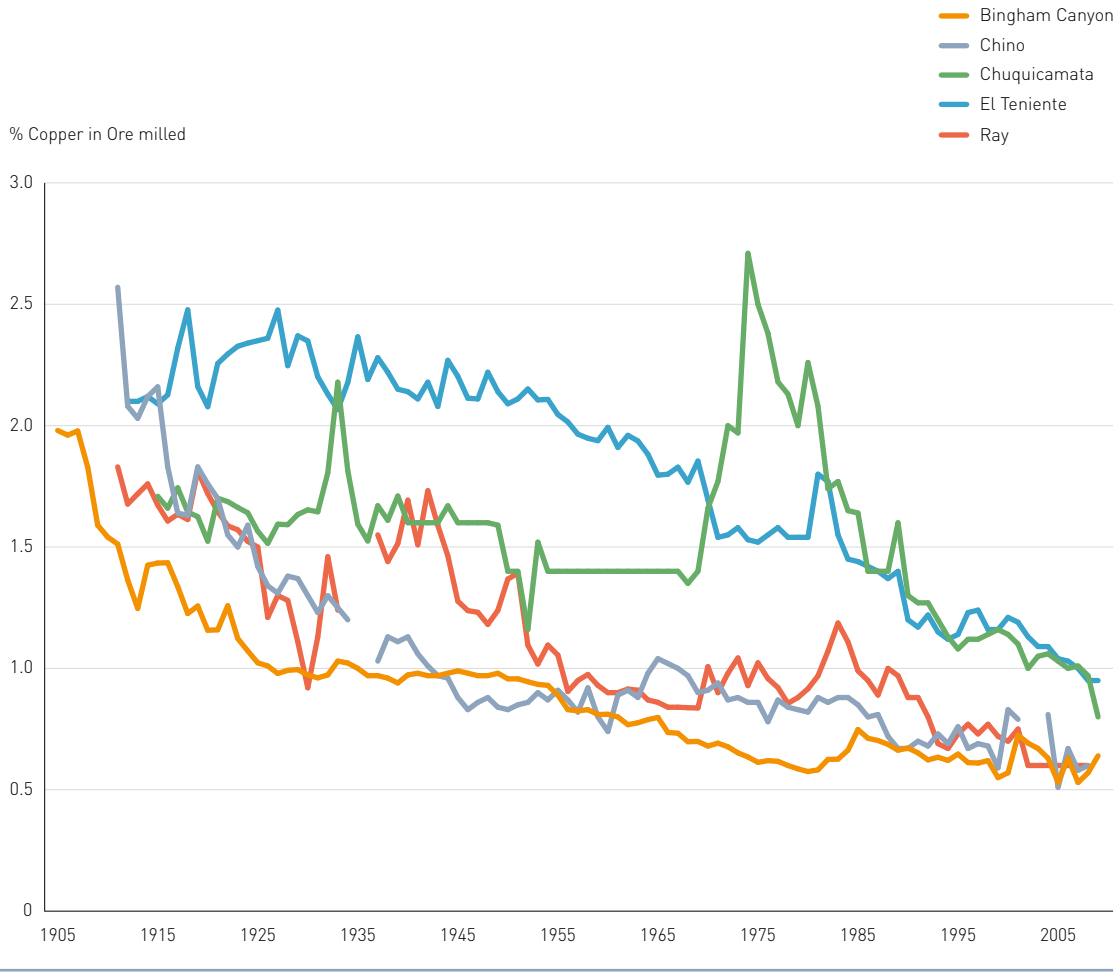


Figure 4.12

Long-term trends in ore grades at some giant Cu mines (Crowson, 2012)

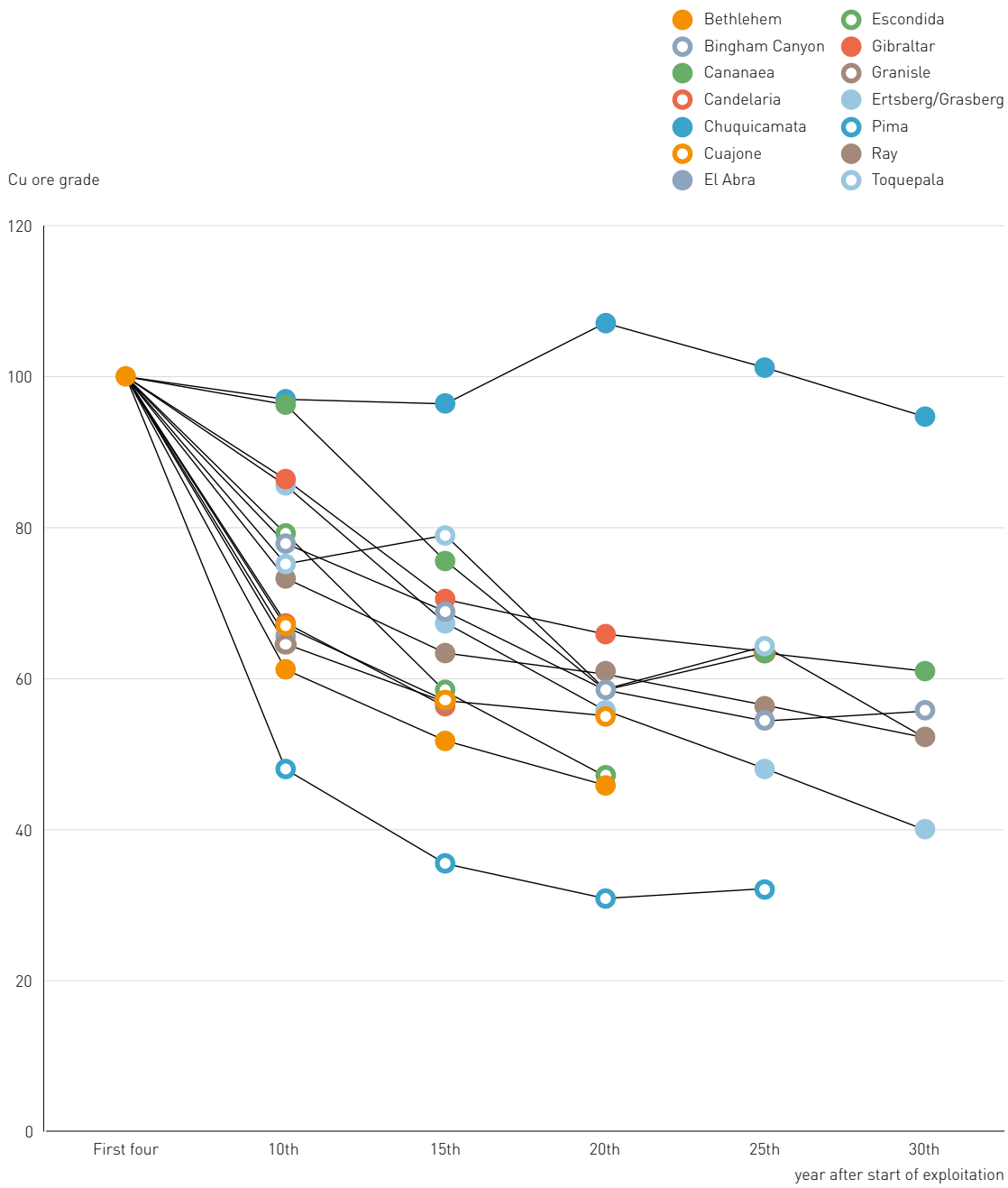


Figure 4.13

Approximate relative trends in Cu ore grades over 30 years from initial production for some major mines (adapted from Crowson, 2012)

As can be seen for the metals shown, there is a range of reliable data showing a general long-term decline in the average grades of ores being processed. These declines have been achieved based on the intersection of new technology (e.g. sulfide flotation, carbon-in-pulp, nickel laterites), growing demand (all examples used have generally strong and sustained growth patterns through the twentieth century, with excellent prospects for continued demand in the twenty-first century) and exploration success. The exploration success is driven primarily by two factors – discovery of new deposits and the inverse grade-tonnage relationship for most deposit styles. In many countries, there is still ongoing success in finding new deposits, either in new regions or in known mining fields (especially for major mining countries such as Australia, Canada, Chile etc). For most mineral deposits, as the ore grade declines, the size of the deposit increases – sometimes exponentially (eg. porphyry Cu deposits). As such, a lower cutoff grade for economic mining and processing leads to a substantial increase in contained metal(s) – as mine scale increases commensurately, this leads to a reduction in the unit cost of production due to economies of scale. Historically, the real price of many metals (and minerals) actually declined throughout the twentieth century as a result of these combined factors (see data from (Kelly et al., 2010).

Although complete statistical data are rarely published for reported resources by country for a variety of metals, it is common that these are lower grade than current processing (see Mudd, 2010a, b, 2012; Mudd & Diesendorf, 2010). The grades of new discoveries can be quite variable, as evidenced by uranium in Canada, but in general most new deposits are typically lower in grade. Although exploration can try and target 'high grade' ores and deposit types, the inverse grade-tonnage relationship dictates that to meet expected future demands for metals requires lower grade ores to achieve large scale production (which is effectively what is presently happening; eg. copper, gold). Overall, this further reinforces the view that ore grades will continue to decline, albeit more gradually in the future than in the past.

Finally, the remaining key aspects of ores being processed are the refractory nature and levels of impurities present. For some metals, such as lead-zinc or nickel, ore types are becoming more complex and difficult to process, due to factors such as fine-grained sulfide mineralogy or the increasing processing of Ni laterite ore. To enable development, this has been accompanied by new technology development, such as the fine grinding and specialised flotation technology for the difficult ores at the McArthur River zinc mine in Australia (see (Mudd, 2010a) or use of high pressure acid leaching technology for nickel laterite ores (see (Mudd, 2010b). At some sites, impurities such as arsenic prevent a deposit being developed (eg. Armstrong Ni mine failure, Australia; see (Mudd, 2010b), or places strict conditions on saleable products (eg. alumina in iron ore).

In summary, in almost every metals sector of the global mining industry for which reliable long-term data is available (as shown above), ore grade declines have been substantial throughout the twentieth century but are likely to be slower in the future. The only real anomaly is uranium, which shows an increase due to the rich Saskatchewan mines, though these are offset by the very low grade mines in Namibia. Increasingly, gradually more complex ore types are also being processed – commonly requiring more intensive processing to extract metals.

4.5 Measures to Reduce Metals-related Energy Use

4.5.1 Increasing Energy Efficiency in the Primary Metals Sector

Metal production facilities are extremely large installations that require significant capital investment. Older plants and process designs tend to be less efficient but they can be kept online for decades as newer, more efficient plants are built, which is one reason for the large variation in energy use in metal production around the world. In general, however, the overall energy intensity of metal production tends to decrease with time, as newer technologies are introduced and older ones are upgraded to be more efficient. In the 1980s, for example, the average energy used to produce one unit of steel in China decreased by more than 8 %, while other major producing countries experienced smaller reductions.

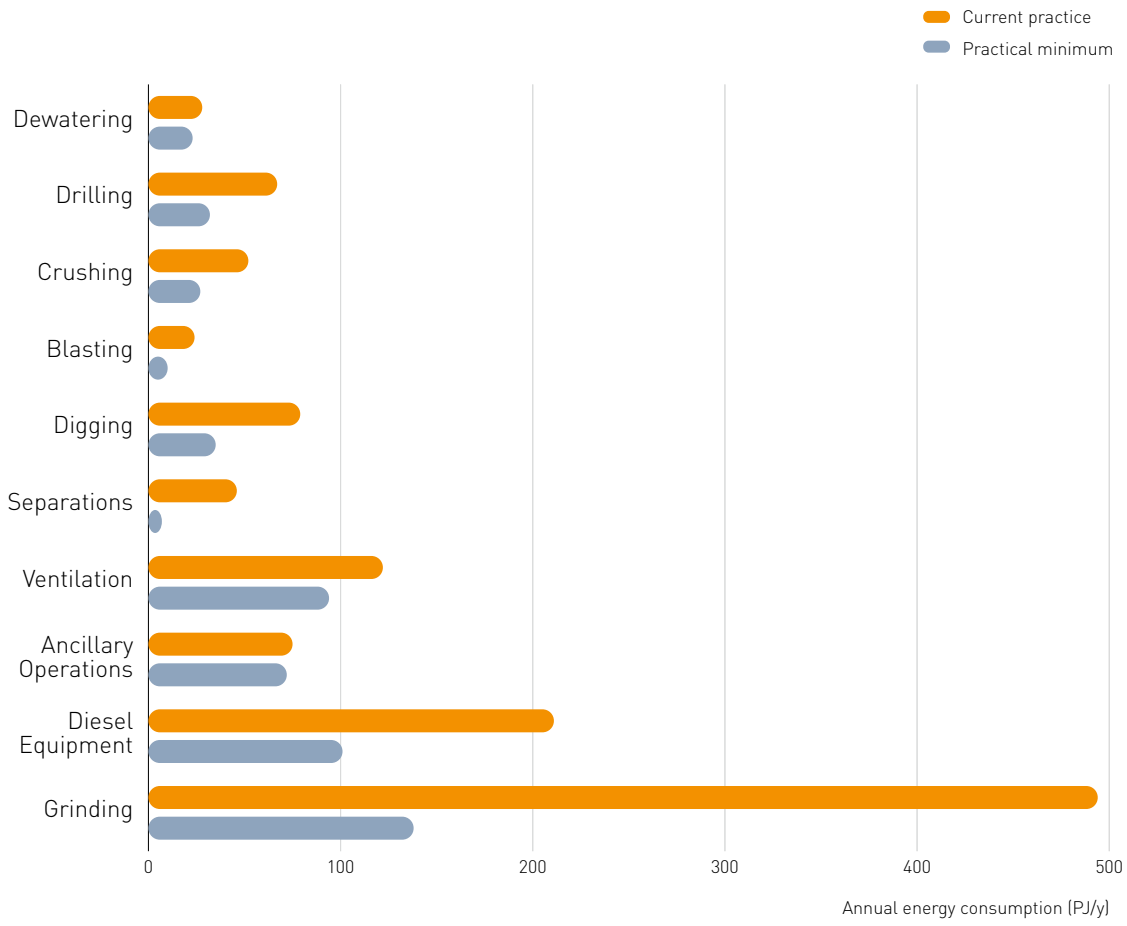
The metal extraction and processing stage has been repeatedly shown to be the most energy-intensive portion of metal production. Several research papers have examined the metals sector in major producing countries and asked how much energy could be saved if every country used the best technology available. For example, the U.S. steel industry might be able to reduce its energy consumption by 20 % in adopting the most efficient processes globally (Worrell et al., 1997).

While metal extraction and refining is the most energy-intensive process in the metal production life cycle, there are also many energy efficiency opportunities within the mining and mineral processing sector. Figure 4.14 shows the current annual energy consumption of this sector in the US, broken down into the various processing steps. The practical minimum energy consumption is also shown in this figure for the various steps for comparison, based on current technology.

It is apparent from this figure that comminution accounts for the majority of the energy consumed by this sector. Therefore in order to reduce the energy intensity consequences of decreasing ore grades (requiring more processing of waste rock per unit of metal), the emphasis should be on reducing comminution energy.

Figure 4.14

Current and practical minimum annual energy consumption for the US mining and mineral processing sector (Data from U.S. DoE, 2007).



Some approaches to reduce the energy used in comminution include:

- Comminute less material – ore sorting, pre-concentration, improved mining practices to reduce dilution by waste.
- Comminute more efficiently – optimizing the design of comminution circuits including process control, use of more energy-efficient comminution equipment, such as high pressure grinding rolls, stirred mills.
- Do less comminution – less liberation of the valuable mineral to achieve higher recovery at the expense of lower concentrate grade (more metal and gangue to be separated in smelting and refining stages).
- Direct processing of ore – this is the extreme case of the preceding approach where no (or very little) comminution is done – either pyrometallurgically or hydrometallurgically.
- More comminution in the blasting (mining) stage.

Current opportunities for reducing future energy consumption include (Albanese & McGagh, 2011):

- New technologies for reducing grinding and comminution energy.
- More efficient conveyor and (automated) transportation systems.
- Improved ventilation systems for underground mines (or reduced ventilation in automated mines).
- Advances in mineral flotation and concentration.
- Development of in-situ leaching processes.
- Improved on-line analysis to improve accurate enforcement of cut-off grades.
- Underground or in-pit sorting to reduce the amount of material moved.

Some of the current technology development work of large mining companies in the above areas is aimed at achieving step-change reductions in energy consumption. One of the most advanced of these approaches is the development and application of more energy-efficient comminution equipment. There are several new technologies which may offer energy savings if incorporated optimally into comminution circuits. Two of these are stirred mills and high pressure grinding rolls (HPGR):

- High Pressure Grinding Rolls – energy savings ranging from 15 to 30 per cent compared with former comminution circuits have been achieved with industrial machines grinding cement clinker and limestone. The broader use of HPGR for metalliferous minerals has only been considered more recently. Initial concerns over wear rate of the rolls have been addressed, and as a result there are strong signs of increasing interest particularly in the processing of gold, copper and iron ores.
- Stirred Mills – three stirred mill types have gained industry acceptance for fine and ultra-fine grinding duties; these are the tower mill, the Isa Mill and the detritor mill. The first two mills are vertical stirred mills with steel spirals and long pins respectively to agitate the mill charge, while the latter mill is a large horizontal stirred mill with discs as stirrers. It has been reported that stirred mills are up to 50 % more energy-efficient than conventional ball mills for products finer than 100 µm.

It is unclear at this point how the two opposing trends for primary metal production described in this section – increasing energy use from declining ore grades and decreasing energy use from efficiency measures and advances in technology – will balance each other in the future. In the medium-term, demand for primary metals seems unlikely to decrease in any significant way, and so energy use in the mining and metal extraction sectors will continue to be an important environmental consideration.

4.5.2 Increasing Secondary Production and Improving Material Efficiency

From Section 4.3, it is clear that secondary production of metals is much less energy intensive than primary production, with energy savings ranging from 55 % (lead) to 98 % (palladium). An obvious way to reduce energy use related to metals production is therefore to increase secondary production, focusing on sources of scrap, such as new scrap from manufacturing and fabrication operations, that do not require energy-intensive sorting and separation steps. Options for this are discussed in Chapter 5. Other measures such as direct reuse of metals, for structural applications for example, or recycling without melting will significantly reduce the energy use associated with secondary metal production (WellMet2050). As the use of metals and the use of energy are linked through the concept of embodied energy, material efficiency measures for metals may also save energy through designing metal products with longer lifetimes, reducing losses in production, decreasing the use of metals to provide a giv-

en service, substituting one material for another (in general it takes more energy to produce metals than it does to produce ceramic and plastic materials that may substitute for them), or by providing the service in an altogether different way. Several of these options are discussed in Chapter 6.

4.6 Conclusions

The energy use related to primary metals production is considerable, making up nearly 20 % of all industrial energy use globally, and 7 – 8 % of the total global energy use. The gross energy requirement (GER) of primary production varies from 20 MJ (steel) to 200,000 MJ (platinum) per kg of metal produced. This energy requirement is, among others, dependent on the ore grade, the concentration of the metal in the ore. If ore grades decline, the energy requirement increases exponentially. A trend of declining ore grades is currently visible for some metals, such as gold, copper and nickel. For others, it is expected to arise in the coming decades. The reasons for this downgoing trend are various. Technological progress, making it possible to mine lower grade ores in an economically viable way, is one. Another is the availability of high-grade ores, which usually is much lower than low-grade ores. Also, there is a clear linkage with the market scarcity and pricing issue, which is not debated in this report but is a topic of some of the other reports of the Global Metal Flows Working Group.

Improvements in metal mining and processing technology act as an opposing force to rising energy use in the mining and metals sector. Process improvement using currently available technology can increase energy efficiency considerably. A maximum of a factor 2 – 20 energy efficiency improvement is theoretically available, not based on present technology. Future technological developments will realize some of this potential.

Additional energy savings can be realized through increased efforts in recovering and recycling metals. Secondary production requires significantly less energy than primary production. While secondary sources will not completely satisfy society's demand for metal in a world where cities and infrastructure are growing fast, for nearly every metal there is considerable potential for increased recovery. Improving the management and processing of secondary metals will improve the energy efficiency of the metals sector overall.

5. Impacts Related to the Production and Use of Metals

Authors: Gavin Mudd, Terry Norgate, Markus Reuter, Ladji Tikina, Sonia Valdivia

Minimizing the creation of residues and various environmental footprints is the objective of the metals processing and recycling industries. This chapter is divided into two sections: the first discussing various impacts of the primary metals processing industry (i. e. link between mining and metal production) and the second discussing recycling (i. e. link between product design, end-of-life and metal/energy production). It is the endeavour of the metal industry to optimize the use of all materials, metals, alloys, etc., minimizing the ultimate residue creation, implying that flue dusts, sludges, slags, slimes etc. are finally dumped if they have no present economic value. In other words, a key objective in materials and metals processing is resource efficiency.

It is the innovation of the metals processing industry (primary, secondary and recycling industries) that squeezes the last bit of metal from any material, leaving behind as benign as possible material to be dumped, while minimizing the energy consumption. Minimization of energy is implied here to be relative to the amount minimally and thermodynamically required to produce metal from primary and secondary/recycling sources. This chapter is based on the understanding that minimizing systemic losses of resources is constrained by thermodynamics as well as economic considerations. Industrial processes require a minimum of energy to run. Reducing energy and materials losses in these processes may at one point become economically unsustainable, long before the thermodynamic minimum is reached. (Meskers et al., 2008).

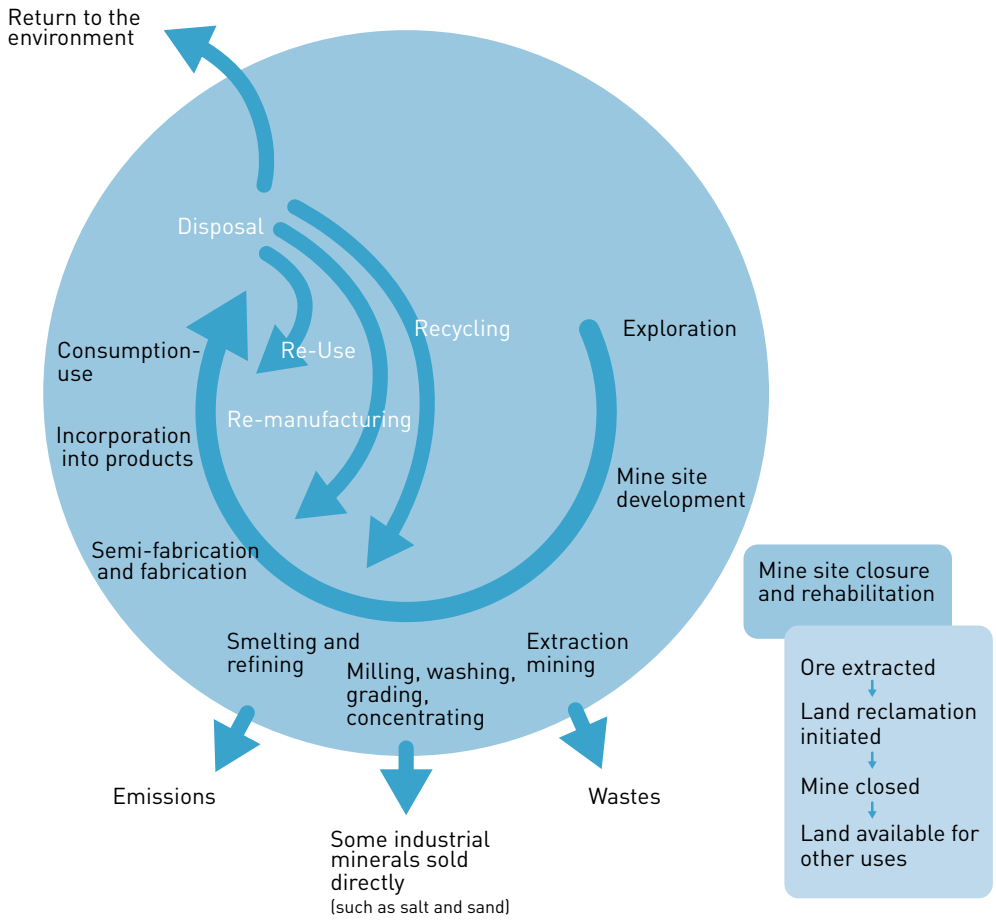
5.1 Impacts of Mining and Primary Extraction

Mining and metals extraction is typically a cyclical activity, starting with exploration for economic mineral deposits, development and operation, finishing with closure and rehabilitation and leading back to exploration for the next deposit. Furthermore, given that most metals can be recycled after use; further links can be made in the overall cycle. A conceptual view of the life cycle for minerals and metals is shown in Figure 5.1.

The primary aspects of environmental impacts for each of the primary metal extraction stages are summarised in Table 5.1, highlighting the importance of sound environmental monitoring and assessment. Further detailed reviews of each of these stages can be found in a variety of papers, reports and studies, most notably Da Rosa (1997), IIED & WBCSD (2002), Spits & Trudinger (2008), Kempton et al. (2010).

Figure 5.1

The Minerals Cycle (IIED & WBCSD, 2002).



The environmental impacts of the mining and extraction of metals therefore need to be considered across all of these stages of the mining cycle. In general, the move from exploration to development and operations leads to considerably greater environmental impacts, with the smelting stage a particularly challenging stage. Following rehabilitation of the original mine site, impacts should reduce significantly, assuming the works are effective and sustainable.

The major issues revolve around water (consumption and quality aspects), mine wastes (tailings and waste rock), energy sources (direct such as diesel, and indirect such as coal-fired electricity) and air emissions (sulfur dioxide, greenhouse gases, dusts and particulates). These will each be briefly reviewed.

5.1.1 Solid Waste Issues

One of the major legacies associated with most of the long-term environmental impacts of mining and metal extraction is mine waste. There are two main types – tailings and waste rock. Tailings are the finely crushed and processed ore which has had the metal (or metals) of interest extracted, and are normally discharged by slurry pipelines into engineered impoundments (or commonly called tailings dams). Waste rock is the rock which has no economic value of metal(s) of interest, but which is extracted during the mining process and requires disposal and management. Underground mining typically has a low ratio of waste rock to ore (less than 1:5), while open cut mining has a high ratio (typically greater than 3:1). Mining produces large amounts of waste rock because the ore is only a fraction of the total volume of material mined. Waste rock disposal areas are commonly one of the most visible aspects of a surface mine, and the disposal of large amounts of waste rock poses tremendous challenges for the mining industry.

Given the strong trend towards large scale open cut mines over the past 60 years, combined with growing mineral production, the amount of waste rock from mining has begun in the case of some metals to grow exponentially around the world. Some individual mines now mine in excess of 300 million tonnes (Mt) of waste rock annually (along with some 80 – 120 Mt of ore), such as Codelco Norte and Escondida in Chile and Grasberg in West Papua. A graph of the minimum reported waste rock for metals in Australia is shown in Figure 5.2, although not all waste rock is reported in the copper and gold sectors. Unfortunately, no waste rock data is reported for the nickel, iron ore and lead-zinc-silver sectors – despite waste rock from iron ore mining likely to be of the order of a billion tonnes per year. In addition, national totals for Canada are included in Figure 5.2.

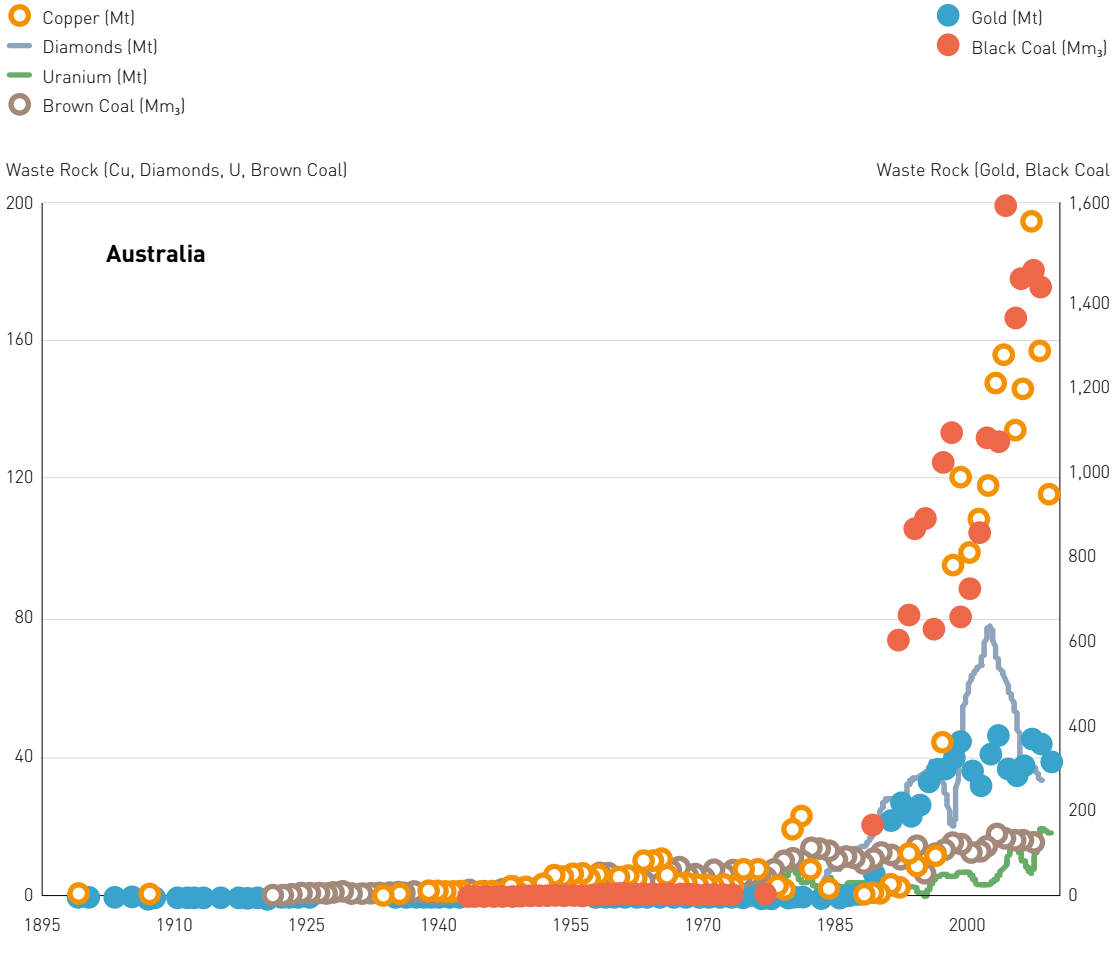
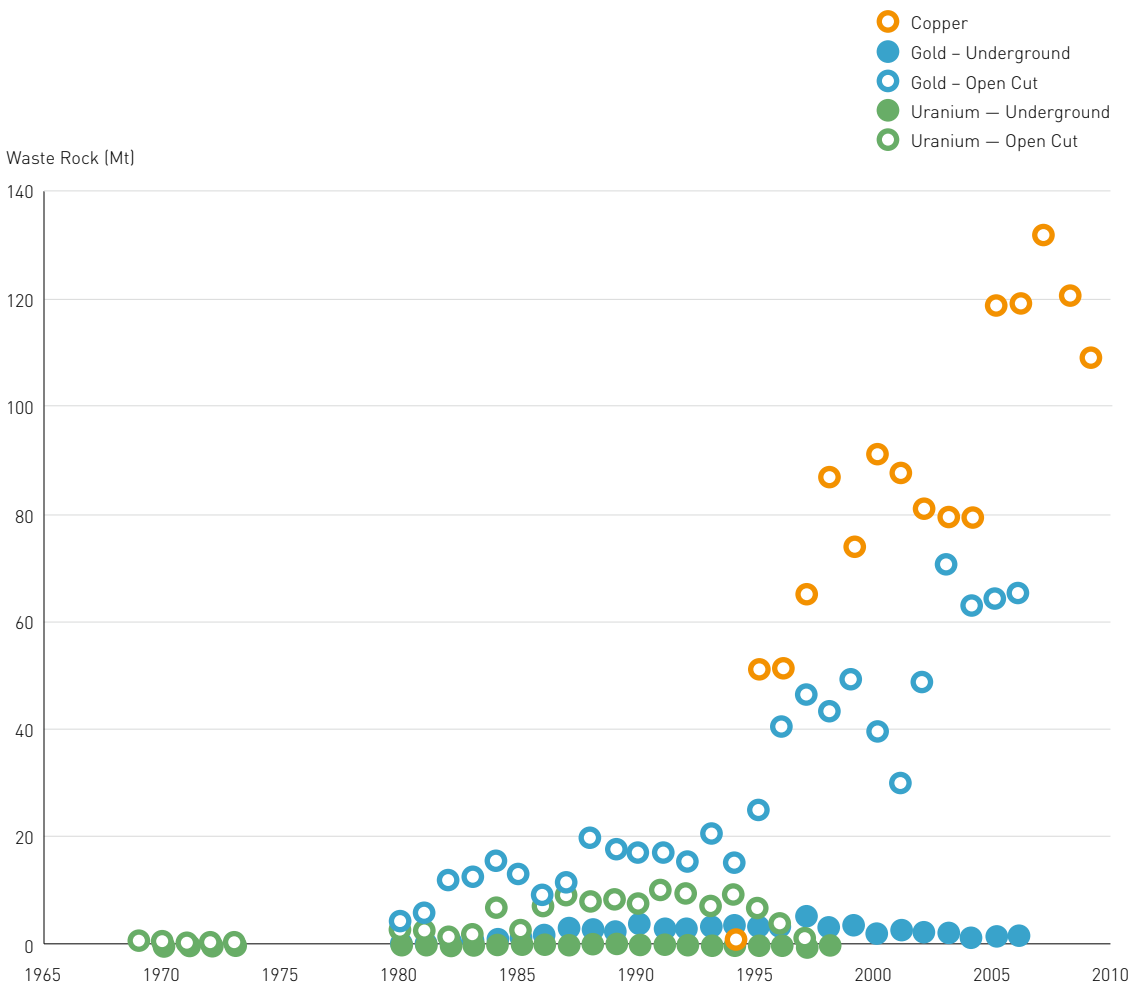


Figure 5.2a

Minimum reported waste rock for some metal sectors of the Australian mining industry (Data from Mudd, 2010).

Figure 5.2b

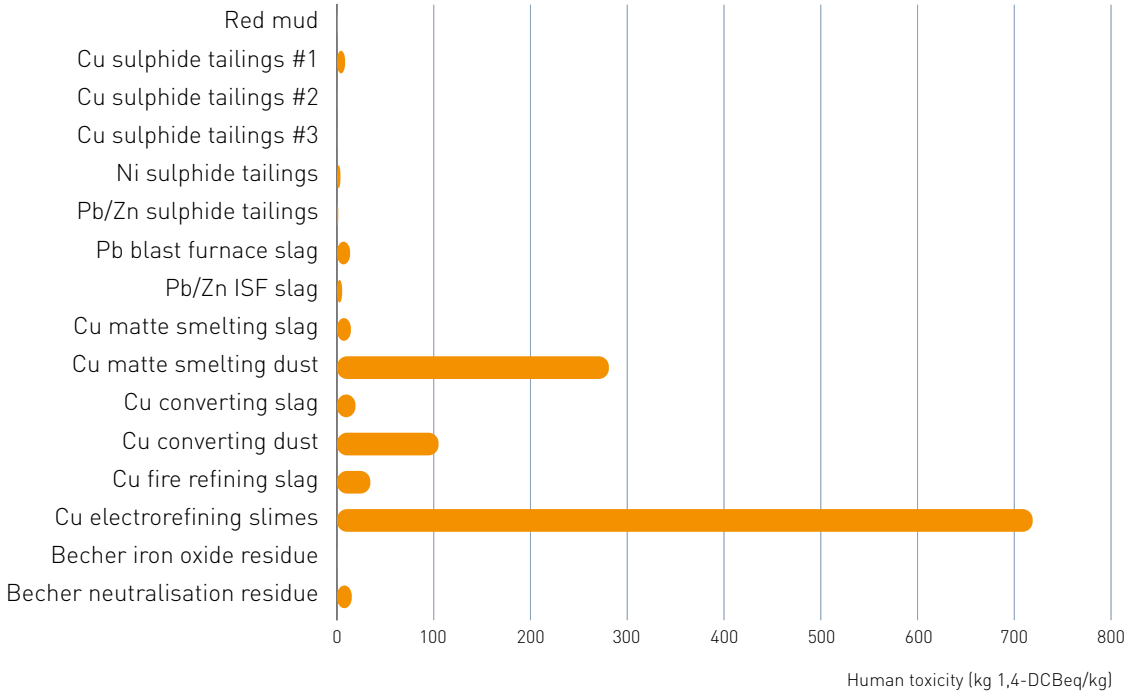
Canadian waste rock by underground/ open cut mining (right) (Data from Natural Resources Canada, var.).



The tailings dams associated with some of the largest mills, such as open pit copper mines can cover areas of tens of square kilometres and be a hundred metres deep. Some tailings dams present reclamation challenges even more significant than those presented by waste rock (Hudson et al., 1999). Tailings may have concentrations of sulfides that are greater than those in the waste rock, and furthermore, because tailings are composed of small mineral particles resulting from the milling operation, they can react with air and water more readily than waste rock. Therefore the potential to develop acidic conditions in sulfide-rich tailings is very high. Tailings are saturated with water upon disposal, and if not prevented or controlled, acidic waters (a form of acid mine drainage – see later) can seep from their base.

Figure 5.3

Human toxicity potential of various metal production solid wastes (Norgate and Haque, 2009[a])



a noting that many of these intermediate products are further processed due to their economic value transforming them into benign final materials.

Seepage from tailings can be prevented or minimised by placing an impermeable barrier, such as clay, at the bottom of the dam before tailings disposal. If tailings dams are not satisfactorily stabilised, erosion by both wind and water can take place (International Commission on Large Dams, 2001). Because tailings contain high volumes of fine-grained material, wind can easily pick up and transport dust from the surface of a tailings dam, which can give rise to human toxicity and eco-toxicity impacts. If tailings are eroded by surface water runoff which then enters waterways, metallic minerals can be dispersed into these waterways.

Slags produced in the smelting and refining stage of the metal life cycle are metal-bearing and may contain elevated concentrations of metals, including lead and arsenic. The actual composition and form of slag will vary depending on the type of ore and smelting technology used. Because of their glassy nature, much of the metals contained in slags are not bio-available, and slags are therefore not generally as significant a potential source of metals released into the environment as mine wastes and tailings. The main problems with slags are the physical disturbances and aesthetic impacts associated with large slag piles that cannot support vegetation (Hudson et al., 1999). Particulate matter (dust) in smelter stack gas emissions may contain metals and have an adverse effect on human health.

The human toxicity impacts of a number of smelting and refining slags and dusts are compared with various mineral processing solid wastes (all emitted to soil) in Figure 5.3. It should be noted that theses results also take into account fate in addition

to toxicity. However, despite being labelled as toxic in Figure 5.3, some wastes such as copper slimes are still valuable and may be processed further to recover metal. This example serves to illustrate that if wastes have value and are processed further such that their toxicity is mitigated, they can be considered as intermediates rather than wastes. A waste is only a waste if it potentially ends up in a dump because it has no economic value.

5.1.2 Land Issues

Mining can cause physical disturbances to the landscape, the most obvious of which is generally the removal of vegetation, which alters the availability of food and shelter for wildlife. Open pit mining disturbs larger areas than underground mining, and thus has larger visual and physical impacts. Soils barren of vegetation are particularly susceptible to erosion, which can lead to further damage of the environment. Wind erosion in particular can cause particulate matter (dust) to become airborne and have an adverse effect on human health. Some of the land impacts of open cut mining are:

- Topography and land scenario changes due to digging of open pits and dumping of overburden rock mass in the form of heaps.
- The land use in the surrounding areas may be affected due to the impacts of mining on the water system.
- The drainage pattern of the surface undergoes a change due to the alterations in the surface topography.

While some land impacts of underground mining are:

- Changes in topography and drainage pattern, if subsidence occurs.
- Disturbances in the effective land use due to changes in the surface, sub-surface and underground water bodies.

5.1.3 Water Issues

Mining and metals production are a large consumer of water, as well as having the potential to cause major impacts on groundwater and surface water resources. In general, water is required for processing ore, dust suppression and potable purposes. Depending on the scale, water consumption for mining projects can easily be in the order of gigalitres (GL) per year (even > 10 GL/year). Furthermore, given the large area of many mining projects, careful management of runoff water is often critical in minimising environmental impacts of any offsite discharges. To achieve this, mines often include large water or retention ponds to store potentially contaminated runoff waters, which can then be used in dust suppression or processing (depending on specific mine factors). A summary of typical water consumption involved in processing is given in Table 5.2, with an example of the relationship between processing water and ore grade shown in Figure 5.4. Operations such as grinding, flotation, gravity concentration, dense medium separation and hydrometallurgical processes all consume substantial amounts of water. Figure 5.5 shows the annual embodied water results for metal production in Australia broken down into the three main processing stages. This figure clearly shows that the mineral processing stage makes the greatest contribution to the embodied water for metal production. Therefore, considerable attention should be given to the minimization of water usage, implying that detailed water system analyses and process control solutions should be part of any mining and mineral producing company. Of importance is not only water usage but also the quality of the water used.

Table 5.1

Reported water consumption during mineral and metal processing (Mudd, 2008) with data derived from the sustainability reports of 36 companies in 20 countries for a period ranging from 1 to 15 years.

Mineral/metal	Total number of years of data	v. ore throughput (e. G. kL/t ore)		v. ore grade (e. G. kL/t metal)	
		Average	SD	Average	SD
Bauxite (kL/t bauxite)	17	1.09	0.44	–	–
Black coal (kL/t coal)	18	0.30	0.26	–	–
Copper (kL/t ore; kL/t Cu)	48	1.27	1.03	172	154
Copper-gold (kL/t ore; kL/t Cu)	42	1.22	0.49	116	114
Diamonds (kL/t ore; kL/carat)	11	1.32	0.32	0.477	0.170
Gold (kL/t ore; kL/kg Au)[a]	311[a]	1.96[a]	5.03[a]	716[a]	1,417[a]
Zinc ± lead ± silver ± copper ± gold (kL/t ore; kL/t Zn ±Pb ± CU ±)	28	2.67	2.81	29.2	28.1
Nickel (sulfide) (kL/t ore; kL/t Ni)	33	1.01	0.26	107	87
Platinum group (kL/t ore; kL/kg PGM)	30	0.94	0.66	260	162
Uranium (kL/t ore; kL/t U_3O_8)	24	1.36	2.47	505	387

[a] If one mine is removed from the data (five points), which ranges from 28 to 48 kL/t ore and 5,800 to 9,442 kL/t Au, the average and standard deviation become 1.372 and 1.755 kL/t ore and 609 and 1,136 kL/kg Au, respectively.

Figure 5.4

Reported water consumption during base metal and uranium ore processing versus ore grade (Mudd, 2008).

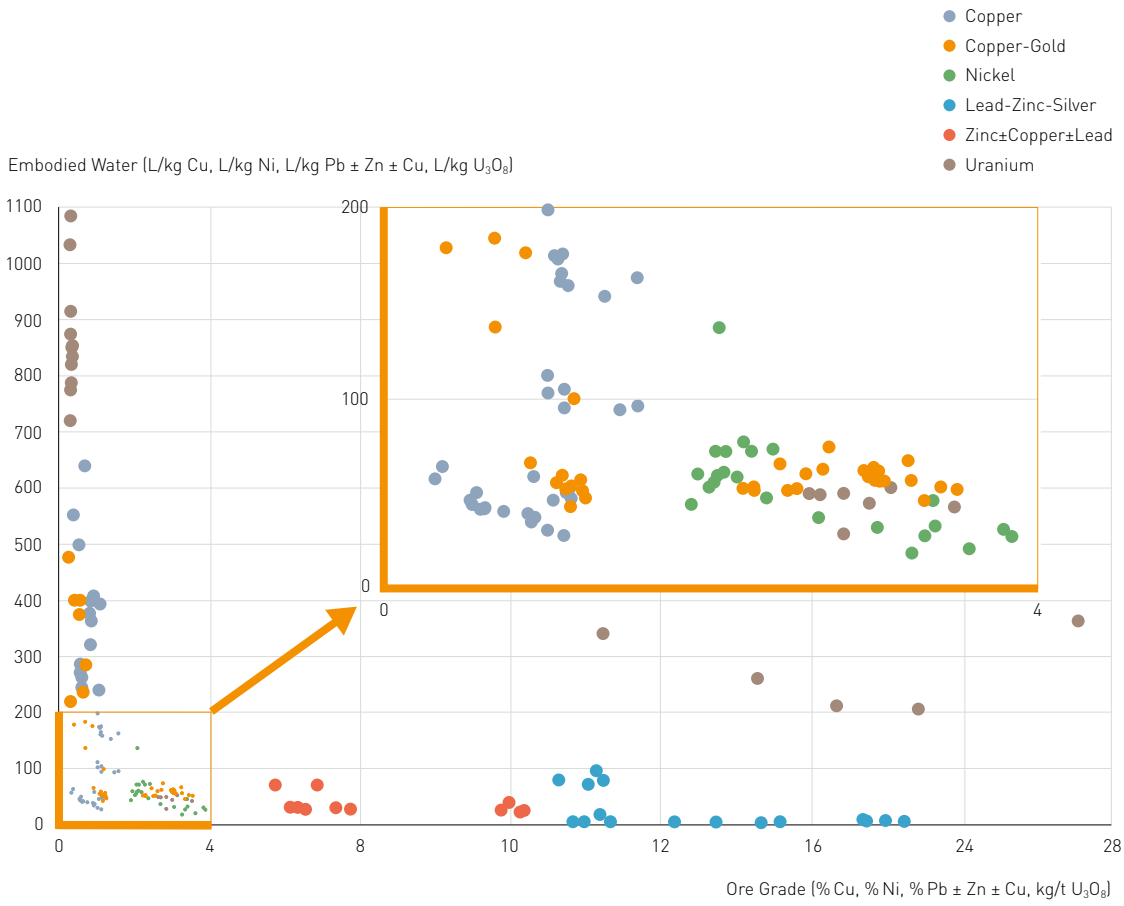
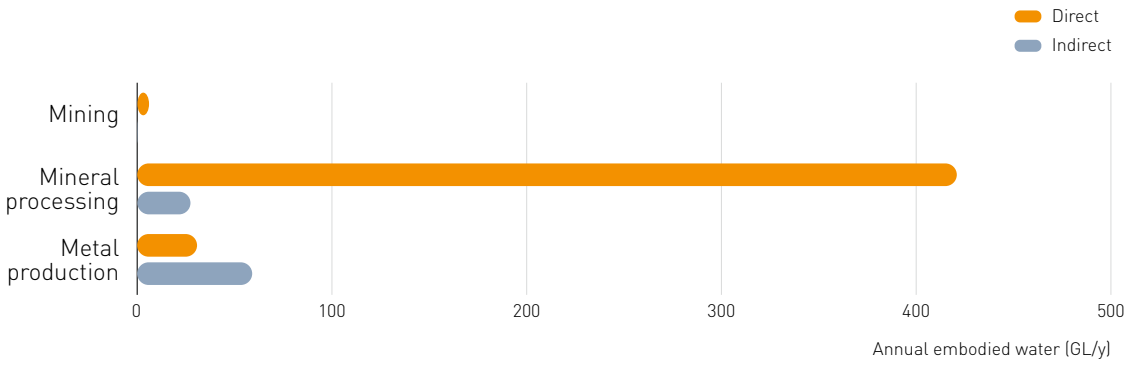


Figure 5.5

Contribution of processing stages to annual embodied water for metal production in Australia (Norgate and Aral, 2009).



The majority of water used by the minerals industry is sourced from purpose-built dams, rivers, lakes and groundwater sources of several kinds, including artesian water. Sometimes the supply is located some distance from the mine site, requiring the use of purpose-built pipelines. If operations are small scale ones, water may be supplied by trucks with additional CO_2 emissions being generated. Mining operations may have a significant impact on local and regional groundwater systems (Hair, 2003) particularly when mining progresses below the groundwater table, creating a groundwater "sink" and altering the local flow regime. In localities deficient in surface water (e. g. when evaporation

rates exceed rainfall or surface water storages (dams) are not reliable) operations may rely on artesian waters that may be sourced a considerable distance from the mining operation itself. Many mining operations use water unsuitable for agriculture and re-use water within the constraints imposed by quality requirements, water availability, and discharge considerations. On the other hand, the location of some mining operations means that they must compete with other demands such as agriculture and communities on the water supply.

One of the most critical areas of water is the potential impacts mining and metal extraction can have on water quality. These impacts can be due to direct discharges of contaminated water (such as retention ponds or free runoff from the mine area), seepage from ponds or tailings dams, or seepage from mine wastes. If there are sulfidic minerals contained in the ore and/or waste rock, when these are exposed to an abundance of water and oxygen in the surface environment they will oxidise to form sulfuric acid – which in turn leaches out numerous metals and salts. The leachate or seepage from sulfide oxidation is commonly known as acid mine drainage or AMD, and is acutely toxic to aquatic ecosystems. In some circumstances, however, there are alkaline rocks present and the leachate may be circum-neutral (i.e. pH ~6 to 8), and thus the more general term used for all such polluted drainage from mining is called 'acid and metalliferous drainage' (AMD) (Taylor and Pape, 2007).

As already discussed in Chapter 3, the generation of AMD is a major, long-term problem for all sulfidic mine wastes, since the oxidation processes can last up to tens, hundreds or even thousands of years (Kempton et al., 2010). Around the world there are countless former mines which closed long ago but are still leaching AMD into adjacent surface waters or infiltrating into groundwater. Examples of AMD are shown in Figure 5.6.

Figure 5.6

Examples of acid and metalliferous drainage impacts on surface water resources: former Rum Jungle U-Cu mine, Northern Territory (Photo courtesy Gavin M. Mudd, July 2007) (top left); Boac River, downstream of failed tailings dam at former Marinduque Cu mine, Philippines (Photo courtesy Oxfam Australia, March 2004) (top right); severe AMD pollution from the former Mt Oxide Cu mine, Queensland (Photo courtesy MiningLegacies, 2008); ongoing AMD pollution from former coal mines in the Neath-Greta area, Hunter Valley (Photo courtesy Col Maybury, June 2006) (bottom right).

If not properly managed, erosion of mineralised waste rock into surface drainages may lead to metal-bearing sediments in waterways. This situation can be potentially harmful, particularly if the metals are "bioavailable" (i. e. in a chemical form that allows them to be easily released from the sediments into water). High sediment concentrations increase the turbidity of natural waters, reducing the light available to aquatic plants for photosynthesis. High sediment loads can also decrease the depth of streams, resulting in greater risk of flooding during times of high stream flow.

Metal pollution is caused if typical heavy metals like arsenic, cobalt, copper, cadmium, lead, silver and zinc contained in minerals or used to separate the target product (e. g. mercury used to extract gold) come in contact with water. Metals are leached out and carried downstream. Leaching can be accelerated by low pH conditions such as are created by AMD. Marine pollution occurs if sub-aqueous tailings disposal is implemented; this practice is illegal in many countries but it is still used in several countries of the developing world. Pollution of groundwater resulting from leakage of metals and chemicals disposed, e. g., in tailings, can also affect the ecosystems and the health of the local population if not properly controlled. Pollution problems have the potential to go beyond the drinking water supply, and also affect the food quality. Erosion caused by disturbed soil and rocks as a result of construction activities and the operation of open pits, tailings and landfills can contribute to significant negative environmental impacts if not controlled. It includes the possible collapse of river banks, destabilization of structures such as bridges and roads and cause influx of water and substantial amounts of sediments flowing into streams, rivers and lakes. Landslides and coastal erosion are other potential negative impacts from erosion and sedimentation.

In-situ mining (i. e. the extraction of metal(s) from ore deposit by leaching into a chemical solution) is increasingly being used in the mining industry. For an ore deposit to be amenable to in-situ mining it must occur within permeable materials, such as sands or sandstones, be saturated (i. e. within an aquifer or groundwater system), and be confined above and below by low permeability materials (such as clays or shales). Such a geological configuration gives rise to the potential for escape of these solutions outside the ore zone, which can lead to contamination of surrounding groundwater systems (Mudd, 1998) The control of movement of the chemical leaching solution (lixiviant) within the aquifer is the most critical part of the in-situ mining process.

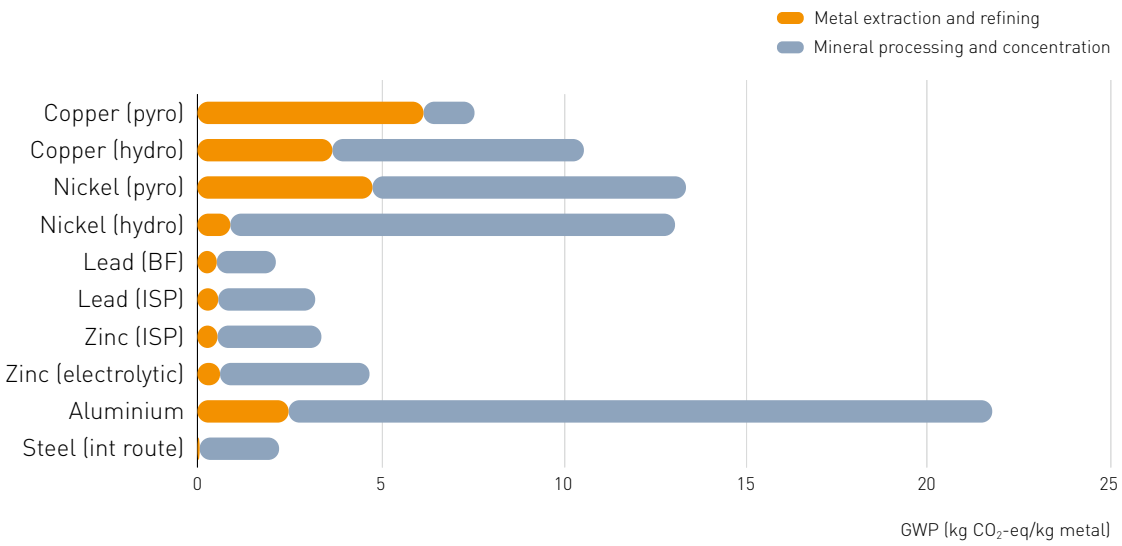
5.1.4 Air Issues

The issue of climate change and global warming has focused attention on greenhouse gas emissions associated with the use of fossil fuels. The minerals and metal production sector uses fossil fuels as both direct and indirect energy sources (e. g. diesel for mining operations, electricity for crushing and grinding, natural gas, coal and oil in smelting) as well as a reductant (e. g. coal and coke in smelting). The life cycle-based greenhouse gas emissions (expressed as Global Warming Potential) for the production of various metals are shown in Figure 5.7. New and emerging technologies to reduce the energy consumption of the various metal production life cycle stages discussed in the previous chapter will have a parallel effect on the greenhouse gas emissions from these stages as well.

Figure 5.7

Greenhouse gas emissions for the production of various metals, Australian situation[a] (Norgate et al., 2007).

a Note that the Australian energy mix contains a large share of coal-based power generation. In other countries, this situation may be different and a high energy use may not automatically translate into high GHG emissions.



The main air issues with regard to smelting are related to the smelter stack emissions. Smelter stack gas emissions may contain particulate matter with metals such as arsenic, copper, cadmium, antimony, zinc, chromium, lead and selenium. In the past, sulfur dioxide has been the most common emission of concern from the smelting of metal sulfide concentrates, because it reacts with atmospheric water vapour to form sulfuric acid or "acid rain". The acidic conditions that develop in the soils where the acid rain precipitates can harm existing vegetation and prevent new vegetation from growing. Most modern smelting plants use processes and technologies that drastically reduce particulate and sulfur dioxide emissions. For example, many plants now capture these sulfur dioxide emissions in acid plants with recovery efficiencies as high as 99.9 percent of the sulfur emitted (Hudson et al, 1999). In some cases, the emissions from older smelters may have affected human health, with elevated levels of lead in blood being measured in residents of some communities located near lead-zinc smelters. Here, too, a reduction in smelter emissions has been observed to lead to reduced lead blood levels (Canadian Ministry of Environment, 2009).

5.1.5 Biodiversity Issues

Biodiversity is best understood as the living world's capacity to change – variability – and the wealth of biological forms and processes that derive as a result – variety. Biodiversity is therefore found everywhere, albeit in different concentrations and configurations. Measuring the impacts of mining on biodiversity, including marine biodiversity, and defining their effects and implications presents certain challenges. The key question is: which proxy is best, as not all species are of equal value. Some species will increase, others will decrease, and some will not change at all following mining disturbance (assuming the entire ecosystem is not being removed) (IIED & WBCSD, 2002). The mining and minerals sector typically occupies less than 1 % of a country's territory (EEA, 2010) and is not necessarily the most important influence on biodiversity in a particular region. Figures released by the National Parks and Wildlife Service in Australia (Leigh and Briggs, 1992) suggest that mining was responsible for 1.1 % of presumed extinctions of endangered plant species, compared with 38.2 % attributed to grazing and 49.4 % to agriculture. Nevertheless, mining does almost always have the potential to significantly impact on biodiversity, and in some cases the effects can be irreversible.

As noted earlier, the removal of vegetation from a mine site can alter the availability of food and shelter for wildlife. Increased acidity in waterways as a result of unabated AMD can destroy living organisms. Many fish are highly sensitive to even mildly acidic waters and cannot breed at pH levels below five. Furthermore, juvenile fish are more sensitive than adult fish, and the presence of some metals in the water may affect critical reproductive and growth stages of fish (Maranda et al., 2003).

Sediment arising from erosion of waste rock piles and tailings can clog riverbeds and smother watershed vegetation, wildlife habitat and aquatic organisms. On a broader scale, mining may impact biodiversity by changing species composition and structure. For example AMD and high metal concentrations in rivers generally result in an impoverished aquatic environment. Some species of algae and invertebrates are more tolerant of high metals and acid exposure and may, in fact, thrive in less competitive environments. Exotic species (e. g. weedy plants and insect pests) may thrive while native species decline (Maranda et al., 2003). The impact of mining on biodiversity also needs to be thought of in relation to 'the miner or human footprint' – the pressures induced by the human communities connected with mining activities. For example, at Mount Isa in Queensland, the human footprint extends 500 kilometres around the township (Yencken and Wilkinson, 2000).

5.1.6 Impurities During Mining and Metals Extraction

A further issue which is receiving increasing attention is impurities in metal products – the presence of deleterious metals (or other pollutants) in various mine wastes or product streams. For example, elevated arsenic in copper concentrates can lead to major airborne arsenic emissions during smelting, and limits are now being placed on arsenic concentrations in copper concentrates to avoid this problem (rather than dealing with the emission or cost of pollution control). The REACH (Registration, Evaluation, Authorisation, and Restriction of Chemical substances) Regulation recently introduced in the European Community is an example of legislation that will be of particular relevance here. One of the main purposes in developing the REACH legislation was to provide information on the hazards that the large number of substances that have been manufactured and placed on the market in Europe pose to human health and the environment (http://ec.europa.eu/environment/chemicals/reach/reach_intro.htm).

5.1.7 Artisanal and Small-scale Mining

While the mining industry is mainly seen as the domain of large companies, in many parts of the world, particularly developing countries, minerals are extracted by artisanal and small-scale mining. There is no widely accepted definition of artisanal and small-scale mining (ASM), and the term can be used to cover a broad spectrum of activities. Artisanal mining is commonly considered to involve only individuals or families and is purely manual, while small-scale mining is more extensive and usually more mechanised (IIED & WBCSD, 2002). It has been estimated that throughout the world ASM involves in the order of 13 – 20 million people from over 50 developing countries directly, and that it affects the livelihoods of a further 80 – 100 million people (IIED & WBCSD, 2002; EITI, 2009). Artisanal and small-scale miners extract a broad range of minerals, although in many countries, most of them produce gold due to it being relatively easy to extract and refine. It has been reported (IIED & WBCSD, 2002, p. 318; Geoviden, 2007) that ASM accounts for 15 – 20 % of the world's non-fuel mineral production.

The main environmental impacts of ASM for precious metals (especially gold) are considered (IIED & WBCSD, 2002) to be:

- Mercury pollution.
- Cyanide pollution.
- Direct dumping of tailings and effluents into rivers.
- Threats from improperly constructed tailings dams.
- River damage in alluvial areas.
- River siltation.
- Erosion damage and deforestation.
- Landscape destruction.

Many consider the use of mercury by gold miners as the activity of greatest concern by ASM. As many of these ASM operations are often subsistence activities, the miners tend to focus more on immediate concerns rather than the long-term consequences of their activities. As a result, ASM tends to have a greater environmental impact per unit of output than modern mining enterprises (IIED & WBCSD, 2002). However, given the significantly greater mineral production by large-scale mining compared to small-scale mining, the bulk of the environmental impacts (particularly mining waste) from the global production of primary metals is due to large-scale mining despite improved environmental management of these operations over the last decade or two.

5.1.8 Summary

Table 5.2 shows the most important impacts of the different mining and extraction processes.

Table 5.2

Principal environmental aspects and impacts of the major metal extraction stages.

Mining Stage	Major Inputs	Major Outputs	Land	Water	Air	Biodiversity
Exploration	vehicles, drilling, energy (diesel, electricity), geophysics surveying, surface sampling, water, drilling fluids, roads	drill cuttings, rock samples, rock core, dust, water	clearing, erosion, visual	surface water, groundwater, quantity, quality (acid mine drainage)	particulates (dust), visibility, vehicle emissions, greenhouse gases	biodiversity loss,weeds, road toll
Development	energy (diesel, electricity), infrastructure (water, sewage, roads), construction, buildings, chemicals (explosives, reagents)	waste rock, vehicle emissions, greenhouse gases, water, dust	clearing, erosion, visual	surface water, groundwater, quantity, quality (acid mine drainage)	particulates (dust), visibility, vehicle emissions, greenhouse gases	biodiversity loss, isolation, weeds, road toll
Mining & mineral processing	energy (diesel, electricity), chemicals (explosives, reagents), water	tailings, waste rock, vehicle emissions, greenhouse gases, water, toxic substances, dust	clearing, erosion, visual	surface water, groundwater, quantity, quality (acid mine drainage), toxic substances (eg. cyanide emissions)	particulates (dust), visibility, vehicle emissions, greenhouse gases, toxic substances	biodiversity loss, isolation, weeds, road toll
Smelting	energy (diesel, electricity), chemicals (reagents), water	slag waste, sulfur dioxide, greenhouse gases, toxic substances, dust	visual	surface water, groundwater, quantity, quality (acid mine drainage), toxic substances	particulates (dust), visibility, sulfur dioxide, greenhouse gases, toxic substances	polluted ecosystems, weeds, road toll
Refining	energy (diesel, electricity), chemicals (reagents), water	solid waste, greenhouse gases, toxic substances	visual	surface water, groundwater, quantity, quality (acid mine drainage), toxic substances	greenhouse gases, toxic substances	polluted ecosystems
Closure	energy (diesel, electricity), water	waste rock, vehicle emissions, greenhouse gases, water, dust	stable (?)	stable (?)	stable (?)	stable (?)

Crucial issues to the mining industry are:

- The management of water and water quality by, among others, use of water recycling technology. It would reduce impacts even more to use solar power to drive water purification plants, use BAT for solids liquids separation (www.outotec.com) etc. to optimize this.
- Acid mine drainage (AMD) from waste rock dumps and tailings, which can continue long after the mine has closed.
- Optimization of process efficiency and technology to maximise recovery of metal(s) from a given ore deposit, while at the same time minimising waste.
- The disposal of waste rock, which results because the ore is only a fraction of the total volume of material mined, particularly due to the strong trend towards large scale open cut mines and the trend to processing lower ore grades.
- Emissions of greenhouse gases over the entire primary metal production chain, as well as particulate matter and sulfur dioxide in smelter stack gases, although the use of sulfuric acid plants in most modern smelting plants has largely eliminated sulfur dioxide emissions from these plants.
- Introduction of innovative bio-processes during the operations to create new ecosystems adapted to new conditions and at the closure of the project to restore the biodiversity, land and landscape, where feasible.

5.2 Impacts of Use

Metals and their compounds are being used in products because of their unique physical and chemical properties and therefore the functionality they impart to the product. While it is relatively straightforward to allocate the impacts of mining and production to materials, in this case metals, this is not so straightforward for the impacts in the use phase. Metals are then applied in a product, and any use phase impacts are related to the product, not the material it is composed out of. The only impacts that can be directly related to the material is the emissions from corrosion in the use phase. These have been treated in Chapter 3. The other use phase impacts are mostly related to energy. The application of metals may contribute to the use of energy, but it can also decrease energy use depending on the application.

In this section, a number of metal applications in various types of environmentally beneficial technologies that enable sustainable and resource efficient solutions are treated in Sections 5.2.1 and 5.2.2, and the embodied energy and energy use related to the products which in general promote resource efficiency in Sections 5.2.3 to 5.2.6. In Chapter 6, some examples are given of LCA studies of metal containing products, where it can be detected how much alternatives containing more, less or different metals contribute to specific environmental impact categories.

The energy requirement of products in their use-phase is related to the functionality of the product in question. For example, a lighter aluminium/magnesium/carbon fibre containing car uses less fuel and hence mitigates the use of these energy intensive metals. Product design is therefore essential to optimise the product with regard to energy use, and metals may play a role in that.

Of considerable importance is the use of metals in, for example, renewable energy and battery technologies, and therefore can be regarded as environmentally beneficial and sustainability enabling. Renewable energy

prevents the use of fossil fuels with concurrent emissions to the environment as discussed with examples below.

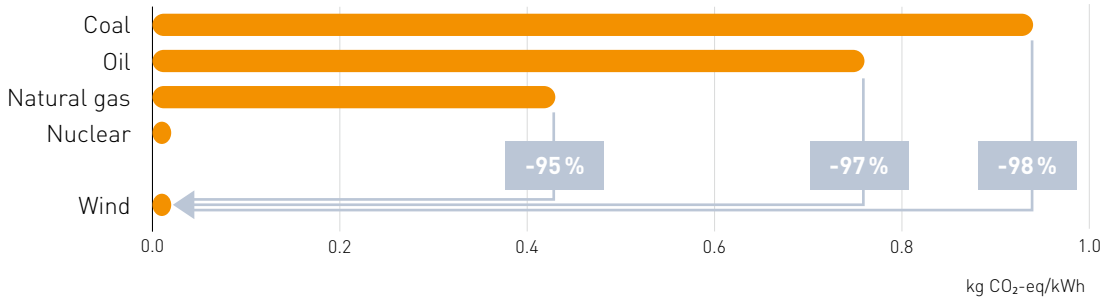
In this section, some examples of metals' applications will be discussed. The environmental impact of metals is determined for an important part by their application. Metals, due to their properties, fulfil certain functions in a product that are difficult to replace, and as this chapter shows in some cases allow for a reduction of emissions as well. Moreover, the same properties allow for their excellent recyclability."

5.2.1 Metals and Rare Earths in the Energy Sector

Figure 5.8 gives an overview of average CO_2eq/kWh data for various energy generation sources. Especially for enabling the technology within the renewable sector, various metals play an important role, hence enabling the change of the energy mix to lower carbon footprints. This section discusses some of these important "sustainability" enabling metals. Some of these metals may be scarce on the market; therefore their recovery at end-of-life is of strategic importance. This will also from a life cycle perspective mitigate the footprint of the recovery of these metals.

Figure 5.8

Average kg CO_2/kWh for different sources (www.worldsteel.org).



Copper Cables

Modern social and business life would be impossible without electricity, available instantly at the point of use. A cost calculation in relationship to the energy loss and the conductor cross section shows that the bigger the cross section of the conductor the higher the energy efficiency is. With the right material choice the above-mentioned efficiency can be further optimized. For instance copper has the second best electrical conductivity after silver and is therefore a material of choice for power generation, transmission, distribution and use. Electricity conducted by copper encounters much less resistance compared to any other commonly used metal; its electrical conductivity is 60 % higher than that of aluminium. It is assumed (European Copper Institute, www.eurocopper.org) that "the judicious use of 1 tonne of copper in the energy sector makes it possible to reduce CO_2 emissions by 200 tonnes per year on average".

Rare Earths

Rare earths (RE) are a collection of chemical elements which the lanthanide series of elements in the periodic table (atomic numbers 57 through 71) and also include yttrium (atomic number 39). They are abundant in the earth's crust, but often they are found in quantities that are uneconomically mined. Most of the production currently takes place in China. A small but growing share of the production is located elsewhere, for example in Australia, USA and South Africa (McGill, 2005). Of importance is the use of rare earth elements in various sustainable energy generation applications such as wind mills, electricity generators etc.

For energy generation in wind mills, neodymium, dysprosium and terbium are used in powerful permanent magnets. Quoting below from a World Steel Association case study on windmills (www.worldsteel.org/dms/internetDocumentList/case-studies/Wind-energy-case-study/document/Wind%20energy%20case%20study.pdf), the use of this application

has an important impact over its use-phase not only in energy supply, but the excellent recycling properties of steel ensure a high resource efficiency for these at the end of their lives. Dismantling the magnets (which is relatively easy) will also lead to excellent reuse/recycling possibilities of these valuable magnetic materials.

"The Horns Rev offshore wind farm is one of the world's largest. It was installed in 2002 in the North Sea, 14 km west of the coast of Denmark. The location provides some of the best conditions for wind energy. The wind farm has 80 2MW wind turbines, which are 70m tall and have an estimated lifetime of 20 years. These turbines are made primarily of steel, with high-strength steel foundations. The 28,000 tonnes of steel in the turbines accounts for 79 % of all materials used in the wind farm. An estimated 13,000 GWh of electricity will be generated during the lifetime of the farm. If this energy replaces global average electricity the lifetime CO_2 saving provided by the farm is nearly 6.5 million tonnes. Using LCA, it is estimated that 6 GWh of energy is required to construct, operate and dismantle a turbine.[a]" This example highlights the contribution that metals make to the development and use of renewable energy technologies by reducing inputs through enhanced functionality.

REs also have important applications in battery technology. Lanthanum is used as a catalyst in fuel cells, while it is also used in for example rechargeable Nickel Metal Hydride batteries (NiMH). Related to this is the use of a variety of REs in the phosphors of energy efficient lighting such as praseodymium and europium or terbium and yttrium in colour electronic screens, LCDs etc., having marked lower energy consumption than the usual light bulbs society has been using over the last century.

a http://www.altprofits.com/ref/se/re/we/we.html

5.2.2 Metals and Rare Earths in Electric Motors and Batteries

In electric motors and other components steel, aluminium and copper are largely used. Many comparative studies (Fassbinder, 2004b; Parasiliti et al, 2004; Manoharan et al, 2010) show that optimising the use phase by reducing wasteful heat loss is critical for such applications. For example, increasing the quantity of copper usage improves efficiency by reducing wasteful heat loss. This means less energy demand per unit of output which means fewer greenhouse gas emissions that are associated with climate change. Motor modelling by a number of manufacturers had shown that further optimisation of motors would yield overall loss reductions from 15 to 20 % compared to standard solutions (Fassbinder, 2004). In the U.S.A. alone, a one percent increase in motor efficiency would save 20 billion kWh (20 TWh) per year.

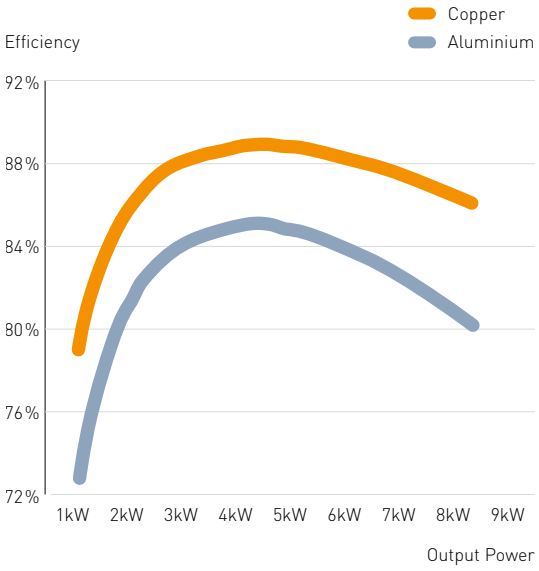


Figure 5.9

Efficiency comparison between a simple EFF3-motor and an optimized one with copper rotor (Fassbinder, 2004).

The use of REs in electric motors is important for the automotive sector, especially for electric motors (McGill, 2005). It is clear that the impact of these metals on the transport sector especially during the use phase is of utmost importance. An issue will be to recover these at the end-of-life of these vehicles to ensure maximum resource efficiency.

Metals have a very important role in battery technology, providing the functionality required in various applications used daily (Bernardes et al. 2004, Briffaerts et al. 2009, Müller and Friedrich 2006, Sayilgan et al., 2009, Xua 2008).

5.2.3 Automotive Sector

Lowering the carbon footprint of the automotive sector can be driven by lowering vehicle weight which lowers energy consumption over its life time (Koffler and Rohde-Brandenburger, 2010; Bertram et al, 2009; Das, 2000). There are various initiatives in this regard, which range from multi-material concepts to new steel types being used. Also not to be forgotten is that these new designs will also become part of the electric vehicles of the future. Reaching high recycling rates for these vehicles is required (dictated by EU legislation) to maximize the resource efficiency.

Multi-Material Lightweight Concept

The objective of a recent project by the automotive industry in Europe (Krinke et al., 2009) was to develop a SuperLightCar (SLC) design that lower the carbon footprint over the life of the product, in spite of the multi-material light weight design which may contain materials that have a higher embodied energy, as shown in Figure 5.10.

Advanced High-Strength Steel Car Concept

The functionality of the multi-material concept clearly shows the environmental benefits of such innovative designs. Another path towards this is the mono-metal Advanced High-Strength Steel car concept, which uses innovative steels to bring about a lowering in weight, which has been reported to save 2.2 tonnes of CO_2eq, or 5 %, over its lifetime (www.worldsteel.org/dms/internetDocumentList/case-studies/Automotive-case-study/document/Automotive%20case%20study.pdf).

5.2.4 Metals in Infrastructure

The importance of metals in infrastructure goes without saying i. e. steel in buildings, bridges, transport infrastructure etc. For example, bridges such as the Millau Viaduct in France (which is the longest cable-stayed road bridge in the world with a length of 2460 and with 343 m also the world's highest bridge, containing 65,000 tonnes of steel) shorten transport routes with associated decrease in CO_2 footprints. Their galvanic protection by zinc ensures that the steel remains durable (mitigates corrosion) and delivers its service over the 100 years of modern bridges' designed life time.

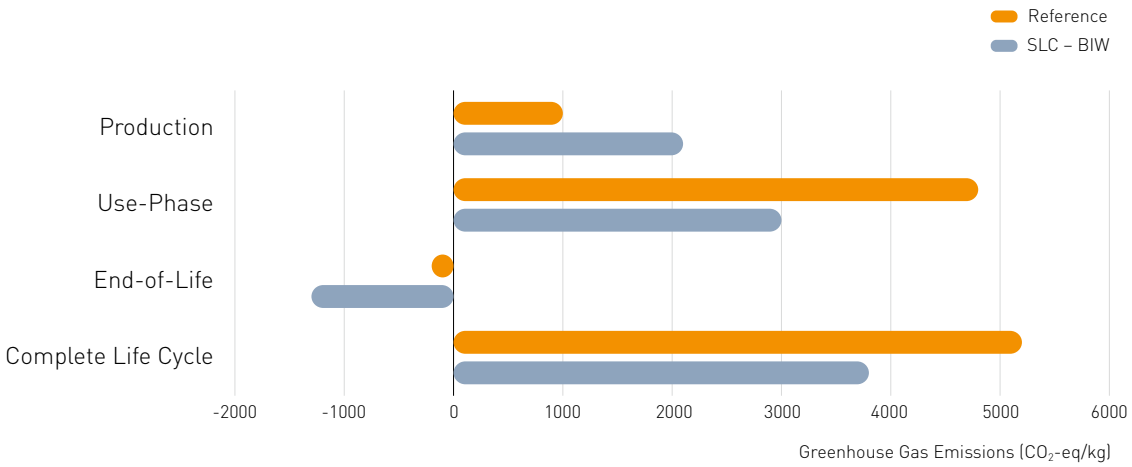


Figure 5.10

Overview of Greenhouse Gas Emissions for the different phases of the SuperLightCar (SLC) car relative to a reference model (Krinke et al., 2009).

Aluminium also plays a key role in infrastructure. Its corrosion resistance minimizes maintenance. Furthermore the building of light weight structures are possible due to the high strength-to-weight ratio. Finally, high recycling rates of up to 95 % from buildings make it possible to tap into the around 200 million tonnes of aluminium in buildings. (The International Aluminium Institute, www.world-aluminium.org).

5.2.5 Light Metals for Transport and Packaging

Light metals (aluminium, magnesium and titanium) are increasingly being used in transport and packaging applications due to their unique properties such as lightness, strength, corrosion resistance and formability. While these metals have high energy and greenhouse gas footprints for their production, their light weight results in significant energy and greenhouse gas savings over other metals such as steel during the use stage (in transport applications) of their life cycle. While aluminium has been used in transport applications for some time, the use of magnesium in these applications is increasing. The use of titanium in aerospace applications is also increasing. Aluminium is also used extensively for the protection and storage of food and beverages as well as medicines and cosmetics, typically in the form of cans or foil. It provides an impermeable metal barrier to light, ultra-violet rays, water vapour, oils and fats, oxygen and micro-organisms. Aluminium drinking cans are the most recycled packaging product in the world.

5.2.6 Metals Enable Sustainability and Resource Efficiency during their Use Phase

The above-mentioned examples show that it is not only the material content of the product that has to be considered during the use phase but rather to the system output and how the product and system is designed and how its use/functionality promotes sustainability. It is obvious that the slogan here for example for copper wires is "use more metal e. g. copper to be efficient and therefore sustainable". On a first view this sounds somehow contradictory to the above-mentioned general understanding of "less is more", when talking about material efficiency.

Therefore the above examples (showing the importance of aluminium, copper, steel, titanium and rare-earths) answer the following questions that are of interest in this regard:

- Metals and metal compounds/materials enable sustainability in the products that they use, therefore they contribute substantially to the theme "decoupling economic growth from environmental degradation" or in other words resource efficiency.
- Metals used smartly in various applications ensure less energy demand worldwide.
- Technology and its development and the use of metals/compounds/alloys/multimaterials ensure "greener" energy production through for example wind-, solar-, geothermal-, or wave power generation. Hence, metals and their applications enable the change of the energy mix which is crucial to resource efficiency.
- Products, their design and system design affect material use and recycling to facilitate resource efficiency.

An overall systemic picture is required to best evaluate the most "sustainable" concepts, products, designs, processing systems etc. There is an important link to design that maximizes the recovery of metals and metal containing compounds from end of life goods. This will be the brief focus of section 5.3, to show, that once the materials have successfully gone through their use phase and delivered their respective impacts, recycling can recover these to improve the resource efficiency.

5.3 Impacts of Recycling

Recycling feeds metals back into the resource cycle, hence replaces primary material and thereby prevents impacts related to primary production from occurring. These impacts include large energy savings with concurrent emissions reduction (see Chapter 4), as well as avoidance of some of the risks related to mining, as well as lowering the embodied energy of products. However, there can also be negative environmental impacts associated with metal recycling, although these are generally outweighed by the positive impacts mentioned.

A resource efficient society will therefore maximize the recycling of metals to lower the general footprint. However, various issues affect and limit the efficiency of recycling (Reuter et al., 2005 and Reuter 2011):

- Recycling is a complex function of numerous parameters such as best available technology, product design, economics, separation physics/thermodynamics, sorting, and process dynamics, among others. To minimize losses to landfill and maximize resource efficiency these have to be understood well in a techno-economic context.
- Product design, product complexity, the number of elements in the product and the way they are connected influence among others the recyclate qualities, the recycling rate and the degree of down cycling.
- The recycling infrastructure and technology determines the ultimate recovery of metals, materials and energy. This has to be well guarded by legislation; well-conceived policy based on technological and thermodynamic argumentation will maximize resource efficiency.
- Any geographic region in the world wanting to secure metal supplies for high tech products must among others take considerable care to safeguard a metal/material infrastructure in order to maximize recovery of metals from post-consumer products (EC 2001&2002, and European Parliament and Council Directive (EC, 1994, 1999, 2000, 2002, 2003), Committee EV, 2012; Ontario Electronic Stewardship, 2008). Only first principles and engineering system analysis suffices to provide answers to this rather complex techno-economic problem. This depth will reveal true recycling rates of for example scarce metals from consumer products to safeguard supply.
- A well-designed collection system has to be in place to minimize losses and leakage from the system. For industrial waste, collection is easy and to a large extent already is taken care of, driven by sufficiently high value recyclates due to high metal and material prices. For household waste a collection system is more complicated as various degrees of collection exist globally. Aspects to be optimized are energy/fuel usage during collection, collection infrastructure, as well as activities to motivate people to cooperate, amongst other things and its acceptance, amongst other things (Wäger et al. 2011).

Waste electrical and electronic equipment (WEEE) is one of the fastest growing waste streams globally. The composition of WEEE depends on the type and the age of the equipment. For example, WEEE for information technology and telecommunications systems contain a higher amount of precious metals than scrap from household appliances. Generally WEEE contains about 40 – 60 % metal, with iron/steel, copper and aluminium being the main metallic components, but also may contain lead, nickel, zinc and other metals (Critical raw materials for the EU 2010, UNEP, 2010c). Major categories of hazardous materials and components of WEEE are shown in Table 5.3. Due to its hazardous materials content, WEEE may cause environmental problems involving the release of these materials into air, soil or water during the waste management phase if it is not properly treated. Many countries in the world have drafted legislation to improve the reuse, recycling and other forms of recovery of such

wastes to reduce disposal, such as the Directive on the Waste from Electrical and Electronic Equipment adopted by the European Parliament in 2003.

Recovering and recycling the numerous metals in batteries will ensure that the metals and compounds in this important resource do not go lost to landfill (Bernardes et al. 2004, Briffaerts et al. 2009, Müller and Friedrich 2006, Sayilgan et al., 2009, Xua 2008).

Table 5.3

Major hazardous components in waste electrical and electronic equipment (Cui and Forssberg, 2003).

Materials and components	Description
Batteries	Heavy metals such as lead, mercury and cadmium are present in batteries
Cathode ray tubes (CRTs)	Lead in the cone glass and fluorescent coating cover the inside of panel glass
Mercury containing components, such as switches	Mercury is used in thermostats, sensors, relays and switches (eg. on printed circuit boards and in measuring equipment and discharge lamps); it is also used in medical equipment, data transmission, telecommunication and mobile phones
Asbestos waste	Asbestos waste has to be treated selectively
Toner cartridges, liquid and pasty, as well as colour toner	Toner and toner cartridges have to be removed from any separately collected WEEE
Printed circuit boards	In printed circuit boards, cadmium occurs in certain components, such as SMD chip resistors, infrared detectors and semiconductors
Polychlorinated biphenyl (PCB) containing capacitors	PCB-containing capacitors have to be removed for safe destruction
Liquid crystal displays (LCDs)	LCDs of a surface greater than 100 cm2 have to be removed from WEEE
Plastics containing halogenated flame retardants	During incineration/combustion of the plastics halogenated flame retardants can produce toxic components
Equipment containing CRC, HCFC or HFCs	CFCs present in the foam and the refrigerating circuit must be properly extracted and destroyed; HCFC or CFCs present in the foam and refrigerating circuit must be properly extracted and destroyed or recycled
Gas discharge lamps	Mercury has to be removed

In addition, recycling systems and technology can create their own impacts, which include the following (Williams et al. 2008, Wäger et al 2011, Sepúlveda et al. 2010):

- Poor collection or lack of take-back systems can lead to dumping waste and end-of-life products to uncontrolled landfill.
- Leakage from the recycling system can direct for example e-waste to back yard operations which have shown a large impact on health. There are efforts to improve this situation (Chi et al., 2011).
- Due to complex designs and thermodynamic laws economically low value residues, recyclates and waste are created that are dumped, potentially to be leached by water to report to the environment.

The Metal Wheel (Figure 3.1, Chapter 3) shows that many sustainability enabling metals are connected to various base metals and hence their supply is linked to the demand of the base metals. Due to this linkage of minor elements to base metals, recycling plays an important role to replenish these and satisfy the large demand for these in modern products.

5.4 Impacts of Final Waste Disposal

As discussed in the previous section, thermodynamics and especially the 2nd Law of Thermodynamics prohibits within a reasonable economic framework the closure of the materials loop. However, with a well designed system and technology contained in it, it will be possible to minimize losses especially if it is linked to good product design, informed and sustainable consumer behaviour and best practice/technology linked to good and reasonable global legislation.

Nevertheless, there will be losses from the materials processing and energy recovery system requiring waste disposal in some limited form as shown for the fluff fraction after shredding in the previous section. The two main waste disposal options are landfill and waste-to-energy.

Landfill involves burying the waste, sometimes in abandoned mines, quarries or pits. Although metals and their compounds may leach out into the soil and contaminate nearby water bodies, modern landfill designs include thick bottom liners and leachate (liquid run-off) collection systems that minimise this problem. Furthermore, only a small fraction of the metals found in soils and in natural waters is generally bioavailable (i. e. capable of being taken up by an organism). This is because the larger fraction is usually bound with reacting chemicals in the environment. Laboratory toxicity tests are conducted with artificial media by which all or most of the metal is made bioavailable and these tests therefore tend to overestimate the toxicity of metals in the environment. It is the toxicity of the bioavailable fraction that should be used to categorise and rank the hazards of metal wastes. New leaching tests are being developed to address this issue and Figure 5.11 compares human toxicity and ecotoxicity results for red mud (the solid waste stream from bauxite processing) based on total and bioavailable metal concentrations (Norgate and Haque, 2009).

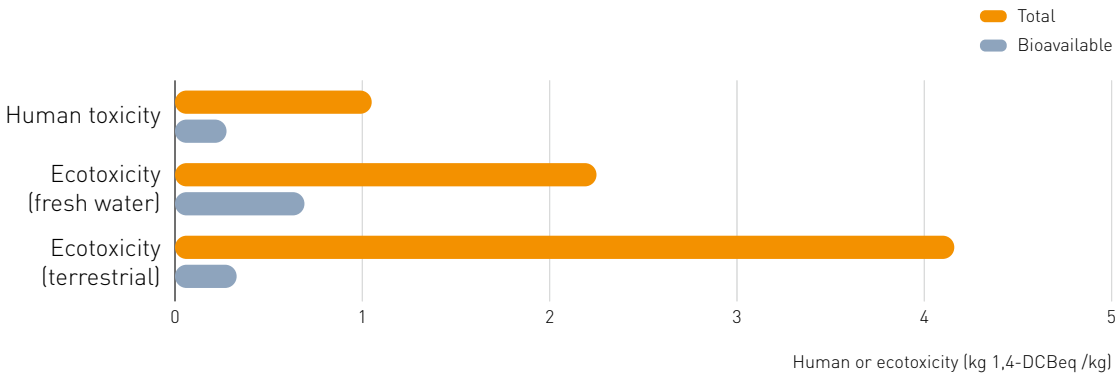


Figure 5.11

Comparison of total and bioavailable toxicity results for red mud (Norgate and Haque, 2009).

Waste-to-Energy involves subjecting the waste to combustion so as to convert it into residue and gaseous products. Strictly speaking, only the organic materials in the waste are combusted, but the non-combusted materials can also undergo a transformation under the influence of the heat released. The residue consists mainly of ash, soot and inert particles and is generally treated and disposed of as a hazardous waste as it may contain heavy metals (Aucott et al, 2010) and other toxic materials. The gaseous emissions from incineration depend on composition of the initial waste, but generally included gases such as CO, CO_2, NOx and SO_2, mineral dust (fly ash), metals and organic molecules (e. g. soot). Waste-to-Energy facilities are usually equipped with flue gas treatment systems to reduce all these emissions to levels that usually fall well within the levels required by legislation (Münster and Lund 2010, Pavlas et al. 2010, Stehlik 2009, Yang et al. 2007).

5.5 Measures to Reduce Impacts of all Life Cycle Stages

Some of the environmental impacts occurring over the life cycle of metal production and use have been outlined in the preceding sections. A number of options for reducing some of these impacts over the entire metal production and use life cycle are discussed below.

5.5.1 Mining

Many opportunities for avoiding the above environmental impacts exist at the mine planning stage. Specific measures to reduce environmental impacts are typically agreed, together with stakeholders, during impact assessment and permiting procedures. Preventive measures might typically include (Nelson, 2011; Borden, 2011);

- Siting of ventilation and infrastructure to minimise their effects on land, biodiversity, water.
- Storage and maintenance of topsoil for later use in site rehabilitation.
- Interception and redirection of surface and stormwater flows to avoid contamination.
- Capture and treatment of drainage and run-off water as required.
- Revegetation of disturbed areas.
- Selective handling and placement and consolidation of wastes to reduce possible sources of contamination.
- Design and construction of waste dumps to minimise run-on and erosion and promote run-off.
- Control of noise air blast, ground vibration, and dust emissions.
- Integrated closure planning including flooding, capping or covering of wastes as required.

With regard to artisanal mining, the Communities and Small-scale Mining (CASM) initiative was launched in 2001. The CASM is a global networking and co-ordination facility with a stated mission " to reduce poverty by improving the environmental, social and economic performance of artisanal and small-scale mining in developing countries (http://artisanalmining.org/casm). CASM has developed comprehensive stategies to mitigate the environmental impacts of ASM.

5.5.2 Mineral Processing

The international mining industry has learnt many lessons over the last decades that have helped to develop leading practice tailings management in Australia (Commonwealth of Australia, 2007). Drawing from a range of tailings storage facility failures and incidents, the main causes were:

- Lack of control of the water balance.
- Lack of control of construction.
- A general lack of understanding of the features that control safe operations.

Tailings containment wall failures were (in order of prevalence) due to:

- Slope instability
- Earthquake loading
- Overtopping
- Inadequate foundations
- Seepage

The European Commission Reference Document on Best Available Techniques for Management of Tailings and Waste Rock in Mining Activities (EC, 2009) describes, with examples, some of the practices employed to minimise the impacts of mine tailings.

While there are a number of approaches that potentially can be made to reduce the water consumption of the mineral processing

stage, the most promising would appear to be (Norgate and Aral, 2009):

- Water treatment and re-use.
- Water quality "fit for purpose".
- Dry processing.

5.5.3 Water Treatment and Re-use

The treatment and re-use of process and mine waters are now becoming a significant means of minimising overall water consumption as well as minimising the volume of contaminated water that may require treatment prior to discharge. The effect of recycled water properties on plant performance, including issues regarding the recycle of organic molecules, inorganic and microbiological species, and the build-up of collectors, must be considered prior to implementing a water recycling process. The appropriate treatment process depends on the characteristics of the water, the environmental discharge requirements, the economics of water re-use and the value of water.

Water Quality "Fit for Purpose"

Water supply issues have seen many mining and mineral processing operations shifting to poorer quality make-up waters (e. g. seawater, saline waters, grey water, treated and partially treated sewage and industrial effluents). This can have adverse effects on process water quality and the performance of mineral processing operations. In general, water quality is relevant whenever the chemical nature of the mineral surface is important, e. g. flotation. However, high quality water is not always required. The quality of water can range from very high quality to poor quality hard water (high levels of dissolved calcium and magnesium) from underground aquifers and to even lower quality saline groundwater[a] and seawater (very high levels of dissolved solids including sodium chloride). Therefore the water strategy that is most appropriate for mining and mineral processing operations to reduce raw or fresh water consumption is to use water that is "fit for purpose", i. e. water quality matched to application.

Dry processing

While increased water treatment and re-use is an obvious option to help reduce the water footprint of mining and mineral processing operations, a more radical alternative is dry, or near-dry processing. Dry separation processes used now and in the past include:

- Screening (which can also be done wet).
- Classification by winnowing.
- Classification by air cyclones.
- Shape sorting on shaking tables.
- Magnetic separation (which can also be done wet).
- Electrical separation.
- Gravity and dense medium separation (which can also be done wet).
- Ore sorting, by optical, conductivity, radiometric, or X-ray luminescence properties.

Dry processing routes are not without their problems, with the main one being dust, but another problem is the low throughput of most of the current processes, as well as low energy efficiency and poor selectivity in some cases. Nevertheless, the challenge to reduce water use in the minerals industry has led to renewed interest in dry processing. Other water reduction technologies include floating modules to reduce evaporation and paste thickeners (Norgate and Aral, 2009).

a Some underground water is much more saline than seawater, a phenomenon well known in Western Australia.

5.5.4 Metal Extraction and Refining

As pointed out earlier, one of the main impacts of the metal extraction and refining stage is the emission of greenhouse gases associated with the use of fossil fuels as fuel and carbon sources. Some of the options referred to in the previous chapter for reducing the energy consumption of primary metal production will also have a corresponding effect on greenhouse gas emissions. The estimated potential reductions in annual global greenhouse gas emissions for a number of new and emerging technologies, particularly for iron/steel and aluminium production, are shown in Figure 5.12.

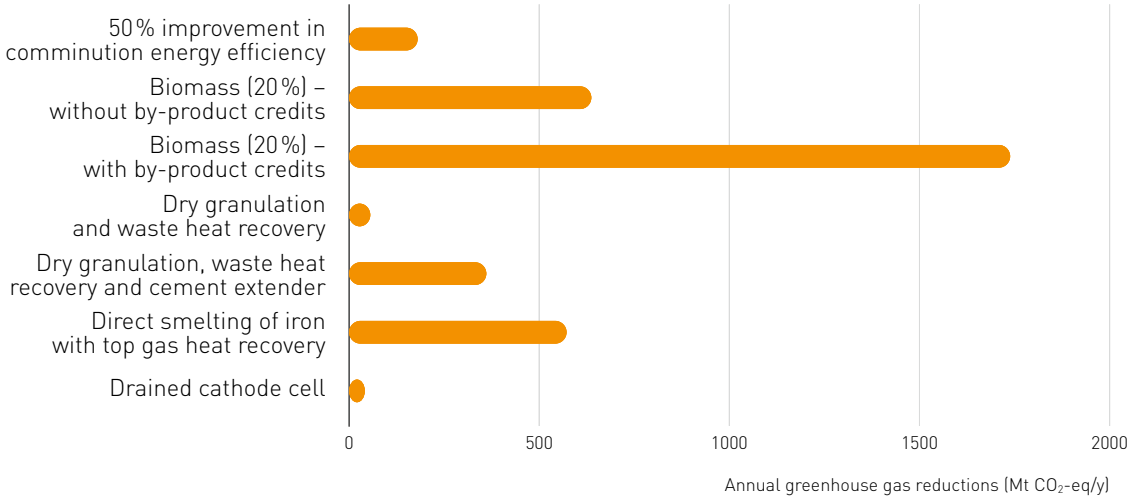


Figure 5.12

Potential annual global greenhouse reductions for various technologies (Norgate and Jahanshahi, 2010).

5.5.5 Product Use, Recycling and System Optimization

The complex interactions between product design, best available techniques and recycling systems have a direct impact on recycling efforts and thus resource efficiency, as outlined in the IRP's recent report on "Metal Recycling – Limits, Opportunities, Infrastructure" (UNEP 2013). To maximize resource efficiency requires rigorous models that evaluate and show in first principles where and how the resource efficiency can be achieved both technologically and economically while minimizing the impact of metals and materials (Van Schaik & Reuter, 2007, Reuter, 2011 & Krinke et al., 2009).

A first principles basis can suggest solutions if there are, if not, radical alternatives should be found within the boundaries of physics and economics.

If significant reductions are to be achieved in this stage of the metal life cycle, it is essential that the combined efforts of all stakeholders take place (producers, suppliers, consumers, policy makers). The following issues are being considered in this regard under a number of initiatives:

- Re-think the relationship consumer/supplier.
- Exchange/replacement-service.
- Deposit on some small electronic goods to cover costs of the take-back system and processing into recyclates.
- Incentive regulatory directives towards producers, suppliers and consumers emulating those of the European Parliament.
- Various end of life legislations, e. g. the EU WEEE-Directive.
- Global initiatives such as the StEP-Initiative of UN (Solving the E-waste Problem), which has as a goal to harmonizes e-waste recycling globally, understand the role of hand sorting and the informal market in recycling etc.

- Eco-design and design for recycling and sustainability in order to maximize resource efficiency.

- Technology improvement both for production and end of life recovery, however, this is limited to what thermodynamics and technology can provide within a reasonable technological framework (Cui and Forssberg 2003, Cui and Zhang 2008, Floyd 2005, Fraunholcz 2004, Froelich et al. 2007, Genaidy et al. 2009, Gielen and Moriguchi 2002, Hoang et al. 2009, Kepplinger et al. 2009, Leczo 2009, Matusewicz et al., 2008, Shent et al. 1999).

- Development of a worldwide modern recycling economy with well designed system structure and harmonized legislation that promotes best practice.

While the above points specifically refer to metals and recycling, the sludges and residues from for example the water system also contain among others metals, materials, organic, pharmaceutical residues etc., which also could and should be processed rather than just sent to landfill. These considerations obviously depend on local legislation and economics and have to be analyzed case by case.

However, a true system analysis to increase the resource efficiency will in future consider the linkages between the different systems that produce metals, residues, sludges, slags, ashes, scrap etc. so that contained metals can be recovered, while producing benign products.

It is therefore of increasing importance to analyze the interaction of the material flow system with the water and other systems as shown by a recent analysis of the water system south of Rotterdam Harbour (The Netherlands). A detailed model based system analysis of water quality as a function of various materials and available processing infrastructure was done with an optimisation simulation model, analyzing the flow of various metal containing compounds in residues originating from the water processing system and investigating the optimal manner in which these can be treated in metallurgical and energy recovery infrastructure (Van Schaik et al., 2010).

This rigorous physics/technology based approach enables the pinpointing of the problems in the bigger system, which via its first principles engineering basis also provides economic solutions to mitigate these issues and above all maximize the resource efficiency.

5.5.6 Substitution

Solid materials can conveniently be subdivided into two groups – metals (and alloys and compounds) and non-metals (ceramics, polymers/plastics, glass, wood). These various solid materials differ in their physical properties largely as a result of differences in their atomic/molecular structure. Many non-metals are cheaper and lighter than metals, are usually easy to shape, and are being increasingly used in transport and other applications. Metals on the other hand are generally more recyclable than non-metals. Another significant advantage of metals over non-metals is their ability to deform plastically under stress. The reasons for substituting materials in an existing product are many and varied and include (Cornish, 1990):

- New production routes become available.

- New materials become available.

- Reduction of cost.

- Impact of new legislation (eg. health, environment).

- Supply of key material is unreliable.

- Reducing dependence on imports.

- Wider performance limits needed to satisfy new markets.

Some representative examples of materials substitution are:

- Abundant materials for more scarce ones – aluminium can be used in place of copper in electrical applications, or ceramics in place of high-temperature alloys in turbine engines.
- Non-metals for metals – plastics can be used in place of zinc or aluminium in some structural applications, or glass for metals in containers.
- Renewable materials for non-renewable materials – wood can be used instead of metallic materials for some constructional purposes.
- Synthetic materials for natural materials – synthetic diamond in cutting and polishing applications.
- Composite materials for monolithic materials.

There are specific situations where substitution does not work at all, generally because the scale of use or the cost requirements cannot be met by any other material. For example, no material could replace steel in structural applications in buildings.

In terms of reducing the environmental impact of metal production and use, materials substitution involves the replacement of a potentially hazardous metal or processing route by one that is less problematic. Some examples of metal substitution have been reported by Graedel (2002), including the replacement of lead with bismuth in ammunition and the use of lead-free electronic solder. However, while the principle of materials substitution is simple, its implementation is often not straightforward, noting that bismuth is mainly sourced from lead ores! The material flows are altered by substitution, and this may create other problems (e.g. resource supply) in various parts of the materials cycle. For example, Graedel (2002) has pointed out that while modest use of bismuth ammunition has obvious local environmental benefits, its universal use in place of lead ammunition would not be sustainable for some time as this would require an increase in the current mining rate of bismuth by a factor of about fifty. Furthermore, it would not avoid environmental problems because of the mining of co-occurring lead in the same ore.
It is clear that the selection or substitution of materials should not be done by assuming that adequate supplies of a material will automatically be available. Many processes, once established, are in use for decades and resources sufficient to maintain such a time span should be assured (Graedel, 2002).

Another factor that should be borne in mind when considering materials substitution is the time required to effectively implement such a substitution. This time period may be substantial because of the requirements of examining alternative materials, of developing design and reliability data, and evaluating the substitute in a manufacturing environment. For small consumer products this time can be short, while for key industrial processes it can be several decades. In addition, the proposed substitute material may require new processing methods or may influence related technologies that interact with its intended use. Think for example of the well established lead-tin solder being replaced by other solders that may fail – this could have catastrophic consequences.

5.5.7 Final Waste treatment

Waste prevention is a first option to prevent emissions from waste treatment. Options for improving re-use and recycling have been discussed above.

Waste to energy and incineration in the waste hierarchy is the next preferable option. However, for metals the hierarchy may not be representing the ideal order. Metals do not degrade, nor are they reduced by incineration. The first and preferable option is to use pre-treatment and classification to stop as much of the metals of concern as possible from entering the waste-to-energy plant in the first place. Because the scope for this op-

tion is generally limited, the second option is to decrease their bioavailability. This may achieved by further immobilisation of the collected dust, ashes and slags after combustion. Lack of space for landfills is reportedly (European Commission, 2002) forcing some countries to use such residues for civil works and similar purposes, but the leachability of metals in residues should constrain this kind of material recycling. Outotec for instance has Top Submerged Lance (TSL) technology that melts the bottom ash of a waste to energy plant in Seoul (South Korea) to produce material for producing pavement bricks and the like (Matusewicz & Reuter 2008).

Treatment of these materials for example in a furnace to melt them to produce benign slags used for building mitigates this. As the economic environment changes and land becomes more valuable these high temperature and other solutions will become more attractive, especially also to improve the image of the industry in this regard.

Landfill is the least preferable option in the waste hierarchy used for EU waste policy, nevertheless for metals it may be the only final disposal there is. Traditional landfill will likely disappear as dictated by legislation such as "European Parliament and Council Directive 1999/31/EC of the European parliament and of the council of 26 April 1999 on the landfilling of waste". The World Business Council for Sustainable Development (WBCSD) vision (WBCSD, 2010) is similar and will have landfill be phased out by 2020, that "Closing the Loop" will be part of daily life and by 2050 "Not a particle of waste" will be the norm. Considering the whole material cycle, it would be clear that reaching minimum landfill would require the optimization of the complete system. The impact of landfill should in future diminish if society is to achieve its goal of minimizing waste. Landfill is a "unit operation" just like any other, which will be optimized according to best practice.

5.6 Conclusions

The first stages of the life cycle – mining, beneficiation, metal extraction and refining – produce a range of solid, liquid and gaseous waste streams. Elements not recovered in the metal production process report to these streams. Many of these waste streams contain valuable elements and compounds that could potentially be recovered, as well as elements and compounds of no real value. A number of these elements and compounds are toxic and can cause environmental problems and health-related problems for humans if not well managed on mining and smelter/refinery sites.

The most important environmental impacts of primary metal mining and extraction revolve around water (consumption and quality aspects), mine wastes (tailings and waste rock), energy sources (direct such as diesel and indirect such as coal-fired electricity) and the associated air emissions (sulfur dioxide, greenhouse gases, dusts and particulates). Wider implementation of a number of so-called Best Available Techniques is needed to reduce the environmental impacts of metal production, use and disposal. Scientific and technological research and development, focused on understanding the underlying processes associated with these impacts, is an essential component to provide the foundation for new, cost-effective improvements. These will build on the lessons already learned from past environmental experiences. Such approaches would likely include a wider adoption of the following techniques:

- Reclamation of disturbed land.
- Treatment and stabilisation of metal-bearing soils.
- Prevention and treatment of contaminated water.
- Controls on the amount and character of emissions to the atmosphere.

- Optimal system design to maximize resource efficiency.
- Minimising waste and recycling raw materials and by-products.
- Balanced approaches for the supply of minerals and metals and environmental protection are complex and demanding, and if society is to achieve such a balance, it will require a combined effort on the part of all stakeholders (producers, suppliers, consumers, policy makers, recyclers).

Water is an extremely important issue to the mining industry as it is to society in general. To maximize resource efficiency it is obvious that the water recycling system should be linked to the recycling and metals/recycling system, not only to conserve water but also the maximize metal recovery and hence maximize the resource efficiency. This is a key issue for the future: resource efficiency will be maximized by integrating different systems and also understanding the physics, technology and economics of this in detail.

In the use stage, it is difficult to attribute impacts to metal-containing products. Main impacts are related to energy use. Impacts refer to the product, not the material: only occasionally is it possible to pinpoint a specific role for metals, and then only comparatively. Metals are used in many new technologies. Especially renewable energy technologies, where metals play a specific role, can be regarded as beneficial for the environment since they avoid emissions related to fossil fuel use. The up-scaling of such technologies on a global scale however may lead to impacts in the chain: the use of lesser grade ores leads to exponential rises in the energy required to produce the metals, lowering resource efficiency.

Minimizing the creation of waste streams and their associated environmental impacts, while at the same time maximizing the amount of valuable metal(s) recovered from a given ore deposit, is the primary objective of the metals processing and recycling industries. Recycling rates are increasing, but could be increased far more if a systems optimization, including also product design, would be adopted. However, thermodynamics, in particular the 2nd Law of Thermodynamics, prohibits within a reasonable economic framework the complete closure of the materials cycle. Hence there will always be losses from the production and use of metals, and there will always be a need to make up for these losses by primary production from metallic ores. While there may be opportunities to substitute other materials for metals in some applications, these may not be without their own environmental and supply issues. Furthermore, metals are generally more recyclable than non-metals. Unavoidable losses and leakages from the cycle will always occur due to physics, which means that a sustainable metals management must always include a final waste treatment option such as waste-to-energy, waste processing, incineration etc. Since metals and their compounds cannot be destroyed, the only way to prevent them from entering the environment is to remove possible pathways to sensitive receptors so they do not pose unacceptable risks: immobilize them and landfill them where they cannot reach the environment.

As shown above, metals have an important function in enabling sustainable solutions in the future to lower society's footprint. Their role is therefore critical and hence their recovery at the lowest possible footprint is the norm that society and industry must be striving for.

6. Life Cycle Impacts of Metals

Authors: Roland Hischier, Patrick Wäger, Michael Hauschild

6.1 Introduction

According to the Division of Technology, Industry and Economics of United Nations Environmental Programme (UNEP) industrial development will only be truly sustainable if it is built on firm ecological foundations. UNEP provides in this context substantive support to national and regional initiatives through its global programme on Sustainable Consumption, Cleaner Production as well as in the UNEP/SETAC Life Cycle Initiative (a joint effort of UNEP and SETAC). Europe e. g. adopted in 2001 a sustainable development strategy (EC, 2007), expanded in 2006 to the new member countries as well.

In this context, the concept of "Life Cycle Thinking" (LCT) constitutes the basis of this initiative and got an important element of the European environmental policy. According to JRC (2007), LCT is "the process of taking into account in decision making, as far as possible and for example, all resources consumed and all environmental and health pressures that are associated with the life cycle of a product, considering the extraction of resources, production, use, re-use, transport, recycling, and ultimate waste disposal". The main objective that LCT is trying to achieve is the prevention of burden shifting – in the sense of minimizing the impacts at one product stage without resulting in an increase in another stage (EC, 2010b); i. e. is representing a life cycle approach. Such a life cycle approach can help us to make choices that are optimized in a life cycle perspective. It implies that everyone in the whole chain of a product's life cycle, from cradle to grave, has a responsibility and a role to play, taking into account all the relevant impacts on the economy, the environment and the society. The impacts of all life cycle stages need to be considered comprehensively by the citizens, the companies and the governments, when they make decisions on consumption and production patterns, policies and management strategies. A life cycle approach enables product designers, service providers, government agents and individuals to make choices for the longer term and with consideration of all environmental media. Life cycle approaches enable to detect shifting problems from one life cycle stage to another, from one environmental medium (for example air quality) to another (for example water or land), and from one impact category (for example global warming) to another (for example land use).

Many decisions in practice are already based on life cycle approaches, like e. g. consumer purchasing decisions via ecolabels, company reports on environmental and social issues, business design of products and services via life cycle assessments (LCA) studies, design for environment (DfE), total cost of ownership calculations, or management systems that are orientated toward products or facilities. Particularly relevant for metals is the design of technologies for primary and secondary production, which can be guided by LCA (Stewart et al., 2003; Stewart & Petrie, 2006). Furthermore government policy making by involving a wide range of stakeholders (e. g. via product panels) or through integrated product policy (IPP) approaches goes in a similar direction. Within all these different practical applications, the LCA method proves to be a key factor for a successful implementation and application.

In Section 6.2, the LCA methodology is described in general and specific points in relation to (primary/secondary) metal production are highlighted. Section 6.3 deals with the Life Cycle Inventory and lists the most important datasets on processes in the metals life cycle. Section 6.4 is dedicated to Life Cycle Impact assessment and the relevant issues in that stage of the LCA methodology for metals. Section 6.5 treats some LCA case studies related to metals, and in Section 6.6 some conclusions and recommendations are formulated.

6.2 LCA Methodology

Annex 6 contains a description of the LCA methodology. A brief summary is also made below. According to the standards 14040 and 14044 of the International Organization for Standardization, ISO (ISO, 2006a and ISO, 2006b), four phases – as shown in Figure 6.1 – are distinguished within an LCA study:

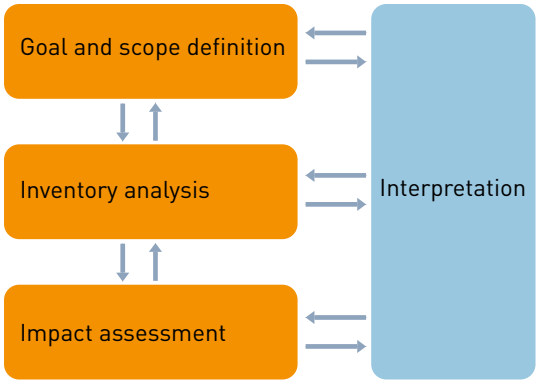


Figure 6.1
The LCA framework according to the ISO 14040/14044 series (ISO, 2006a)

- **Goal and scope definition:** The scope, including system boundary and level of detail, of an LCA depends on the subject and the intended use of the study. The depth and the breadth of LCA can differ considerably depending on the goal of a particular LCA (ISO 2006b).

- **Life cycle inventory analysis (LCI):** It is the second phase of LCA. It is an inventory of input/output data with regard to the system being studied. It involves the collection of the data necessary to meet the goals of the defined study (ISO, 2006b).

- **Life cycle impact assessment (LCIA):** It is the third phase of the LCA. The purpose of this third step is to provide additional information to help assess a product system's inventory results so as to better understand and evaluate the magnitude and significance of the potential environmental impacts related to the inventory data collected in the 2nd step (ISO, 2006a and ISO, 2006b).

- **Interpretation:** It is the final phase of the LCA. Here, the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations (ISO, 2006a).

According to the respective ISO standards (ISO, 2006a and ISO, 2006b), LCA is a relative and iterative approach, based on transparency and comprehensiveness. Relative, as an LCA is always structured around a functional unit that defines what is examined. All further activities then take place relative to this functional unit. Iterative, as shown in Figure 6.1, all steps are related to each other (i. e. each step is using the outcomes of the other steps) ... and thus, only passing several times across the various steps results in the end in comprehensiveness. As almost all life cycles of products include processes that occur all over the world, a high-quality, global environmental inventory database is essential to ensure sound and credible results of LCA studies.

In relation to the topic of this report – i. e. the production and use of various metals – the goal and scope of the therefore relevant LCA studies is the examination of the impacts of the production of a specific amount (e. g. 1 kg or 1 tonne) of either of the metals covered by this report – produced out of the respective ore, or via an adequate recycling procedure, out of appropriate scrap – a so-called cradle-to-gate assessment. As soon as not only the production, but a complete life cycle of a metal for a specific use context is taken into account, the goal and scope step has to ensure that all functionalities of the metal for this context are taken into account and adequately covered by choosing an appropriate functional unit as well as the system boundaries. This is particularly the case when the goal of the study is a comparison e. g. of different metals or of metals and other materials fulfilling a certain function like a panel in a car body. Here it is essential for the relevance of the study results that the compared quantities fulfil the same function.

It is important to realize that LCA is not the appropriate tool for risk assessments based on local situations. For that, other tools exist, as treated in Chapter 2. LCA uses information out of risk assessment in its impact assessment (LCIA, see section 6.4) to enable comparison between alternative, even in the absence of local data. LCA therefore is not the most suitable tool to assess local impacts of mining. It is, however, the most suitable tool to obtain a picture of the impacts over the total life cycle of a product or service, wherever (and whenever) these impacts may take place, since it integrates over all processes in the life cycle and over all environmental impacts.

6.3 LCI Data

6.3.1 Available Inventory Data

The following table gives an overview of available LCI data for those metals covered by this report here. The table is the result of a thorough literature and internet research by the authors of this chapter and additions from industrial sources. LCI data are unit process data: they record all inputs of environmental and economic goods (raw materials and products) and all outputs of co-products, waste and emissions to produce a unit of product or service. The cradle-to-grave product chain is composed out of such unit processes. Most processes in LCI databases are production processes, but consumption and waste management processes are included as well. Thus, a specification is made of all environmental interventions (extractions, emissions and land use) related to the product or services being assessed. This overview then is submitted to the Life Cycle Impact Assessment procedure (see Section 6.4).

Table 6.1 lists the most important databases on metal production. They include all steps from mining until the production of the refined material. Data on consumption and waste management often are not included, although these can be quite relevant. In some cases, data on secondary production (metal production from scrap) are available as well. This enables a comparison between primary and secondary production of metals. Other organisations may have relevant data as well, especially industry associations.

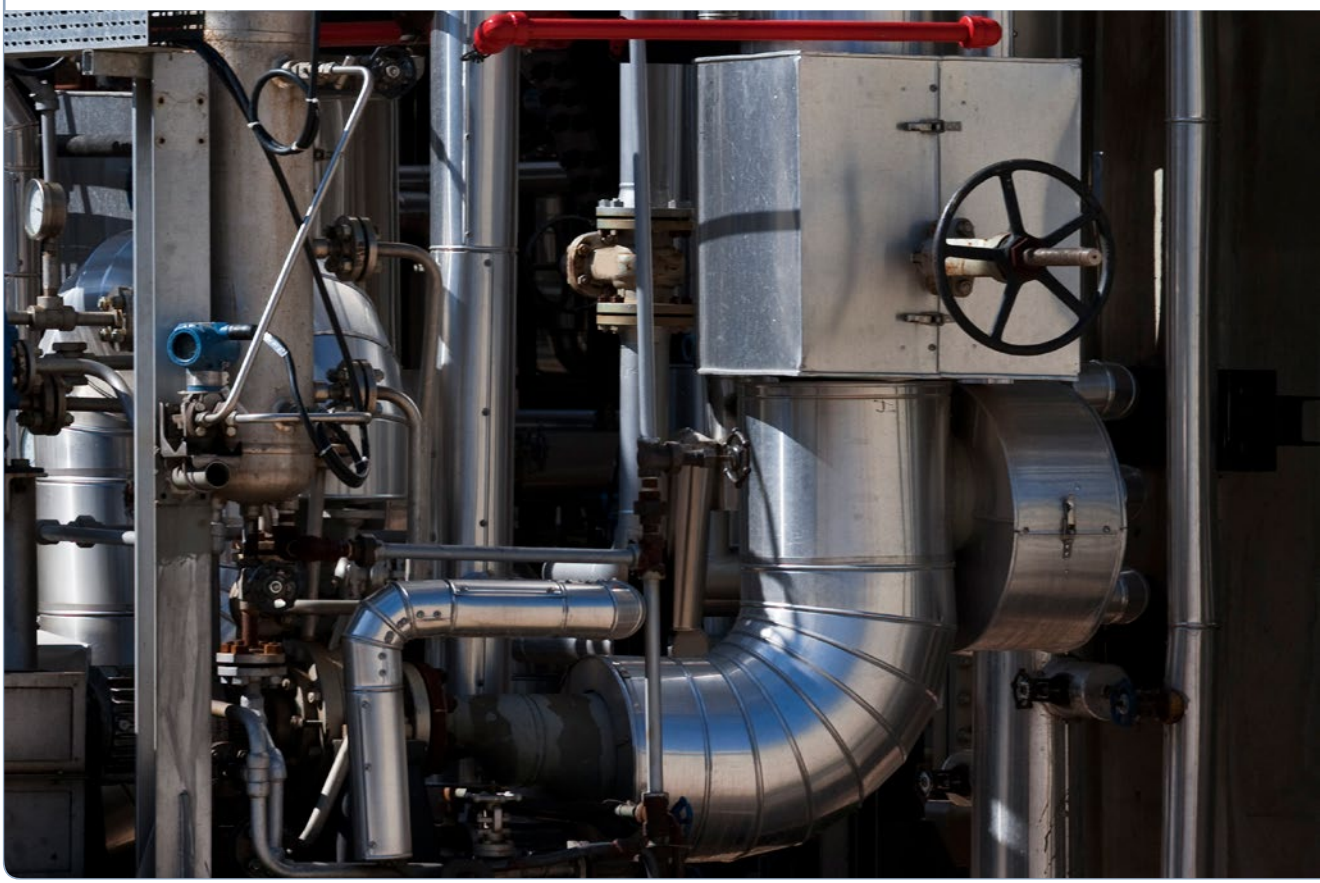


Table 6.1

Overview of available LCI data for primary and/or secondary metal production

Metal	Data publisher	Form			Data characterisation/description			Further remarks
		U	I	R	System boundaries	Covered technology	Data source(s)	
Iron (Fe) and steel	CSIRO minerals (reported in Norgate et al. 2007).			X	Cradle-to-gate, i. e. from the iron ore extraction to the produced steel.	Integrated route (blast furnace, BF) and basic oxygen furnace (BOF) steel.	Process data based on various, mainly literature, sources.	–
	ecoinvent Centre (reported in Classen et al. 2009).	X	X	X	Cradle-to-gate, i. e. from the iron ore extraction resp. the collection of iron scrap to the produced primary, secondary steel.	Primary & secondary production; using blast furnace, basic oxygen furnace steel.	Main sources: Roth et al. (1999) and IPPC (2000).	Split into 12 different datasets.
	European Life Cycle Database (ELCD) v2.0 (available free of charge in the internet); worldsteel data supersedes this data.		X		Cradle-to-gate, i. e. from the iron ore extraction to the produced steel and includes the end-of-life recycling of the steel products.	Primary & secondary production; using blast furnace and electric arc furnace steel.	EUROFER resp. worldsteel data, modelled for average European or Global situation, based on data from various sources.	Split into 4 product datasets (hot rolled coil, sections, hot dip galvanised steel and stainless steel).
	World Steel Association (worldsteel) (available in case of study-specific request at worldsteel.org – Methodology report 2011 also available for download).		X		Cradle-to-gate, i. e. from the iron ore extraction to the produced steel. Also cradle-to-gate including end-of-life recycling of the steel products (net credit).	50 sites operated by 16 companies, including blast furnace operations, electric arc furnace operations, and direct reduction operations participated in the study. The companies contributing data to the LCI study account for over 25 % of global crude steel production. Additional sites and companies are currently being added to the database.	Primary data from member companies (see "covered technology").	Datasets for 15 products – representing the main finished products of the steel industry. Included are hot rolled coil (with and without pickling), cold rolled coil (with and without finishing), hot dip and electrically galvanised sheet, painted sheet, tinplate and tin-free sheet, tubes, sections, plate, rebar/wire rod, and engineering steels.
	PE INTERNATIONAL GaBi 5 (2011).		X	X	Cradle-to-gate and unit process data.	EAF route – Speciality steel.	ThyssenKrupp AG, 2004. Best Available Techniques in the Ferrous Metals Processing Industry – Endentwurf 2005. Best Available Techniques Reference Document on the Production of Iron and Steel., 2001. UCLCI database EUROFER worldsteel.	163 data sets of different steel and alloyings. See also GaBi Modelling Principles 2011.
Copper (Cu)	CSIRO minerals (reported in Norgate et al. 2007).			X	Cradle-to-gate, i. e. from the copper ore extraction to the produced copper.	Smelting/converting and electro-refining resp. heap leaching with subsequent solvent extraction/electrowinning (SX/EW).	Process data based on various, mainly literature, sources.	–

Metal	Data publisher	Form			Data characterisation/description			Further remarks
		U	I	R	System boundaries	Covered technology	Data source(s)	
Copper (Cu)	ecoinvent Centre (reported in Classen et al. 2009).	X	X	X	Cradle-to-gate, i. e. from the ore extraction resp. the collection of copper scrap to the produced primary, secondary copper.		The production is modelled for global situation, based on data from various sources.	Split into 24 different datasets.
	European Copper Institute (ECI). (available in case of study specific request at www.copper-life-cycle.org).		X	X	Cradle to gate i. e. from the copper ore to copper cathode (here allocation due to multiproduct ore is applied) as well as to copper products tube, sheet and wire. The study represents the European average mix reference year 2005.	Mining, concentrating, Primary and secondary production including smelting, converting, fire refining and electrorefining. Hydroroute (leaching, solvent extraction and electrowinning is included). Coverage is more than 90 %.	Primary data from member companies (11 mining companies, 7 smelter and major fabricators). Additionally imports into Europe (from America, Asia and Russia) is included in.	Datasets for copper cathodes and semi-finished products (copper tube, copper sheet and copper wire). Secondary scrap for the cathode production and clean scrap for the semi production (except for wire) is considered.
	International Copper Association (ICA) (available in case of study specific request at www.copper-life-cycle.org).		X		Cradle to gate i. e. from the copper ore to primary copper cathode (here allocation due to multiproduct ore is applied). The study represents the world average mix reference year 2005-2009.	Mining, concentrating, Primary production including smelting, converting, fire refining and electrorefining. Hydroroute (leaching, solvent extraction and electrowinning is included). Coverage is nearly 30 % production mass based or 60 % regional coverage based.	Worldwide Primary data from member companies (22 mining sites, 14 smelting sites and 11 leaching/solvent extraction sites).	Global Dataset for primary copper cathodes.
	Kennecott (reported in Kennecott, 2004).			X	Cradle-to-gate, i. e. from the ore extraction (in Kennecott's Bingham Canyon Mine) to the produced Cu cathode.	Flash smelting furnace, followed by two further furnaces, in order to produce 99.6 % purity Cu.	Company data.	Only LCIA results published.
	PE INTERNATIONAL GaBi 5 (2011).		X	X	Cradle-to-gate and unit process data.	Various Primary and secondary routes.	Outokumpu Technology, 2004. Mitsubishi Materials, 2004. Gresik Smelter – copper production in Indonesia, 2004. National Mining Association, 1999-2004. Mining Pollution Inventory in Australia, 2002-2003. Reference Document on Best Available Techniques in the Non Ferrous Metal Industry, 2000. ECI.	53 data sets of different copper qualities. See also GaBi Modelling Principles 2011.
Zinc (Zn)	CSIRO minerals (reported in Norgate et al. 2007).			X	Cradle-to-gate, i. e. from the lead-zinc ore extraction to the produced zinc.	Electrolytic process with imperial smelting process.	Process data based on various, mainly literature, sources.	–

Metal	Data publisher	Form			Data characterisation/description			Further remarks
		U	I	R	System boundaries	Covered technology	Data source(s)	
Zinc (Zn)	ecoinvent Centre (reported in Classen et al. 2009).	X	X	X	Cradle-to-gate, i. e. from the ore extraction (lead-zinc ore) to the produced primary zinc (secondary zinc is not taken into account).	Primary production – mix of 20 % pyro- and 80 % hydrometallurgical processes – of high-grade (SHG) primary zinc.	Values taken from Ayres et al. (2002), Xiao et al. (2003), IPPC (2001) and EEA (1999b).	Split into 3 different datasets (whereof the primary zinc dataset represents the use of zinc in coating processes and is not suitable for comparison of products containing zinc in a high degree).
	European Life Cycle Database (ELCD) v2.0 (available free of charge in the internet).		X		Cradle-to-gate, i. e. from the ore extraction to the produced high grade zinc.	Primary production – mix of 10 % pyro- and 90 % hydrometallurgical processes – of high-grade (SHG) primary zinc.	International Zinc Association (IZA), based on data from various sources.	1 single dataset – representing 32 % of global zinc production activities in 2005.
	International Zinc Association 2009.		X	X	LCI data for primary zinc (ingot at refinery gate), providing data for the "cradle-to-gate" system – zinc ore at the mine site to the production of primary zinc and shipment of zinc ingot from the gate of facility where it is produced Reference year 2005/6.	Data collection effort included zinc mining and smelting operations. The technological coverage for zinc smelting included both electrometallurgical and pyro-metallurgical production routes. The dominant route world-wide is the electrometallurgical production route.	Primary date from IZA member companies Mining – A total seven companies representing nineteen sites provided data on zinc mining which represented 44 % of the global zinc mine production volume for the reference year 2005 Smelting – a total of 10 companies representing seventeen sites provided the data. The participating companies represented approximately 3.38 million tons of refined zinc (3.27 million tons in form of special high grade zinc and 0.1 million tons in form of prime western zinc or cathode zinc). This data coverage represents 32 % of the global zinc production volume for the reference year 2005.	Zinc Environmental Profile (cradle to gate) published with select LCI data and related LCIA data. In addition environmental profile published for zinc sheet with LCI and LCIA data. Primary Zinc data submitted to US LCI Database and ELCD. Internal studies done on tier 2 products.
	PE INTERNATIONAL GaBi 5 (2011).		X	X	Cradle-to-gate and unit process data.	electrometallurgical smelting – roasting, leaching, purification, electrolysis and melting of a high grade zinx ingot.	The Production of Zinc, 2007. IZA. Reference Document on Best Available Techniques in the Non Ferrous Metal Industry, 2000. MIM Environment and Community Report, 2002.	high grade zinc and redistilled zinc.
Aluminium (Al)	CSIRO minerals (reported in Norgate et al. 2007).			X	Cradle-to-gate, i. e. from the bauxite ore extraction to the produced aluminium.	Bayer refining, followed by Hall-Heroult smelting.	Process data based on various, mainly literature, sources.	–

Metal	Data publisher	Form			Data characterisation/description			Further remarks
		U	I	R	System boundaries	Covered technology	Data source(s)	
Aluminium (Al)	ecoinvent Centre (reported in Classen et al. 2009).	X	X	X	Cradle-to-gate, i. e. from the bauxite extraction resp. the collection of aluminium scrap to the produced primary, secondary aluminium.	Primary & secondary production; using Bayer process for $Al(OH)_3$, Hall-Héroult cells with prebaked C-anodes or Söderberg-anodes for primary aluminium production; aluminium melting furnace for secondary production.	Production is modelled for the European situation, primarily based on data from EAA (2000) and personal communications. The mining represents a worldwide situation, based on Mori&Adelhardt (1998).	Split into 11 different datasets.
	European Life Cycle Database (ELCD) v2.0 (available free of charge in the internet).		X		Cradle-to-gate, i. e. from the bauxite extraction resp. the collection of aluminium scrap to the supplied aluminium (mix).	Primary & secondary production as a mix – including Bauxite mining, alumina and subsequent aluminium production.	European Aluminium Association (EAA), based on various sources.	Split into 2 different datasets for semi-finished products, one for sheet and one for profile.
	Forthcoming – ecoinvent v3 (2012).	X	X	X	Cradle-to-gate, i. e. from bauxite ore extraction to the primary aluminium casting; with industry specific regional power mix "children" datasets.	Mining, refining, smelting (inc anode production), casting.	IAI 2010 life cycle inventory data, with annual updates based on key IAI collected data: energy intensity (refining & smelting), power mix/fuel mix, PFC emissions, net anode consumption.	Split into 8 datasets: Bauxite Mine Operation. Aluminium Hydroxide Production. Aluminium Oxide Production. Aluminium Production, Wrought Alloy. Anode Production (Paste). Anode Production (Prebake). Aluminium Production (Søderberg). Aluminium Production (Prebake). Plus regional power mix.
	European Aluminium Association (reported in EAA, 2008). http://www.alueurope.eu/wp-content/uploads/2011/08/EAA_Environmental_profile_report-May081.pdf		X		Cradle-to-gate, i. e. from the bauxite extraction resp. the collection of aluminium scrap to the produced primary, secondary aluminium.	Primary & secondary production; using Bayer process for $Al(OH)_3$, Hall-Héroult cells with prebaked C-anodes or Söderberg-anodes for primary aluminium production; aluminium melting furnace for secondary production.	Primary data through surveys covering the year 2005 and focussing respectively on alumina production (6 sites), on anode (16) and paste (6) production and on electrolysis and casting (27 pre-brake and 8 Söderberg). Coverage for each step 90 %.	Datasets for 6 processes – representing primary aluminium production, semi-finished aluminium production (sheet, foil, profile), clean process scrap melting, and recycling of special scrap and end of life aluminium products.
	PE INTERNATIONAL GaBi 5 (2011).		X	X	Cradle-to-gate and unit process data.		AA, EAA, Alukey.com. Gesamtverband der deutschen Aluminiumindustrie e. V., 2006. European Aluminium Association, written communication, 2006. EAA Environmental Profile Report for the EU Aluminium Industry, EAA, April 2008.	175 data sets of different aluminium alloys sheets and profiles. See also GaBi Modelling Principles 2011.

Metal	Data publisher	Form			Data characterisation/description			Further remarks
		U	I	R	System boundaries	Covered technology	Data source(s)	
Nickel (Ni)	CSIRO minerals (reported in Norgate et al. 2007).			X	Cradle-to-gate, i. e. from the nickel ore extraction to the produced nickel.	Flash furnace smelting with Sherritt-Gordon refining (in case of sulphide ore), pressure acid leaching with SX/EW (in case of laterite ore).	Process data based on various, mainly literature, sources.	–
	ecoinvent Centre (reported in Classen et al. 2009).	X	X	X	Cradle-to-gate, i. e. from the ore extraction (part of nickel-copper ore) to the produced primary nickel (secondary nickel is not taken into account).	Primary production – mix of pyro- and hydrometallurgical processes – of class I primary nickel.	Data mainly based on Hilbrans & Hinrichs (1999), plus description taken from Kerfoot (1997).	1 single dataset – representing a world-wide average production of class I nickel.
	Nickel Institute (results reported on website, methodology reported in Nickel Institute, 2001).		X	X	Cradle-to-gate, i. e. from the ore extraction to the produced primary nickel products.	Primary production – including underground and surface mining (sulphidic and lateritic ores), beneficiation, primary extraction and refining by pyro- and hydrometallurgical processes.	Primary data through surveys from 9 companies, representing 55 % of world production.	Datasets for 3 products – representing class I nickel, nickel oxide and ferronickel.
	PE INTERNATIONAL GaBi 5 (2011).		X	X	Cradle-to-gate.	5 countries represent the nickel production mix according to the country-specific parameters and the different processing applications. The Australian route was modelled based on the procedure at two mines belonging to WMC Resources Ltd., the largest Australian nickel producing company. The modelling of the Russian route is based on literature and personally communicated information from the Russian company. MMC Norilsk Nickel Group, the largest nickel producer worldwide. The Canadian route was modelled using industrial data from Canadian nickel producers and is adjusted with current literature. The nickel produced in South Africa is a by-product out of the precious metal production.	WMC Resources Ltd. MMC Norilsk Nickel Group. Minecost: World Mine Cost Data Exchange Inc., World Mine Cost Data Exchange Inc., http://www.mine-cost.com/datalst.htm, Wilmington/USA, 2000-2004. Reference Document on Best Available Techniques in the Non Ferrous Metal Industry, European Commission, http://eippcb.jrc.es, Seville/Spain, 2000. Canadian nickel producers and is adjusted with current literature.	Nickel and ferro nickel.

Metal	Data publisher	Form			Data characterisation/description			Further remarks
		U	I	R	System boundaries	Covered technology	Data source(s)	
Lead (Pb)	CSIRO minerals (reported in Norgate et al. 2007).			X	Cradle-to-gate, i. e. from the lead-zinc ore extraction to the produced lead.	Lead blast furnace with imperial smelting process.	Process data based on various, mainly literature, sources.	–
	ecoinvent Centre (reported in Classen et al. 2009).	X	X	X	Cradle-to-gate, i. e. from the ore extraction (lead-zinc ore) resp. the collection of lead scrap to the produced primary, secondary lead.	Primary & secondary production; using the sinter/blast furnace (ISP) and direct smelting process for primary production, remelting of lead acid batteries for secondary production.	Values taken from Ayres et al. (2002), Xiao et al. (2003), IPPC (2001) and EEA (1999a).	Split into 5 datasets – among them, one representing the primary production, one for the secondary production and a third dataset representing the supply mix of lead used in Europe (i. e. 25 % primary/75 % secondary).
	European Life Cycle Database (ELCD) v2.0 (available free of charge in the internet).		X		Cradle-to-gate, i. e. from the ore extraction to the produced primary lead.	Lead blast furnace with imperial smelting process.	Dataset created for the ELCD database from PE International, using their own database.	1 single dataset.
	PE INTERNATIONAL GaBi 5 (2011).		X	X	Cradle-to-gate, The inventory is representing the production of primary lead produce imperial Smelting Furnace.	Primary production of lead requires the smelting of lead-bearing ores to produce lead bullion that is then refined. Most primary lead smelters have a complex refining process associated with them and associated processes to recover other metals from the ore as well, such as zinc, silver or gold.	World Mine Cost Data Exchange Inc., 2000-2004. Minerals Yearbook, 2001-2004. MIM Environment and Community Report, 2002. Reference Document on Best Available Techniques in the Non Ferrous Metal Industry, 2000.	Different regions.
Molybdenum (Mo)	ecoinvent Centre (reported in Classen et al. 2009).	X	X	X	Cradle-to-gate, i. e. from the ore extraction (copper-molybdenite ore) to the produced primary molybdenum (secondary molybdenum is not taken into account).	Primary production – mix of 20 % pyro- and 80 % hydrometallurgical processes (using the respective data from the zinc process as proxy!) – of high-grade primary molybdenum.	The production is modelled for global situation, based on data from various sources.	Split into 8 datasets – among them 1 dataset, representing the European consumption mix.
	International Molybdenum Association, IMOA (available from IMOA website www.imoa.info).		X		Cradle-to-gate, i. e. from ore extraction to intermediate and final molybdenum products.	Mix of underground and open pit mining and current technologies used for ore concentration and subsequent production of roasted molybdenite concentrate (RMC), RMC briquettes, ferromolyb-denum, and pure molybdenum oxide.	Primary data from IMOA member companies (see "covered technology").	Split into 4 data sets.

Metal	Data publisher	Form			Data characterisation/description			Further remarks
		U	I	R	System boundaries	Covered technology	Data source(s)	
Molybdenum (Mo)	PE INTERNATIONAL GaBi 5 (2011).		X	X	Cradle-to-gate.			On demand.
Chromium (Cr)	ecoinvent Centre (reported in Classen et al. 2009).	X	X	X	Cradle-to-gate, i. e. from the ore extraction (extraction of chromite ore) to the produced primary chromium (secondary chromium is not taken into account).	Primary production – mix of electrolytic production (via ferro-chromium) and alumina-thermic reduction of chromium chemicals.	Data mainly based on Adelhardt & Antrekowitsch (1998), as well as on IPPC (2001), IPPC (2002), Papp (1994) and EEA (1999).	1 single dataset – representing the European consumption mix in 1994 of chromium.
	PE INTERNATIONAL GaBi 5 (2011).		X	X	Cradle-to-gate.	Ore-Concentrate-smelter – electric arc furnace.	BHP – Sustainability Report 2003, 2003. Information on: Ferrochrome, 2003. Reference Document on Best Available Techniques in the Non Ferrous Metal Industry, European Commission, http://eippcb.jrc.es, Seville/Spain, 2000.	
Tin (Sn)	ecoinvent Centre (reported in Classen et al. 2009).	X	X	X	Cradle-to-gate, i. e. from the ore extraction to the produced primary tin (secondary tin is not taken into account).	Primary production via electro refining of smelted tin minerals.	Values are calculated, based on assumptions and theoretical models (taken from Graf (1997)).	1 single dataset – representing the summed-up efforts of mining, benefication, smelting and final refining.
	PE INTERNATIONAL GaBi 5 (2011).		X	X	Cradle-to-gate.	Ore- beneficiation-melting-Refining The data set represents the 6 largest Tin producing countries: Indonesia, Peru, Malaysia, Brazil, China, Belgium and Thailand focusing on the main technologies, the region specific characteristics and/or import statistics.	Carlin, J. F. Jr., 2009 Minerals Yearbook, U.S. Geological Survey (USGS), Tin, USA, 2011. World Mine Cost Data Exchange Inc., 2000-2004. Minerals Yearbook, 2001 – 2004. MIM Environment and Community Report, 2002. Reference Document on Best Available Techniques in the Non Ferrous Metal Industry, 2000.	
Mercury (Hg)	ecoinvent Centre (reported in Althaus et al. 2009).	X	X	X	Cradle-to-gate, i. e. from the ore extraction to the produced primary mercury (secondary mercury is not taken into account).	Primary production in furnaces, of open-pit mined, hand-sorted and crushed Hg-containing mineral.	Data source Simon (2001) used for the furnace step – preceding steps are based on analogies with other mining activities.	1 single dataset – representing the summed-up efforts of mining, beneficiation and smelting.

Metal	Data publisher	Form			Data characterisation/description			Further remarks
		U	I	R	System boundaries	Covered technology	Data source(s)	
Cadmium (Cd)	ecoinvent Centre (reported in Classen et al. 2009).	X	X	X	Cradle-to-gate, i. e. from the ore extraction (part of zinc-lead ore) to the produced primary cadmium (secondary cadmium is not taken into account).	Treatment of cadmium sludge from hydrometallurgical zinc operations and subsequent refining by electrolysis.	Global average data, based mainly on information in Schulte-Schrepping & Piscator (2002).	1 single dataset – representing the production of primary Cd (99.9 %) on a global average.
	PE INTERNATIONAL GaBi 5 (2011).		X	X	Cradle-to-gate, Cementation and filtration-Redisolution. Electrolysis.	Cadmium is a by-product of zinc production. There are two main zinc production routes used worldwide: From zinc-cadmium ore via hydrometallurgical route to cadmium metal, from zinc-cadmium ore via pyrometallurgical route to cadmium metal.	A.C. Tolcin, S. M. Weaver, L.D. Miller, Mineral Yearbook 2009 – Cadmium [Advanced Release], U.S. Geological Survey (USGS), 2011. Sustainability Report 2010, Nyrstar, 2010.	
Gold (Au)	ecoinvent Centre (reported in Classen et al. 2009).	X	X	X	Cradle-to-gate, i. e. from the gold ore extraction resp. the collection of gold-containing scrap to the produced primary, secondary gold.	Country-specific primary production processes of the 9 most important countries that produced gold/gold-silver. Current technologies from these countries are represented.	Various environmental reports of the mining companies in the 9 countries taken into account.	Split into 13 datasets – among them 1 dataset representing the Global consumption mix.
	PE INTERNATIONAL GaBi 5 (2011).		X	X	Cradle-to-gate.	The use of water-based solutions to extract and recover metals such as gold is called #hydrometallurgy.# Gold mining operations use very dilute solutions of sodium cyanide (NaCN), typically in the range of 0.01 % and 0.05 % cyanide (100 to 500 parts per million).	Outokumpu Technology, 2004. Mitsubishi Materials, 2004. Stoffmengenflüsse und Energiebedarf bei der Gewinnung ausgewählter mineralischer Rohstoffe. Gresik Smelter – copper production in Indonesia, 2004. National Mining Association, 1999 – 2004. Non-ferrous metals market, 1992 – 2004.	
Platinum Group Metal Platinum (Pt) Palladium (Pd) Rhodium (Rh)	ecoinvent Centre (reported in Classen et al. 2009).	X	X	X	Cradle-to-gate, i. e. from the PGM (platinum group metal) ore extraction resp. the collection of PGM-containing scrap to the produced primary, secondary platinum, palladium resp. rhodium.	Primary & secondary production; using a pyrometallurgical process, followed by a refining step (mix of selective precipitation & solvent extraction) for the primary production, pyrometallurgical refining of spoilt automotive catalysts for the secondary production.	Country-specific primary datasets for the two main producing countries (Russia, South Africa), based on Hochfeld (1997) – data from current recycling activities in Germany, again based on Hochfeld (1997).	Split into 4 datasets (for each of the three metals) – among them 1 dataset each time representing the respective European consumption mix.

Metal	Data publisher	Form			Data characterisation/description			Further remarks
		U	I	R	System boundaries	Covered technology	Data source(s)	
	PE INTERNATIONAL GaBi 5 (2011).		X	X	Cradle-to-gate and unit process data.	The Russian production route differs from the South Africa production route because the main focus in Norilsk Nickel is on nickel production and not on the precious metal production. Therefore the design of the production process is different and follows the production steps mining, beneficiation, smelting (Outokumpu and electric furnace), nickel electrolysis and the PGM refinery.	BHP – Sustainability Report 2003, 2003. Crown Minerals – Mineral Commodity Report 17, 2004. Gipronickel Institute, 2002. Stoffmengenflüsse und Energiebedarf bei der Gewinnung ausgewählter mineralischer Rohstoffe. Overview of Murmansk Region, U.S. & Foreign Commercial Service and U.S. Department Of State, 1999. KITCO Homepage, 1999-2005. Norilsk Nickel RAO, 2002. Bilanzierung der Umweltauswirkungen bei der Gewinnung v. Platingruppen-Metallen. Russia Mining Magazine, 2002. Autoabgaskatalysatoren Grundlagen – Herstellung – Entwicklung – Recycling – Ökologie 2002, Band 612. The Metals and Minerals Industry in South Africa – Part 1, 1989. Mineral and Metal Extraction – An Overview, The South African Institute of Mining and Metallurgy, 19. Information on: Mining, 2000.	
Cobalt (Co)	ecoinvent Centre (reported in Hischier 2009).	X	X	X	Cradle-to-gate, i. e. from the ore extraction to the produced primary cobalt (secondary cobalt is not taken into account).	Primary production pathway with reduction of oxides – using the nickel data as proxy for the mining and beneficiation steps.	Values are calculated, based on proxies, assumptions and theoretical models (taken from Donaldson (2000)).	1 single dataset – representing the summed-up efforts of mining, beneficiation, smelting and final refining.

Metal	Data publisher	Form			Data characterisation/description			Further remarks
		U	I	R	System boundaries	Covered technology	Data source(s)	
	PE INTERNATIONAL GaBi 5 (2011).		X	X	Cradle-to-gate and unit process data.	The Cobalt mix of the three available technology routes of the four production countries Norway, Canada, Australia, and South Africa is made up of 28 % Norway, 43 % Canada, 27 % Australia and 2 % South Africa. Statistical data of the composition are taken from the production statistics of the „Cobalt Development Institutes". Included in the model are the country specific mining conditions, Cobalt refining as well as transports to the refining countries.		On demand.
Arsenic (As)	-				-	-	-	-

Legend: U = unit process inventory data / I = cumulative inventory data / R = LCIA results

6.3.2 Coverage of the Various Data Sources

General

As described in chapter 4, metals require significant amounts of energy along their production chain, to be produced – but in function of the actual usage, this could also be true for the use phase, as well as in the subsequent recycling and/or end-of-life activities. Consequently, the energy consumption along the whole production chain is an important element to be taken into account here. As elaborated already in details in the preceding chapter 5, "mining, beneficiation, metal extraction and refining produces a range of solid, liquid and gaseous waste streams. [...] The main environmental impacts of primary metal mining and extraction revolve around water (consumption and quality aspects), mine wastes (tailings and waste rock), energy sources (direct such as diesel and indirect such as coal-fired electricity) and the associated air emissions (sulfur dioxide, greenhouse gases, dusts and particulates)". Hence, in the following the various data sources reported in Table 6.1 are – as far as this is possible with the support of the provided/published information – further examined and analysed in accordance with these points taken from chapters 4 and 5. The analysis is done according to the data sources, and not according to the individual metals, as data sources reporting more than one metal use usually a common framework/approach for the inventorisation of these various metals.

European Life Cycle Database (ELCD) v2.0

According to the authors from the JRC in Ispra (reported in the SimaPro implementation of this database) "the ELCD core database (version v2.0) comprises Life Cycle Inventory (LCI) data from front-running EU-level business associations and other sources for key materials, energy carriers, transport, and waste management. Focus is laid on data quality, consistency, and applicability. The respective data sets are officially provided and approved by the named industry association. " And further down it is stated at the same place of the database as a "Disclaimer", that "so far only internally reviewed and only partly harmonized LCI data sets are provided in this second version of the ELCD database. All data sets are carefully selected, of high quality and in line with ISO 14040 and 14044, but are not to be considered as official reference data sets." In other words, the data in the ELCD database are not all based on the same methodology report/the same methodological assumptions, but each industrial association – delivering data to this database – has been using its specific methodology/its specific methodological choices. And thus, it is not possible to describe here general principles for the three specific aspects (water, mine waste, energy) that are further detailed here. Instead, such a description has to be established on the level of the description of the various industry association data (see below).

Ecoinvent Data v2

General. The general objective/goal of ecoinvent is "to provide generic background data to be used in an LCA of products and processes" (Frischknecht et al., 2007). In Classen et al. (2009) it is stated further that "ecoinvent datasets on metal production are not meant to be used directly to analyse the metal producing processes nor can ecoinvent data be used to compare similar alloys of the same metals". Thereby, the data relate to either the year 2000 (those data established in the framework of ecoinvent v1 ... and not updated for the version v2) or then the year 2004/5 (those data newly integrated into ecoinvent v2). Since the various metal markets can be seen as global, additional datasets for other regions have been established as well, in order to be able to calculate respective production mixes for the European supply. As far as possible, co-production processes are modelled within ecoinvent, taking into account the actual composition of ores. Allocation is usually done by economic revenue (Classen et al., 2009).

Water. In general, the water consumption is taken into account in ecoinvent; split into the amount of cooling water (as one single elementary flow "water, cooling, unspecified natural origin") and the amount of process

water (split into 7 elementary flows – "water, lake", "water, river", "water, salt, ocean", "water, salt, sole", "water, turbine use, unspecified natural origin", "water, unspecified natural origin", and "water, well, in ground") that is recorded separately for each unit process step. However, the methodology report of ecoinvent (Frischknecht et al., 2007) doesn't contain any special chapter dealing in more details with the modelling of water consumption/use.

Mine waste. The tailings issue is taken into account since the version v2.1 (i. e. sulphidic, uranium and hard coal tailings including emissions data, e. g. for acid rock drainage (ARD)). A detailed description of the used tailings models for the sulphidic tailings can be found in part XIV of the metals report of ecoinvent (Classen et al., 2009).

Energy. Information about the energy consumption of the various production steps is included on the most detailed level possible, and linked to the respective energy production data within the ecoinvent database. The data about the amount of the consumed energy are taken from various sources (for details, see respective chapters of report Classen et al., 2009); the data for the provision of the respective type of energy (i. e. heat resp. electricity) are taken from the energy part within the database (described e. g. in Bauer et al. 2007).

European Aluminium Association (EAA)
General. According to EAA (2008), the report "provides up-to-date life cycle inventory data (LCI) for aluminium production and transformation processes in Europe. This report and the associated LCI data have been developed in full reference to the 2 relevant ISO standards ISO 14040 and 14044." The goal of this report is an update to the 2005 situation – showing average data for the European aluminium production. Data have been collected from the various member companies. According to EAA (2008) allocation has been avoided as far as possible by the application of the system expansion principle. Finally, the cumulative inventory data have been calculated by using the GaBi database and its content.

Water. In general, the water consumption is taken into account in the EAA data; however, only split into the amount of fresh resp. sea water. A distinction between process and cooling water is not done here.

Mine waste. No such data have been collected and/or reported, as these are considered irrelevant for bauxite mining.

Energy. Information about the energy consumption of the various production steps is included on a rather detailed level, distinguishing between various fuel sources as well as the input amount of electricity and linked to the respective energy production data within the GaBi database for the calculation(s).

European Copper Institute (ECI)
General. The scope of the ECI study is "the building of a cradle-to-gate life cycle inventory and life cycle assessment from the extraction of the copper ore at the mine to the production of copper products (tube, sheet, wire) through the production of primary and secondary copper cathodes".

The geographical scope is the European market mix (primary and secondary cathode produced in Europe and cathode imported to Europe resp. copper semis produced in Europe). The data sampling include annual representative data for the year 2005, representing an average of all production sites and technologies relevant for Europe. The study meets the requirements of the ISO 14040 and ISO 14044 standards as it has been stated by a critical review. System expansion as well as allocation has been used to isolate the LCI and the impact share of copper, because of the associated metals in the copper ore. Finally, the cumulative inventory data have been calculated by using the GaBi database and its content.

Water. In general, the water consumption is taken into account in the ECI data; however,

only split into the amount of river resp. surface water. A distinction between process and cooling water is not done here.

Mine waste. Due to the fact that impacts for tailings, waste rock as well as overburden are under discussion in the international LCA community, these data don't contain such information.

Energy. Information about the energy consumption of the various production steps is included on a detailed, step-by-step level, distinguishing e. g. the input amount of electricity (on a site-specific level) and linked to the energy production data within the GaBi database for the calculation(s).

International Molybdenum Association (IMOA)

General. Data represent global average cradle-to-gate data for roasted molybdenite concentrate (RMC) in powder form, RMC in briquette form, and ferromolybdenum in chip form from a 2008 study commissioned by the International Molybdenum Association and performed by Four Elements Consulting, LLC. One objective of the study was to provide high-quality, technologically and temporally representative data on molybdenum products to life cycle management or LCA practitioners to use in such studies. Nine member companies contributed data from 21 facilities that include primary and by-product mining and conversion facilities located in Europe, North America, and South America. 2007 process data on energy and materials consumed and environmental outputs were collected in detailed questionnaires. The data represented 52 % of the total molybdenum produced in the world and 75 % of western world production (which includes all production with the exception of molybdenum from China, Mongolia, and CIS). Co-production processes take into account the actual composition of ores as reported by IMOA member companies.

Water. Water consumption has been taken into account in the inventories. Its origin has not been specified so is reported only as coming from an unspecified origin. A distinction between process and cooling water is not done here.

Mine waste. Emissions from waste rock and tailings and related emissions are included in the data.

Energy. Information about the energy consumption of the various production steps is included on a detailed, step-by-step level, for detailed energy usage from mining to concentration (beneficiation), to roasting into RMC, and further transformation into RMC briquettes and ferromolybdenum. For both sets of data, the energy consumption data has been linked to the respective energy production data to obtain cumulative inventory results, provided to the public.

Nickel Institute

General. According to Nickel Institute (2000), the report "provide the Nickel Industry with a current LCA of three nickel products (i. e. Class 1 nickel metal, Nickel oxide, and Ferronickel), using current, robust data on nickel production." The study is in accordance with the ISO standards about LCA. Data, representing western world production (plus Cuba), have been collected from the various member companies and may be used for benchmarking purposes as well. The collected data represent about 55 and 87 % of the respective global production. A cut-off criteria of 99.5 % mass of inputs resp. outputs is applied in each major process step. Concerning the allocation issue, the principle of a partitioning on a mass basis (of the metal in the coproducts) is applied to the data. Finally, the cumulative inventory data have been calculated by using the TEAM software and its database content.

Water. Water consumption is taken into account in the Nickel Institute data; According to the input categories in the Nickel Institute data, only a split according to the origin of the water (e. g. public network, river, well, sea resp. unspecified water) is done; but no distinction between process and cooling water is made. However, further down in the Nickel

Insitute (2000) it is mentioned that not only the source of water, but also the type of water (process/cooling) is distinguished.

Mine waste. The Nickel institute data distinguish three types of solid material output – i. e. "waste rock and backfill", "tailings and process residues" and "solid materials: others" – however, no further treatment of these materials is taken into account.

Energy. Information about the energy consumption of the various production steps is included on a detailed, step-by-step level, distinguishing between various fuel sources as well as the input amount of electricity (on a national, partly even site-specific level) and linked to the energy production data within the TEAM database for the calculation(s).

World Steel Association (worldsteel)
General. According to the extract of the worldsteel report "LCA Methodology Report", published on the worldsteel website (worldsteel, 2011), the objective of this project was to "update the steel industry's LCI database and improve the already rigorous LCI methodology for steel products". The study is in accordance with the ISO standards about LCA. 'Cradle to gate' data are provided forall the major raw materials, energy usage, air and water emissions, and wastes for 15 different steel products. Data is also provided as cradle-to-gate including (net) end-of-life recycling credits. Primary data is collected from the various worldsteel member companies.

For simplification, around 40 major flow categories (inputs and outputs) are provided free of charge to those requesting the data; the full LCI will be provided on request. According to worldsteel (2011), both worldwide and regional averages (currently only EU; North American data is being developed) are available provided that a minimum of three sites contributed data for that product. According to worldsteel (2011) allocation principles have been applied along the supply chain for steel products. Finally, cumulative inventory data have been calculated by using the GaBi database and its content.

Water. In general, water consumption is taken into account in the worldsteel data. However, no distinction is made between the amount of fresh and sea water, nor a distinction between process and cooling water.

Mine waste. Overburden from mining has been reported as 'deposited material'.

Energy. Information about the energy consumption of the various production steps is included, distinguishing between various fuel sources as well as the input amount of electricity and linked to the respective energy production data within the GaBi database for the calculation(s).

6.3.3 Allocation

An important issue in the LCI stage is allocation. This refers to the allocation of the various environmental interventions to the different economic outputs of a multi-output process. In the field of metals, this is very often the case: from most ores, not one but several or even many metals are produced. It is then important to decide on how to allocate the emissions and extractions of the previous chain to those different metals. Various options exist and are applied, and each has their own advantages and drawbacks. There is no "correct" option, as allocation is a choice. It is however of great influence on the outcomes, as different options can lead to totally different and even opposite result. For example, economic allocation will put most of the burden on small-scale but expensive precious metals such as platinum, while mass allocation will shift the burden to the bulkier metals such as nickel or copper. In LCA-studies involving metals it is therefore important to pay attention to how allocation is treated, since this is of the utmost importance for the comparability of the results between case studies. A sensitivity analysis is indicated when metals contribute significantly to the impacts.

6.4 Life Cycle Impact Assessment (LCIA)

6.4.1 Single Aspects

In relation to the topic of this report – i. e. the production of various metals – important indicators among the huge amount of various LCIA indicators available in a variety of LCIA methods (for a recent overview see e. g. European Commission, 2010a) are the Abiotic Resource Depletion (ARD), the Global Warming Potential (GWP) – or alternatively the Cumulative Energy Demand (CED) – as an indicator for the energy intensity of a process, the Acidification Potential (AP) and the Ecotoxicity Potential (ETP), both representing the releases of acidic substances into the environment. In some publications (e. g. Norgate et al., 2007), additional indicators can be found for the amount of waste produced – like e. g. the Solid Waste Burden (SWB); although there are nowadays data available for different waste treatment activities in order to avoid this kind of indicator; and include instead the total amount of emissions occurring in these treatment activities into the overall amount of emissions across the life cycle. In general, impact factors are calculated by using models for the fate of a unit of emissions, specifying in what environmental compartments it will end up in, and models for the impact, including both the exposure and the actual effect. More information about the modeling of these impact categories can be found in Annex 6.

Toxicity

For metals, toxicity impacts are relevant. Toxicity impacts have a large variety, as explained in Chapter 2. In the LCIA methodology development, it is still an impact category in development. Data are incomplete, but also for the modelling approach no consensus yet exist. Nevertheless, there are some approaches that can be used. In LCA studies, toxic effects are often expressed in two indicators, i. e. the toxicity potential for ecosystems and the toxicity potential for humans. Toxicity indicators for ecosystems are sometimes further subdivided into terrestrial and aquatic systems toxicity, and the latter into marine and freshwater aquatic system toxicity. The most relevant toxicity indicators in recent LCA, which both address human and ecosystem toxicity, are implemented in the following impact assessment methods: USEtox (Hauschild et al., 2008; Rosenbaum et al., 2008), CML 2001 (Guinée, 2001), ReCiPe (Goedkoop et al., 2009). Other LCIA methods to evaluate ecosystems or human toxicity are: EDIP 2003 (Hauschild and Potting, 2005); Eco-indicator 99 (Goedkoop and Spriensma 2001); EPS 2000 (Steen, 1999a; Steen, 1999b); Impact 2002+ (Jolliet et al., 2003); Stepwise 2006 (Weidema et al., 2007; Weidema, 2009); and TRACI 2 (Bare et al., 2002).

Pizzol et al. (2011a) evaluated eight LCIA methods (CML 2001; EDIP 2003 ; Eco-indicator 99; Impact 2002+; ReCiPe; Stepwise 2006; TRACI 2 ; USEtox) regarding the eco-toxicity of metals by measuring the contribution of metals and other toxic substances to the total eco-toxic impacts and to reference-processes. Results showed that there is a poor agreement between methods in the determination of the total eco-toxic impact attributable to metals, and in defining which metal provokes the highest eco-toxic impact per unit emission. Furthermore, the characterization phase was found to be critical in determining the disagreement between methods. However, some similarities were found: there is the tendency in most methods to associate the largest share of the total eco-toxicological impacts to metals.

The observation that metals have strong contributions to ecotoxic impacts is not new and already in 2004 an expert workshop held under the auspices of the UNEP-SETAC Life Cycle Initiative in Apeldoorn, the Netherlands, gathering metal risk assessment experts and LCIA experts, recommended that specific focus must be given to the characterisation modelling of metals (Ligthart et al., 2004) in order to address some of the characteristics of metals better in the modelling of fate, exposure and ecotoxic effects. In 2008 a follow-up expert workshop in Clearwater, Florida gave recommendations on how to address central issues in the modelling of freshwater

ecotoxicity of metals in LCIA (Diamond et al., 2010). The metal characteristics that are not well addressed in current characterisation models for ecotoxicity are in particular the fact that in contrast to organic compounds, metals do not degrade in the environment and this means that in principle they are present infinitely after emission. The fact that the bioavailability of metals and hence their ability to expose organisms and cause toxic effects changes after emission is not well captured by current characterisation models that are mainly based on risk assessment models developed for organic compounds. The ability of metals to appear in the environment in different forms (species), depending on the characteristics of the surrounding conditions thus has an important influence on the bioavailability and the resulting toxicity of the metal. In practice it is mainly the free ion that is toxic, and often it is but a very small fraction of the dissolved metal in water that is present as the free ion (Christiansen et al., 2011). Inclusion of the speciating behaviour of metals in freshwater has recently been addressed in the development of new freshwater ecotoxicity characterisation factors intended to be implemented in the USEtox model (Gandhi et al., 2010 and 2011).

Pizzol and co-workers also evaluated LCIA methods (CML 2001; EDIP 2003; Eco-indicator 99; Impact 2002+; ReCiPe; Stepwise 2006; TRACI 2 non carcinogens ; USEtox) applied to human toxicity (Pizzol 2011b). The results also here showed poor or no agreement between the methods. The differences are due mainly to the number of metals included in each method and to the technique used to calculate the characterization factors. Results obtained with USEtox, which today is recommended as the best model for LCIA on human toxicity despite high uncertainties, show no apparent correlation with results calculated with other methods.

Resource Extraction and Depletion
Compared to emissions, environmental impacts related to depletion of resources are in an early stage of development. No generally accepted assessment method exists for these issues. Several approaches are outlined, including mostly fossil fuels and sometimes metals. For this report, no attempt has been made to apply depletion potentials, as the focus is on environmental impacts.

Land and Water Use
Land use and land use change is presently under debate in the LCA community. This issue has come up especially in relation to the assessment of biofuels. It has led to much progress in the area of consequential LCA (see section 6.5). With regard to water, a recent activity is the development of water footprints (van der Hoek et al., 2011). These include all cradle-to-gate water extractions, specified in grey, green and blue water, connected to certain products or services. Presently, no water footprints of metals yet are agreed on. It is, however, a relevant issue and it is worthwhile to follow developments in that area.

6.4.2 Weighing and Ranking of Results

LCA studies generate environmental impact score results for a number of very different categories of impact. In the comparison between impacts of different metals, there may be trade-offs between the impact categories, i. e. one metal has lower impacts in GWP but another metal has lower impacts in ARD. Comparisons thus call for a ranking of the different impact categories or even a quantitative weighting of the impact categories allowing the LCA practitioner to aggregate the weighted results across the impact categories and arrive at one score representing the environmental cradle-to-gate impact per kg metal. Both for ranking and weighing there is no consensus about how to rank or weigh and not even about the criteria to apply and how to apply them (Finnveden et al., 2009). This is a strongly value-based part of the LCA, and according to the ISO standards for LCA, weighting is not allowed in LCA studies supporting comparative assertions to be disclosed to the public (ISO, 2006a and ISO, 2006b). Weighting is not always a necessary step – often, the information out of the LCIA is sufficient. Sometimes it is, for example when one indicator of environmental performance needs to be compiled. The ISO recommendation is then to use various options to show the sensitivity of the results for different weighting approaches. Weighting, like allocation, can have a large influence on the outcomes.

The impact categories can be defined ad midpoint-level, i. e. for all of them the category indicator is chosen as some intermediate point in the impact pathway between emission and damage to the areas of protection (Human health, Natural environment and Resources). Examples of such midpoint impact categories are Global warming potential, Eutrophication potential, Toxicity potential etc. Another school in characterisation modelling is the Endpoint or Damage school that chooses the indicator at the level of the area of protection and thereby includes the whole impact pathway in the characterisation model. Recent years have seen the development of several LCIA methods including characterisation at both midpoint and endpoint level (e. g. the Japanese LIME method (Itsubo et al., 2003) and the Dutch ReCiPe model (Goedkoop et al., 2009). With endpoint methods the need for ranking or weighing is much reduced – there are only three indicator results per metal (damage to human health, damage to natural environment and damage to resources). This simplification, however, comes at the expense of an increased uncertainty. The impact pathway connecting the typical midpoint indicator to the area of protection is often very uncertain, and the midpoint-to-endpoint characterisation models are therefore generally associated with a high level of uncertainty (in particular for impacts on a global scale and with long time horizons like climate change).

6.4.3 Scaling up LCA Results to the Global Level

LCA is a methodology that is developed for micro-scale assessments: a single functional unit. The assumption is then, that changes at this scale are too small to have an impact on the wider economy. When assessing options for change for the future, this assumption in many cases won't hold. In such cases, arrangements must be made to estimate the wider impacts. For this, various approaches have been developed. One is the so-called hybrid-LCA (see e. g. Suh and Huppes, 2005), linking the product system to an Input Output model at the (supra)national level. Another is the development of consequential LCA (see e. g. Ekvall and Weidema, 2004 – a paper with a comprehensive overview of further publications dealing with consequential modelling), where changes at the macro-scale are translated down to the micro-scale. This last form of LCA is used often in assessments of bio-energy, as a response to the debate on food competition (see e. g. van der Voet, 2010 – a comprehensive review paper about recent studies in this area).

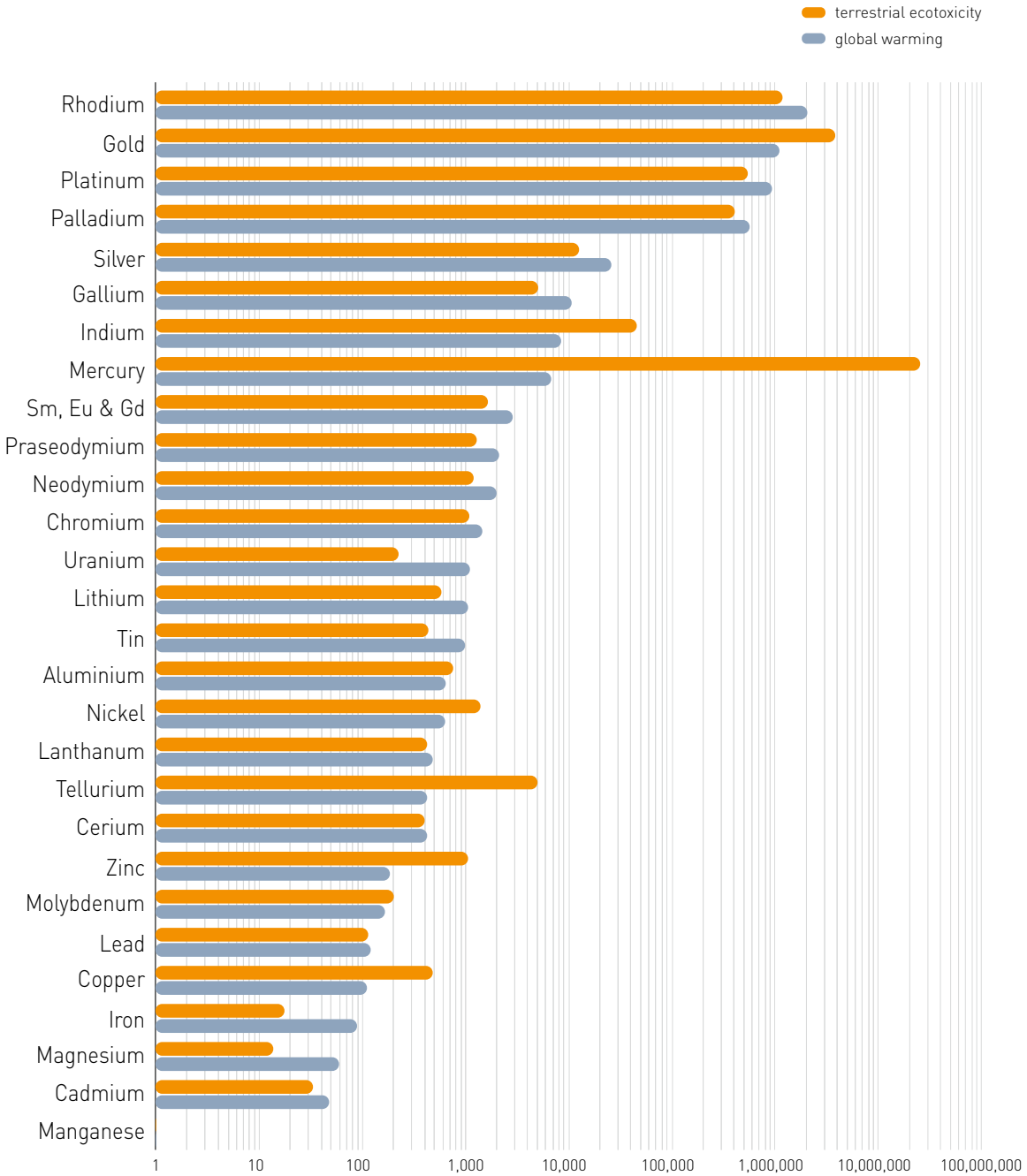
However, when we are looking at the global level, even such approaches will leave relevant aspects out of the picture. A newly emerged concept is that of Life Cycle Sustainability Assessment, LCSA (Heijungs et al., 2010). The concept is as yet rather undefined, but the aim is clear: to enable analysis at the global, or at least larger, scale level while maintaining the essential and valuable LCA view, the cradle-to-grave chain or life cycle approach. Only at the global level we can see what it truly means to use new technologies, new materials or to replace one system with another. At the global level we see the shortcomings of the single-focus assessments and scenario development. Graedel & van der Voet (2010) point to the linkages between the main resources of the world: land, water, energy and materials. In order to mobilise one for human use, the others are needed as well, and there may be developments and linkages that are spiralling out of control.

This issue is crucial for sustainable development as well as resource efficiency, and is as yet hardly explored. Some first global assessments have been made with regard to metals, which will be discussed in Section 6.5.

6.5 LCAs of Metals and Metal Products

6.5.1 LCAs at Micro Scale

A straightforward exercise of a cradle-to-gate LCA of metals, with the aim to discover priority metals from an environmental impact point of view, has been included in a previous report of the IRP (UNEP, 2010a). Applying Ecoinvent LCI data for a number of metals led to the conclusion that, on a per kg basis, small-scale metals from the PGM group, gold and others have a cradle-to-gate impact that is orders of magnitude larger than that of the more bulky metals such as Fe and Al.



Contribution of 1 kg of metal to global warming and terrestrial ecotoxicity, relative to Mn (=1), logarithmic scale, based on Ecoinvent process data

Figure 6.2

Cradle-to-gate contribution of 1 kg of metal to emissions of greenhouse gases (in CO_2-equivalent) and emissions of toxic substances (in kg 1,2 dichloroethane equivalent), relative to Mn (=1) (UNEP, 2010a).

However, such a simple comparison of the LCA results of 1 kg of metals is generally not very useful, as the same amount of different types of metals can be used to fulfil very different purposes and objectives. Thus a more detailed discussion, but based on a different approach would make much more sense. Starting point for such a discussion should be the life cycle perspective of a (metal containing) product; i. e. its split into production (including extraction and refinement of metals), use phase and end-of-life treatment (e. g. recycling). While the production phase can be considered in all cases as rather similar (i. e. we have to extract, refine a certain amount of one or several metals that then – via more or less intermediate steps – are "put together" to a specific product), the use phase can be very different, i. e.

(i) A use phase with a considerable energy consumption – resulting usually in the fact that the use phase has the main environmental impact.

(ii) A use phase with almost no energy consumption – resulting usually in the fact that the production phase gets much more important, even dominant.

(iii) A use phase with an energy production – i. e. the use of these materials in infrastructure for energy (heat/electricity) production.

On a general level, there exists a huge bunch of different application examples (LCA studies) for each of these three types. However, interesting in the context of this report here are only those examples that report in details about the impacts related to the respective employed metals. However, a first literature review by the authors of this chapter has not yielded studies that report about these impacts (i. e. those of the used metals) as opposed to the total impacts. Hence, the following two examples – dealing with mobility and ICT (information and communication technology) – are mainly based on work from the chapter authors; here it was possible for the authors to have a more detailed insight.

Case No. 1 – "Mobility"

In the last couple of years, LCA studies in the area of mobility gained again more importance – mainly due to the discussion of alternatives to the currently used internal combustion engines (ICE). In the framework of her work about electro passenger cars, Habermacher (2010) made an extensive review of existing LCA studies not only about electro mobility, but also about conventional cars; showing in both cases that there are various such studies available. More important is however the fact that Habermacher (2010) – in line with further publications from the same research group (e. g. Althaus and Gauch 2010; Notter et al. 2010) – makes a clear distinction between the – from the engine independent part of a car – called "glider" and the parts that depend on the type of engine, called "powertrain". The study focuses on mini, city and compact cars – i. e. on cars of the size of a Smart, up to the Golf class. Here the "glider" represents about 75 % of the total weight – containing 82 % of the totally used steel, 6 % of the aluminium, 32 % of the non-ferrous metals and 77 % of the plastics (Habermacher, 2010).

In terms of Global Warming Potential (GWP) and Cumulative Energy Demand (CED), Habermacher (2010) shows the following pictures for the three different car sizes (mini cars, represented by a Smart/city cars, represented by a Fiat 500/compact cars, represented by a Golf VI) examined.

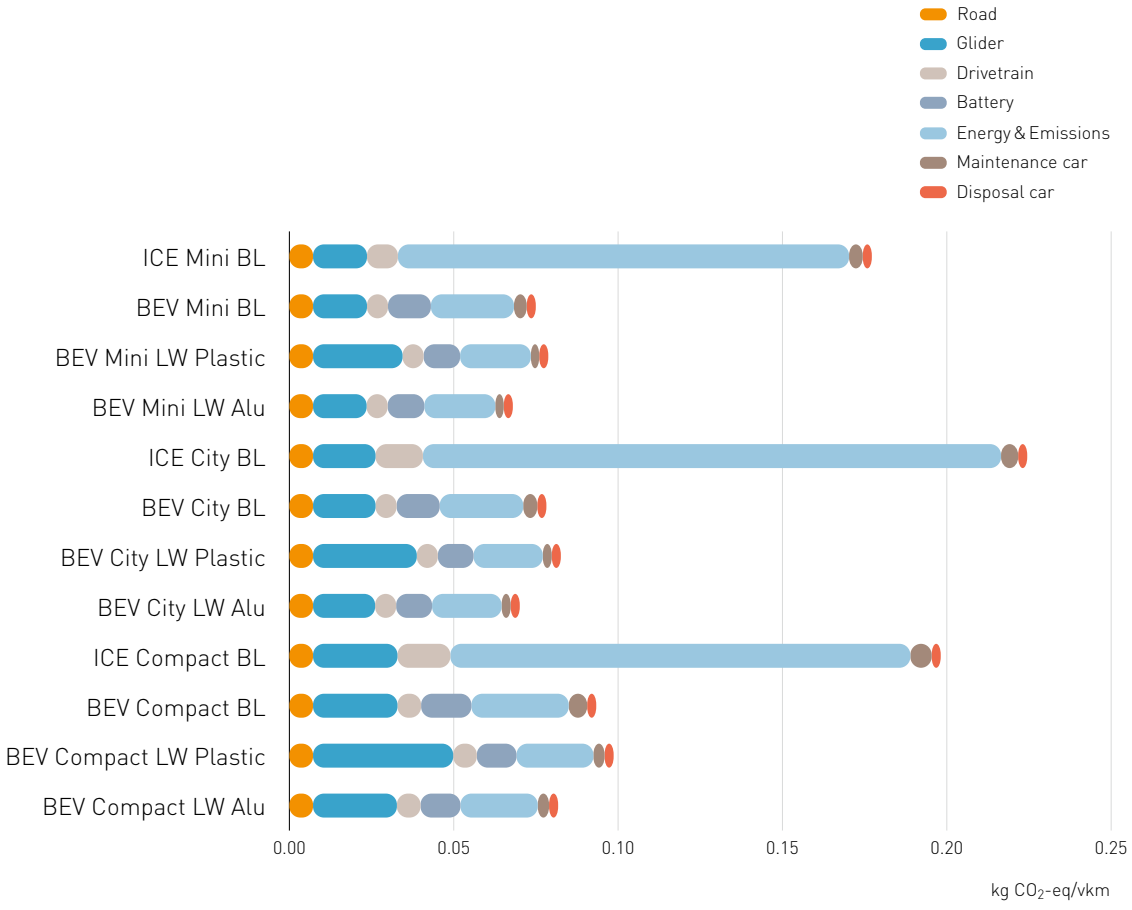
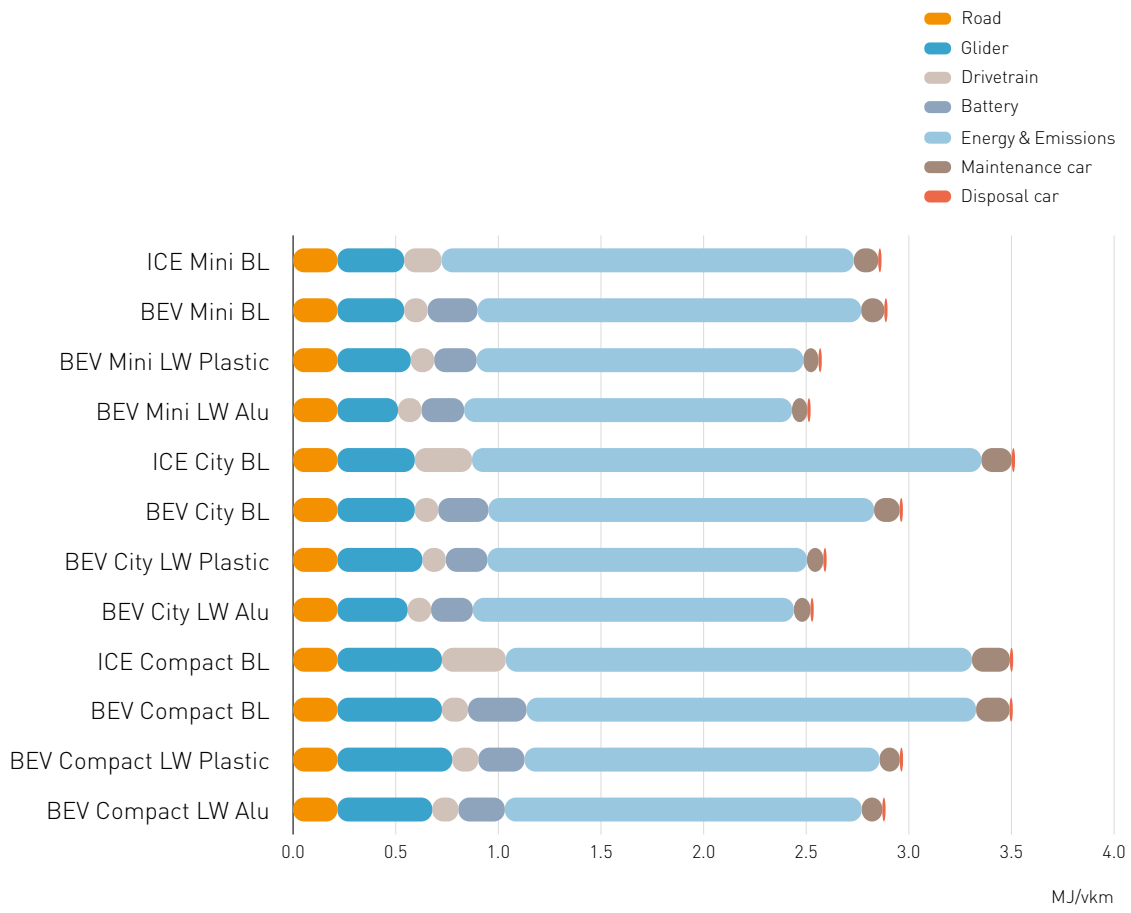


Figure 6.3

Global warming potential related to three types of cars, broken down into the various life-cycle stages (Habermacher, 2010).

Figure 6.4

Cumulative energy requirement related to three types of cars, broken down into the various life-cycle stages (Habermacher, 2010)



From these two figures it could be clearly seen that the use phase is dominating – not only in case of the traditional, internal combustion engine (ICE), but also in case of the battery electric vehicle (BEV). Within the infrastructure, i. e. the car itself, the drivetrain seems to have a slightly higher impact than the glider – then (as shown especially by the three ICE cases) the proportion is rather 1:2 instead of 1:3 as in case of the weight. More detailed information concerning the importance of the used metals (in relation to the environmental impact) can't be found in the examined literature – for this, additional calculations would be required.

Case No. 2 – "ICT"

Another important area for the application of a broad variety of metals is the Information and Communication Technology (ICT). Probably the most often examined device within this sector is the traditional desktop Personal Computer (desktop PC). One of the first – and since then often cited – studies about a desktop PC has been established in 1998 (Atlantic Consulting 1998). Since then, a broad variety of different LCA studies on desktop PCs have been carried out (e. g. Choi et al. (2006), Hikwama (2005), Duan et al. (2008), Tekawa et al. (1997), Williams (2004) or Yao et al. 2010). Also in large databases (like e. g. the ecoinvent database), such a dataset can be found nowadays.

A comparison of the Desktop PCs reported in Kemna et al. (2005), Hikwama (2005) and Duan et al. (2009), by calculating these systems with the database ecoinvent data v2.0 as a background system, and a subsequent comparison of all these systems, shows a rather similar picture for all described PCs in comparison to the one reported in ecoinvent data v2 (Hischier et al. 2007). The results show less than 10 % difference between the model with the highest impact (original ecoinvent data) and the one with the lowest impact (EuP model, reported in Kemna et al. (2005)); despite their rather big difference in the degrees of details concerning the actual modelling of the composition of such a desktop PC model.

Hence, for a more detailed analysis of the desktop PC, the model in the database ecoinvent can be used, as it represents all these various models as well. Such an analysis (established in the software tool Simapro, using the LCIA method "Eco-Indicator'99") shows that the main environmental impact of a Desktop PC is due to the various printed wiring boards (PWBs) and the Power Supply unit (PSU); together responsible for about 70 % of the overall impact of a Desktop PC (without a screen!). On the other hand, the metallic housing (about 8 kg of steel) that is responsible for almost 70 % of the total weight, represents only about 5 % of the overall environmental impact. Within the two above mentioned modules (PWBs, PSU), the electronic components – and there especially the various integrated circuits (ICs) that are part of the device – are responsible for the high impact of these two components.

Having a look on the level of the basic materials (i. e. metals, fuels, plastics, etc.), the picture shows the highest environmental impact for the precious metals (palladium, gold and silver) with almost 50 % of the overall impact. Copper, similar as for steel, has only a very minor impact (less than 3 %), although it can be found in much higher quantities within a Desktop PC than the precious metals. All in all, these analysis results show the facts from figure 6.2, i. e. that producing precious metals has a much higher environmental impact than producing base metals like steel, aluminium or copper.

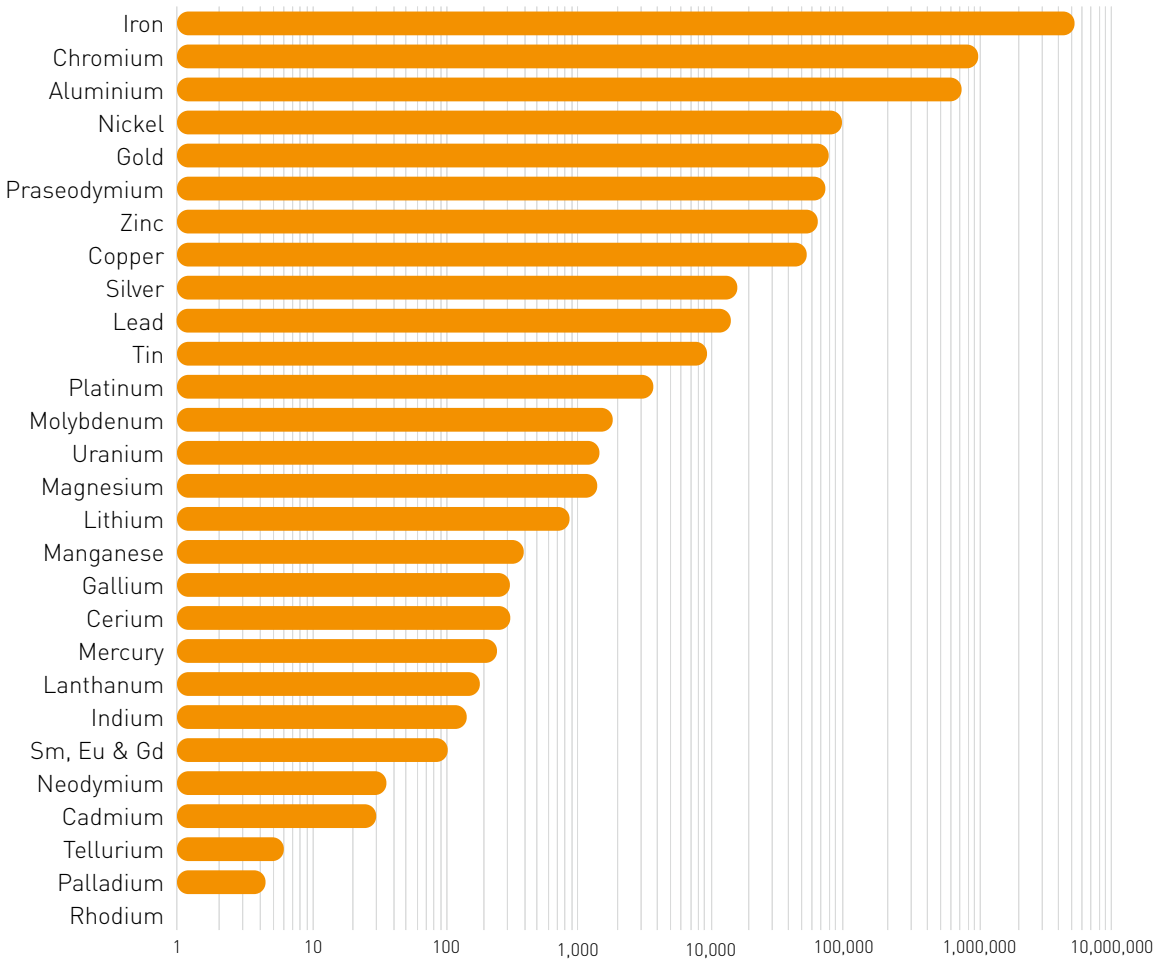
6.5.2 LCA Approaches at Macro Scale

The per-kg impacts as visualised in Figure 6.2 can be multiplied by the annual global production of the metals to obtain an indication of global impacts related to metals production. Figure 6.5 shows the results of such an exercise: global annual production of metals multiplied by their global warming potential. Compared to Figure 6.2, the order of metals based on their contribution to GHG emissions is different: the bulky metals contribute most. Their scale of production apparently is so much larger that it more than compensates for the lower per kg impacts.

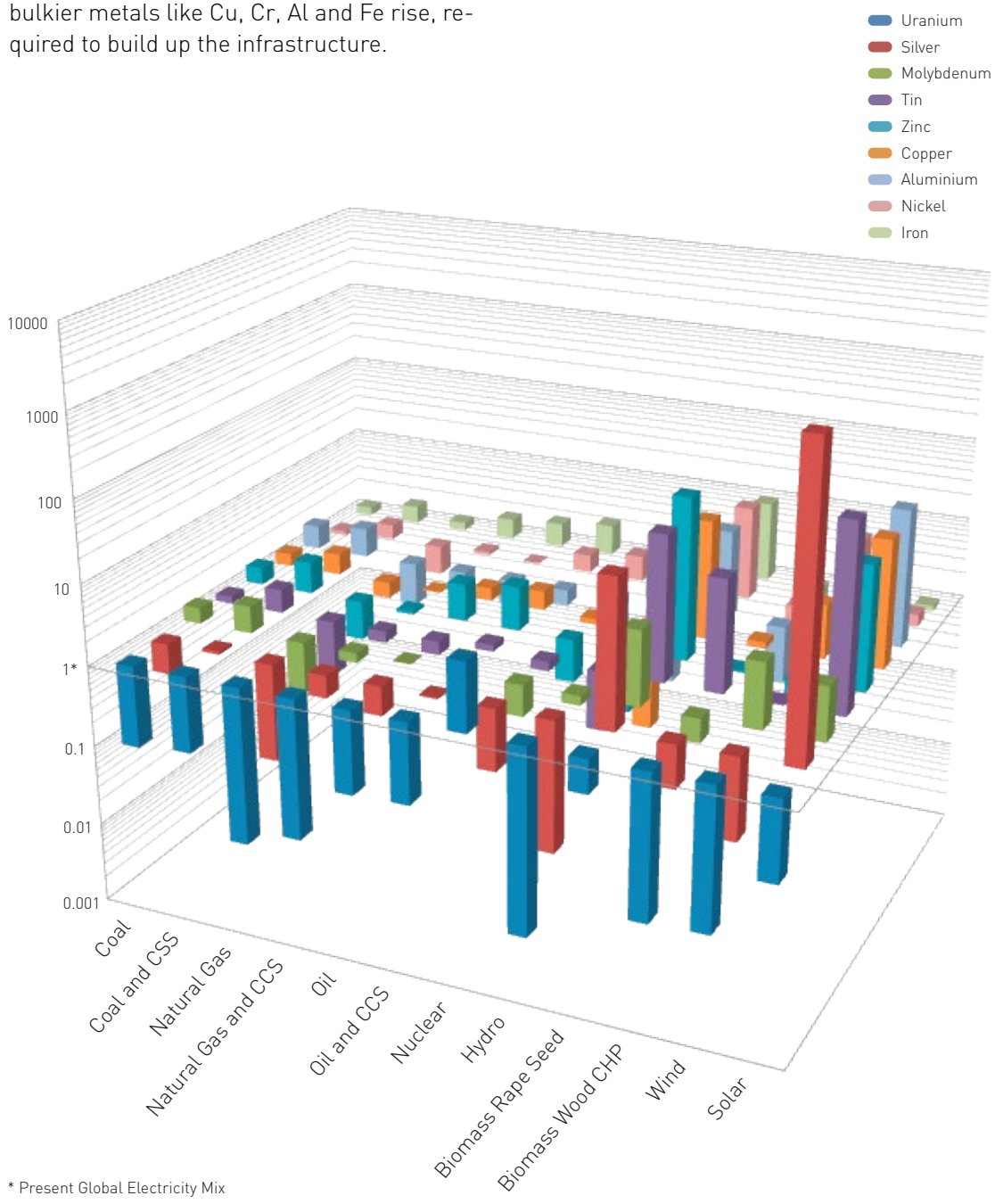
As discussed above, these numbers come from an LCI database and refer to the micro-level. In an attributional sense, they could be used at the global level, although with care. In a consequential approach, for forecasts and predictions, they are unsuitable. Nevertheless, it gives an indication – added together, the total amounts to roughly 10 % of total global GHG emissions, which is a little on the high side but not way off.

Figure 6.5

Contribution of global production of metals to global GHG emissions, normalised to Rh production (=1) (UNEP, 2010a).



Kleijn et al. (2010) and (2011) have assessed, using a life-cycle approach, what the consequences would be for the use of materials if a shift to renewable energy systems would be made. They concluded that renewable energy systems in all cases are far more resource intensive than the present, fossil fuel based system. Specialty metals such as Pt, Ag and Nd, with a high per kg impact, would be subject to steeply rising demand assuming certain technologies would be implemented on a large scale. Even more would the demand for bulkier metals like Cu, Cr, Al and Fe rise, required to build up the infrastructure.



* Present Global Electricity Mix

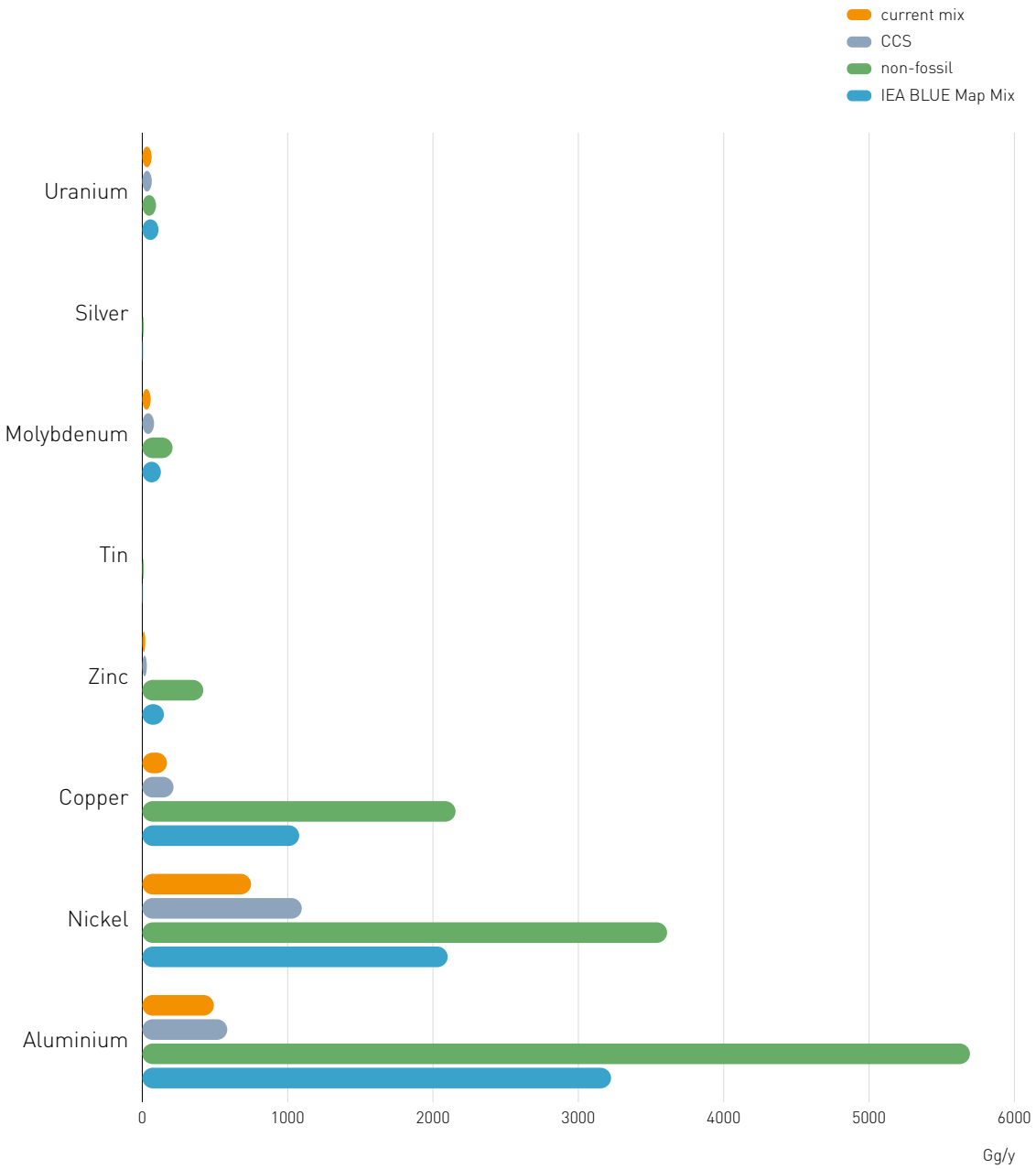
Figure 6.6

Demand for metals for various electricity generating technologies, compared to the present global electricity mix, logarithmic scale (Kleijn et al., 2011)

In various global scenarios, this would work out as depicted in Figure 6.7 below.

Figure 6.7

Demand for metals for the global electricity system under various scenario assumptions (Kleijn et al., 2011)



CCS: current (2007) mix extended with carbon capture and storage on fossil fuel based powerplants

Non-fossil: mix of solar, wind and hydropower

IEA Blue Map: mix according to Shell Blue Map scenario, including fossil fuels as well as renewable energy sources.

It is to be expected that the increased demand will lead to scarcity problems on the market as well as increased environmental impacts, especially if combined with the insight of Chapter 4, that future metal production may require increasing amounts of energy.

6.6 Conclusions and Outlook

Life cycle assessments of metal containing products currently give controversial results. This is due especially to the high energy intensity of production processes versus the high energy consumption and/or production of many products in use; but also due to the fact that the use of a metal usually does not result in direct emissions (to air, water or soil) of the metal itself; whereas mining, smelting and refining can displace large masses of metal compounds that do not necessarily result in large emissions either (to air, water or soil). Finally, only complete product LCAs can successfully take into account the benefits generated by the use of metals to supply a particular functional unit (e.g., energy savings due to durability, conductivity, etc.).

The production of different metals has different potentials to impact the environment. As a general rule, production of the metals being produced in large quantities has a lower per kg impact than production of those being produced in small quantities. The difference between the global warming potential of producing a kg of Fe and a kg of Rh is five orders of magnitude. When multiplied with the annual production, however, Fe production still presents the most potential for environmental impacts. The potential impact of using these metals within single devices – as shown with the example of the Desktop PC – can however look very different.

Studies to support prioritisation of a materials or resource policy come to the conclusion that, compared to other production processes, metals production has a high impact per kg produced (van der Voet et al, 2005). However, other materials are produced in far higher quantities. UNEP (2010a) conclude in a report for the IRP that agricultural resources, especially of animal origin, have most impact on the environment, next to fossil fuels. Although this is not likely to change, it is possible that metals will become relatively more important from an environmental impact point of view, for the following reasons:

- The demand for most metals is rising rapidly, much more so than the demand for agricultural products. For bulk-metals such as iron, copper and aluminium the expected increase is related to the building-up of the infrastructure system in developing economies. For the smaller metals the rapid increase in complexity in and demand for electronics is a relevant trend.

- As shown above, a shift towards a renewable energy system implies that the material, and especially metal, intensity of energy production will increase substantially.

- In future, the energy intensity of the production of metals is expected to increase due to the use of lesser grade ores.

To what extent these events will occur, whether this feedback loop will spiral out of control and to what extent it will be mitigated by increased exploration, cleaner and more energy efficient processes, increased secondary production and other things is difficult to estimate.

Last but not least, the overview in chapters 6.3 and 6.4 shows that LCA data for a broad variety of metals are already available. From the in this report taken into account list of metals, only one element (Arsenic) is not represented in chapter 6.3 with at least one inventory dataset. On the other hand, those metals for which several datasets are available (like e. g. for copper and steel) show that there are sometimes rather large differences between these various data sources – in terms of the shown degree of details (e. g. are unit process data published, or only cumulative inventory data?), but also in terms of the reported LCIA results. Here, common efforts from the various actors in the LCA community are requested in order to come one step ahead … a step that ideally leads (for each single metal) to comprehensive, industry-based, transparently documented inventory data that can then be integrated in a consistent way into the different existing LCA databases and software tools; allowing all LCA practitioners to do LCA studies based on the same basic inventory data for these important materials.

7. Conclusions and Recommendations

Authors: Ester van der Voet, Reijo Salminen, Matthew Eckelman, Terry Norgate, Gavin Mudd, Roland Hischier, Job Spijker, Martina Vijver, Olle Selinus, Leo Posthuma, Dick de Zwart, Dik van de Meent, Markus Reuter, Ladji Tikana, Sonia Valdivia, Patrick Wäger, Michael Hauschild, Arjan de Koning

Metals are used in society since millennia. They are used because of their unique properties, such as their conductivity, malleability, hardness or lustre, in a variety of functions. Metals fulfill an explicit role in many new technologies, including renewable energy technologies required to transform the energy system into a more sustainable direction. Nevertheless, their production and use, as is true for all resources that we extract and use, is associated with environmental impacts. Optimizing metals systems and life-cycles from a point of view of environmental impacts is therefore an integral part of a sustainable metals management.

7.1 Present Situation

Metals, once they enter the environment, tend to accumulate in soils and sediments. They enter the food web via plant uptake and through bio-accumulation can sometimes lead to high concentrations in animals, including humans, in the top of the food chain. Many metals are essential for life. Their intake has an optimum – below that, deficiency symptions may occur, and above it, adverse impacts of too high intakes might show. Environmental metal concentrations generally are higher now than some centuries back due to the anthropogenic mobilization of metals, which has increased the magnitude of metal cycles, sometimes with a fraction but in other cases with factors above 100.

Emissions of metals to the environment have been estimated to be in the same order of magnitude as the natural sources of emissions, weathering and volcanic activity. Those emissions are increasingly dominated by diffusive sources (stocks-in-use) and non-metal sources, especially fossil fuels and phosphate rock.

Important impacts of the metals' life cycles occur in the first stages of the life cycle: mining, beneficiation, metal extraction and refining. The most important environmental impacts of primary metal mining and extraction revolve around water (consumption and quality aspects), mine wastes (tailings and waste rock), and energy sources (direct such as diesel and indirect such as coal-fired electricity) with the associated air emissions (sulfur dioxide, greenhouse gases, dusts and particulates).

A large part of the environmental impacts of metal production is related to energy. The GER per kg of produced metal ranges from 20 (Fe) to 200 (Al) MJ/kg. Altogether, the primary production of metals contributes ca. 8 % to total global energy consumption. In the future, if society needs to access lower grade ores, energy use is expected to increase substantially. The energy required for secondary production is two or more orders of magnitude less. An increased share of secondary production therefore would reduce energy related impacts substantially.

In the use stage of the life cycle, it is difficult to attribute impacts to metals in metal containing products. Only corrosion from stocks-in-use exposed to the weather is clearly related to the metals themselves. This is becoming, in a relative sense, a more important source of emissions, since stocks-in-use are growing and point source emissions declining, as a general trend. Besides this, main impacts in the use phase are related, again, to energy use. Impacts refer to the product, not the material: only occasionally is it possible to pinpoint a specific role for metals, and then only comparatively.

Metals are used in many new technologies. Especially renewable energy technologies, where metals play a specific and often crucial role, can be regarded as beneficial for the environment since by using them, emissions related to fossil fuel use are avoided. The upscaling of such technologies on a global scale however may lead to impacts in the chain.

In the waste stage, impacts occur via final waste treatment. Metals are emitted to the atmosphere (incineration), to surface water (waste water treatment) and especially end up in landfills, where there is a risk they may leach into the environment. Increasing recycling rates in some cases already can be observed to reduce landfill of metals.

Life cycle assessment studies of metal containing products show that main impacts of the metals life cycle occur in the mining and refining stages. This is due to emissions and waste from mining, but especially to the very high energy intensity of those processes. As a general rule, the metals being produced in large quantities have a lower per kg impact than those being produced in small quantities. The difference between the global warming potential of a kg of Fe and a kg of Rh is five orders of magnitude. When multiplied with the annual production, however, Fe is still the metal with the highest environmental impact potential.

Studies to support prioritisation of a materials or resource policy come to the conclusion that, compared to other materials, metals have a high impact per kg to produce. However, other materials are used in far higher quantities. Agricultural resources, especially of animal origin, and fossil fuels are important contributors to environmental impacts; metals at the moment play a modest role.

7.2 Expected Future Developments

In the future, it is possible that metals will become relatively more important from an environmental impact point of view, for the following reasons:

- Presently, the demand for metals is rising rapidly and this trend is expected to continue for the next decades.
- A shift towards a renewable energy system implies the material, and especially metal, intensity of energy production will increase even faster.
- In future, the energy intensity of the production of metals may increase as a result of mining lesser grade ores. For some metals, a trend of decreasing ore grades is visible, and for more it may become visible over the next decades.

To what extent these events will occur, what will be the result of this feedback loop and to what extent it will be mitigated by increased exploration, cleaner processes, increased secondary production and substitution is difficult to estimate. Process efficiency increases continually but slowly. Recycling rates are increasing, which is a promising development. Technologies to increase those even more are being developed and may substantially reduce the need for primary production, and therefore the impacts connected with that.

Developments differ per metal. For metals with a declining use (As, Cd, Hg and to some extent Pb), emissions from old stocks dominate, which will decline gradually over time. For metals with a rising demand, a trend is already visible that recycling rates are increasing. Due to the time delay, the share of secondary production remains low as long as total demand keeps rising. This means that emissions related to mining, production and use will probably rise as well, although at a lower pace than production itself.

Since both population and welfare are increasing and energy will to a large extent remain dependent of fossil fuels over the next decades, a further rise of the emissions from non-metal sources can be anticipated, to some extent modified by exhaust gas cleaning.

7.3 Knowledge Gaps

While there is a large body of knowledge available for metals, yet there are some gaps that it is important to fill in order to make meaningful forecasts and estimate the effectiveness as well as the side-effects of certain changes in management.

- In the area of environmental fate, toxicity and impacts research has progressed most. Nevertheless, it is not complete. Especially the impacts of the presence of a mix of metals is yet unclear.

- In the area of the anthropogenic cycles and their links to the environment, there are many studies at the national or regional level. Information at the global level is becoming available, but needs to be expanded and linked to all the regional and national information. A further cooperation and finetuning between the research with regard to anthropogenic cycles and natural cycles is very relevant. If we are to develop measures and policies to reduce impacts of metals while at the same time keeping their functionality, it is essential that we know the origins of metal-related problems, both in general and more specific.

- LCA data and studies on metals and metal containing products are available. They could be improved and added to. LCI data especially on recycling and final waste management processes could be improved, and allocation of multi-metal production be solved somehow. In LCIA, toxicity factors for metals is still a field under development.

- Combining the life cycle approach with a global level assessment, enabling to include issues of scale as well as enabling to detect side-effects at the global level, is very important to obtain a picture of the overall effectiveness and soundness of certain improvement options, be they technological improvements, substitutions or whole new ways of providing functions. Such a life cycle sustainability assessment is still in its earliest stages.

- Important knowledge is still missing in the linkages that exist between different types of resources: metals, energy, water, and maybe others. In scenario explorations for the future, this is essential knowledge. It requires an interdisciplinary approach and the cooperation of researchers from different fields to build up this type of knowledge.

7.4 Steering Toward a Sustainable Metals Management

Since metals, once in the environment, disappear only at a very slow rate, a sustainable metals management should reduce emissions of metals to a level that keeps pace with that. At the same time, a reduction of the metals' life cycle impacts could be beneficial for a number of environmental impacts, most notably GHG emissions related to the high energy requirement of metal production.

Mining and Production
Better and more cost-effective approaches are available and, as some companies already do, should be implemented on a global scale to reduce the environmental impacts of metal production. Risk management strategies will have to be developed to address the environmental risks as identified in Chapter 2, including:

- Reclamation of disturbed land.
- Treatment and stabilisation of metal-bearing soils.
- Prevention and treatment of contaminated water.
- Controls on the amount and character of emissions to the atmosphere.

Such approaches are already practiced by mining companies, and should be adopted at the global level. A risk management however should include but not be limited to technological constructs.

The energy use of primary production is a major cause of impacts. Reducing this would therefore be of major importance. Energy efficiency increase can be achieved by the following changes:

- A significant process efficiency increase could yet be made, leading to a factor 2 – 20 reduction in energy use per kg produced metal, all else being equal.
- Increase of secondary production, which generally takes two or more orders of magnitude less energy per kg produced.
- Use of waste streams (fly ash, sludges and suchlike) as sources of metals, especially if a variety of metals can be recovered from them.

Such measures, too, are already practiced by responsible industries. They could be adopted at the global level to a substantial reduction in energy use.

Use
Corrosion losses can be reduced by reducing the metal surface exposed to the environment, either by substitution or by technical measures such as coating. It should be kept in mind, however, that while there may be opportunities to substitute other materials for metals in some applications, these may not be without their own environmental and supply issues. Substitution of metals in new technologies is mostly counterproductive – it will come at the expense of either a reduction of resource efficiency or loss or functionality. Metals also have an important function in new energy systems, thus contributing to a reduction of impacts. It should be kept in mind, however, that if implementing these technologies at a large scale will lead to a large increase in the demand for these metals, and consequently to a reduced availability of high quality ores, the production of these metals will become increasingly energy intensive, which reduces resource productivity.

Recycling and Waste Management
In many places in the world, waste treatment can be improved greatly. One example is the upgrading of present environmentally harmful informal treatment of electronics waste. Minimizing the creation of waste streams and their associated environmental impacts, while at the same time maximizing the amount of valuable metal(s) recovered from a given ore deposit, is the primary objective of the metals processing and recycling industries.

Recycling rates are increasing, but could be increased far more if a systems optimization, including also product design, would be adopted. Linking water recycling systems to the recycling and metals/recycling system, not only to conserve precious water but also to maximize metal recovery and hence maximize the resource efficiency. Even so, secondary production can only provide a small portion of total supply if the demand for metals keeps on rising, especially in developing countries where the anthropogenic stock of metals is still small. Real changes towards closing anthropogenic metal cycles can only be made if demand slows down and an equilibrium situation settles in.

Even in such a case, thermodynamics, in particular the 2nd Law of Thermodynamics, prohibits within a reasonable economic framework the complete closure of the materials cycle. Hence there will always be losses from the production and use of metals, and there will always be a need to make up for these losses by primary production from metallic ores. Unavoidable losses from the cycle means that a sustainable metals management also should include a final waste treatment. Also from the point of view of old, unwanted stocks of metals no longer used entering the waste stage, a final waste treatment should be designed. Since metals cannot be destroyed, the only way to prevent them from entering the environment is to immobilize them and landfill or store them where they cannot reach the environment.

Non-metal Sources

Non-metal sources such as fossil fuels or fertilizer are increasing in importance, both relatively and absolutely, and are difficult to address since their use is inherently dissipative. Nevertheless they should be addressed in a sustainable metals management. A reduction of their use is one option. The shift to a renewable energy system, although leading to a higher metal demand, will at the same time lead to a reduction of fossil fuel use. A reduction of phosphate fertilizer use is not likely to occur in the near future. Nevertheless, phosphate rock is a scarce resource in its own right, and solutions may have to be found to solve that problem anyway. A shift to a less animal product-intensive diet will certainly be a step in the right direction.

General

To provide global society with the metals it needs, it is important to make projections of future demand. Various scenarios, using different assumptions, should be explored to obtain insight in how demand may develop for a variety of metals. This will enable to estimate not only where we may encounter issues of availability, but also how metal related environmental impacts may change over time. Such scenarios should include, next to demand, assumptions on technology development in mining and industry, and on waste management and especially recycling. The question when and at what level demand will stabilize is a crucial one. So is the question which metals are really essential and which ones may be replaced by other as yet lesser used metals or materials. New technologies will have to be developed, and accordingly used, which is a time and resource consuming effort.

Metals are the ideal type of resource for closing cycles: they do not degrade and can be recycled virtually indefinitely. Approaching a situation where cycles of metals are indeed to a large extent closed is only possible when the demand for metals levels off: a decoupling between economic development and the use of metal resources. Only in that case can secondary production catch up with the demand and will it be possible to substantially reduce primary production and therefore the energy requirement for metals production. This situation is yet far away. Developing economies are now building up their infrastructure, and the approaching energy transition also will lead to a growing demand. Nevertheless, it has to be the long term goal for a sustainable metals management.

It is clear that a sustainable metals management cannot be defined in isolation. A global issue like this is linked to many other issues at the global level: population and welfare in-

crease, the concurrent expected rise in demand for food, water and energy, the availability of metals and other non-renewable materials, the shift to a renewable energy system, dietary choices etc. etc. Linkages exist between demand and supply for all major resources, and the present scale of production and consumption is such that constraints are becoming apparent in all corners. A sustainable metals management therefore should be part of an overall effort to steer society towards a more sustainable development.

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9. Annexes

Annex 1
Metals in the Environment

Metals in the environment have natural as well as anthropogenic origins. Elevated concentrations usually are due to anthropogenic activities, but sometimes also have natural origins. Figure A1.1 shows an example of that: the high Ni values (same levels as in the Kola Peninsula) in the area of the Ural mountains in the East are due to large ultramafic rock intrusions that have high Ni concentrations (up to 0.2%) despite the absence of anthropogenic impacts.

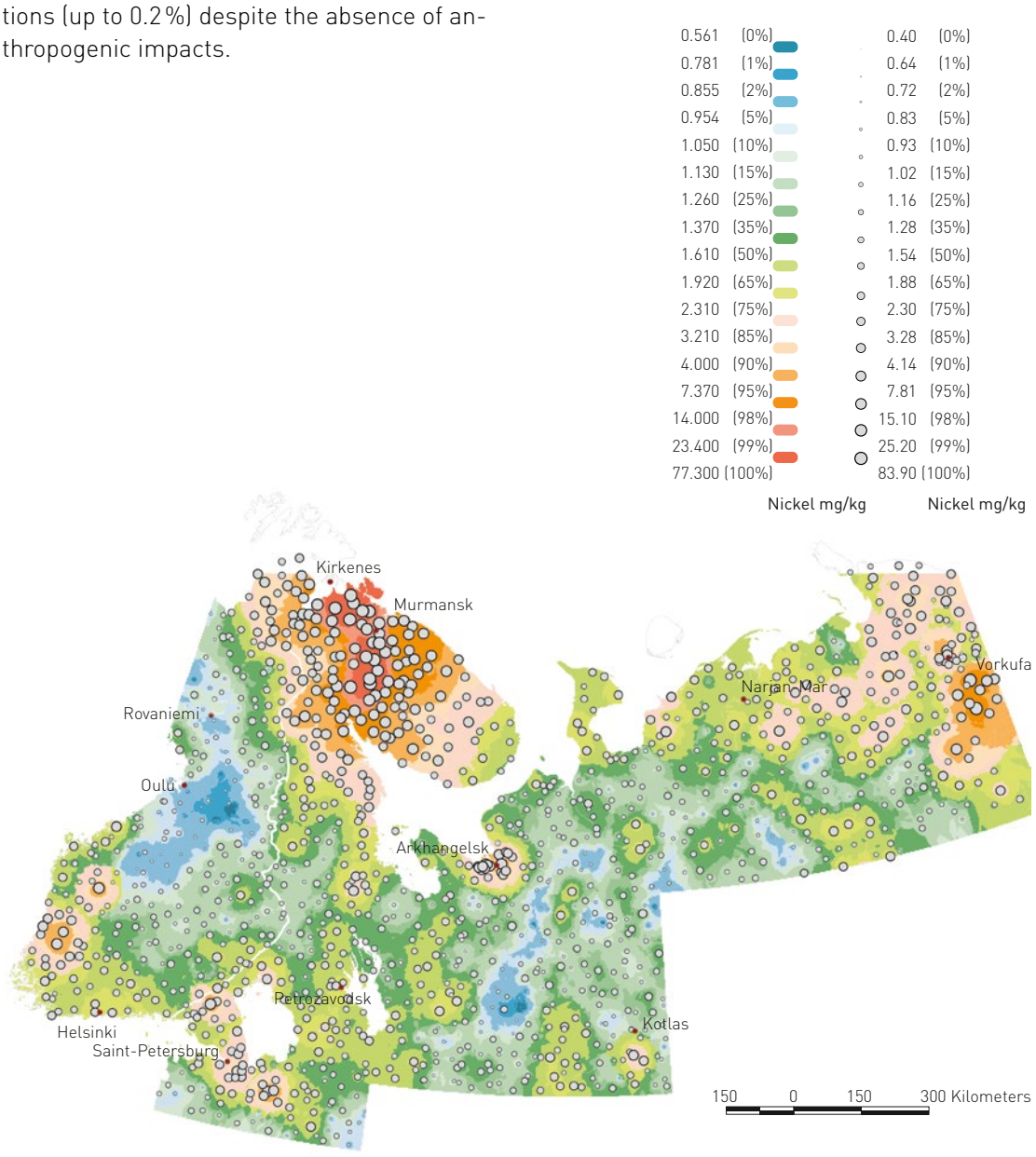


Figure A1.1

Nickel concentrations in terrestrial moss in the Central Barents Region. High Ni values in Kola Peninsula are due to Ni smelters at Monchegorsk, Nikel and Zapoljarny and in the area of Ural mountains to Ni bearing ultramafic rock intrusions (Salminen et al. 2004).

As a result of anthropogenic activities, but also as a result of exogenic geological processes, some metals have become enriched in the topmost part of soil layer. In Europe, only Hg, Cd, Pb and Mo show slight enrichment in top soils (Table A1.1). Among these, Hg, Cd and Pb can be considered to reflect anthropogenic influence. For the other elements in consideration the topsoil/subsoil ratio is 0.9 – 1.1., i. e. no remarkable enrichment or depletion was detected.

Table A1.1

Ratios of topsoil/subsoil for some metals in Europe (De Vos et al. 2006)

Element	Ratio top/sub soil
TOC	2.585
Hg	1.660
Cd	1.477
Pb	1.364
Mo	1.105

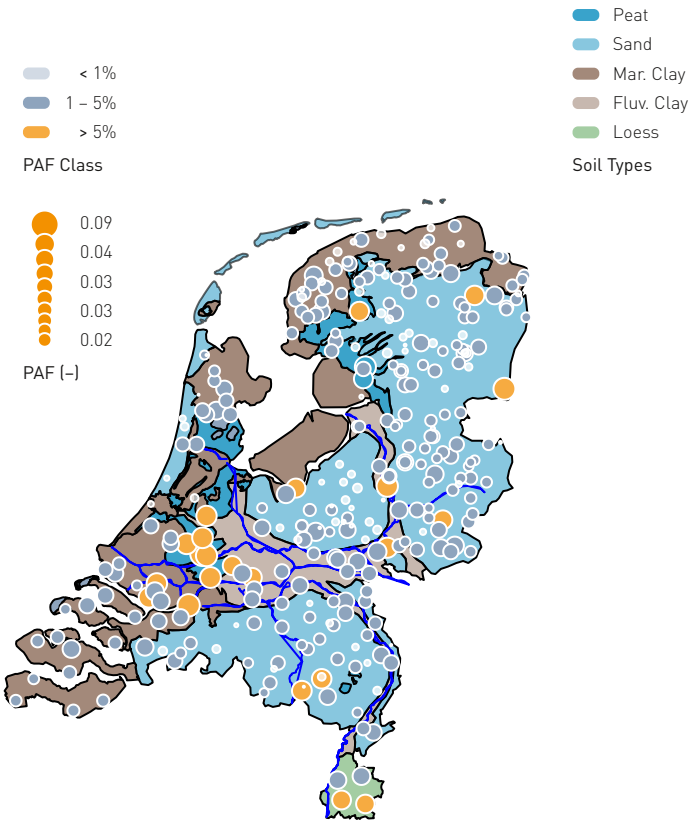
A detailed study of top soil and subsoil samples of the Netherlands is based on top- and subsoil measurements of metals in rural areas, as presented in geochemical atlases (Van der Veer, 2006; Mol et al., 2010). These soils have been subject to a past diffuse emission – deposition process, at least since the onset of the industrial age. This study can be seen as validation of the European-scale CLRTAP study (see section 2.5.1 of the report).

The toxic pressure associated with the anthropogenic enrichment of top soils with Cd, Cu, Pb and Zn and their local mixtures was calculated using chronic ecotoxicity data sets (NOECs). This choice was made, since environmental protection policies for toxic compounds use the so-called '95 %-protection criterion' to set soil quality standards. This criterion concentration is known as the HC5 (Hazardous Concentration for 5 % of the species, Potentially Affected Fraction, PAF, of 0.05, or 5 %) and represents the situation where the fraction of species not exposed to a concentration exceeding a No Effect Concentration is 0.95 (95 %). The HC5 is calculated as the 5th percentile of the metal's chronic SSD. The study focused on the upper limit of risks imposed by top-soil enrichment. That is: local risks will be lower since the enrichment will in part be unavailable for uptake due to sorption to the soil matrix. Note that the Dutch study differs from the CLRTAP results presented in Chapter 2, in that there the toxic pressure assessment is based on EC50-ecotoxicity values, to present probable species loss rather than exceedance of no-effect levels.

The metal enrichments in the diffusely exposed top soils exert low chronic toxic pressures on ecosystems – commonly less than on 5 % of the species i. e. more than 95 % of the species fully protected – and varies spatially among the five major Dutch lithologies (Figure A1.2). Combined chronic toxic pressures typically range between 1 and 5 % chronic toxic pressure, that is: the multi-substance Potentially Affected Fraction (msPAF) is 1 – 5 %, with higher chronic toxic pressures (up to approximately 8 percent) in those peaty soils that were loaded with household waste in medieval times. Held against Netherlands soil quality targets, which are set to reach the protection of at least 95 % of the species against effects of "added" compounds (Crommentuijn et al. 2000; Struijs et al. 1997), the diffuse enrichments do not generally fail on this goal for metals (both separate and in mixtures). Chronic and acute SSDs often differ by a factor of – on average – approximately 10, with the chronic SSD positioned left of the acute SSD. That is, the acute toxic pressure is often (much) lower than the chronic value. Due to this, it is evident that the acute toxic pressures of the enrichments (and thus associated species loss) of Dutch top soil enrichments must be lower than the typical range of 1 – 5 % of the species, which is in line with the findings of the European study.

Figure A1.2

Spatial variance of chronic toxic pressure (expressed as multi-substance Potentially Affected Fraction msPAF of species) exerted by anthropogenic enrichments of metals in Dutch top soils (Spijkers et al., 2011b).



The figure refers to mixtures of Cd, Cu, Pb and Zn. Boxplots of the lithology-specific variances of chronic toxic pressure exerted by anthropogenic enrichments of metals in Dutch top soils (mixtures of Cd, Cu, Pb and Zn). Note that chronic toxic pressure of 5 % implies full protection of 95 % of the species.

In conclusion, diffuse metal emissions have resulted in the long term in metal enrichments in the environment. These can be predicted based on emission data and fate modeling (European study), and verified by geochemical baseline studies on top and subsoil (Dutch study). The predicted diffuse anthropogenic enrichments currently exert acute toxic pressures which are in some areas of Europe predicted to affect at a maximum 1 % of the soil species but usually far less, while the measured enrichments induce chronic toxic pressure (far) below the often-used 95 %-protection criterion set in the regulation of substances and emissions. At the 95 % protection limit itself, the fraction of species acutely affected is far less than 5 %. Toxic pressure values can be presented in a single value for a whole mixture found or expected at a site. That is, a geochemical atlas of all metals can be summarized into a single toxic pressure map, or two maps: one showing acute toxic pressures and associated with major ecological impacts (in terms of species loss), and one showing chronic toxic pressures through which the success of chemical management policies for diffuse emissions can be evaluated (in terms of reaching policy protection objectives). The European example can be worked out for more metals, different geographies, and for different scenarios of metal use. For example, a comparison could be made of the ecotoxicological risks under various metal use and re-use regimes, when emission-deposition scenarios are available.

Annex 2
Processes Determining Bio-availability of Metals

Chemical availability

Chemical availability is a physico-chemically driven supply process. The impact of metals on the environment is closely related to the form in which the metal occurs, so-called metal speciation. By speciation of a metal in soil, the total content of the metal is partitioned over both the solid and the solution phase. In the solid phase, metals exist as precipitates (e. g. ferro sulfides and crystalline FeS, FeS_2 and Fe_3S_4, manganese sulfides), adsorbed on reactive soil surfaces and occluded or bound into soil minerals. Metals in the soil solution can exist as free metal ion or as species bound to inorganic and organic complexes. Table A2.1 shows an example of different metal forms as found in surface waters and soil solutions.

Table A2.1

Metal speciation – examples of metal forms found in surface waters (Campbell and Chapman, 2006).

Species	Examples
Free metal ions	$Al^{3+}(H_2O)_6$ $Cu^{2+}(H_2O)_6$
Hydroxo-complexes	$AlOH^{2+}$, $Al(OH)_2^+$, $Al(OH)_4^-$ $FeOH^{2+}$, $Fe(OH)_2^+$, $Fe(OH)_4^-$ $Cu(OH)_2^0$
Simple inorganic complexes	AlF^{2+}, AlF_2^+ $CdCl^+$, $CdCl_2^0$, $CdCl_3^-$ $HgCl_2$,$HgOHCl^0$ $CuCO_3^0$ $CdSO_4^0$
Simple organic complexes	
synthetic	$Cu\text{-}EDTA^{2-}$ $Cd\text{-}NTA^{1-}$
natural	Cd-alanine Cd-citrate Fe-siderophore
Polymeric organic complexes	Al, Fe, Cu, Pb or Hg – fulvic or humic acids

The metal concentration in the solution phase (of the soils or sediment) is regulated by adsorption; in a more or less descending order of affinity (Wijdeveld and Smits 1997) metals are bound to:

- Organic matter (particulate and dissolved humic substances having many active carboxylic and phenolic hydroxyl groups, highly depending on the origin and history of the organic matter (Senesi 1992).
- Hydrous iron oxides (Fe(OOH), amorphous goethite).
- Oxides of manganese (MnO_2, amorphous birnessite).
- Aluminium hydroxide and silicates ($Al(OH)_3$, amorphous, gibbsite, $Al(SiO_2)_3$, amorphous allophanes).
- Clay minerals (e. g. the dominant clay minerals in many Dutch soils are illite, kaolinite, vermiculite and bentonite. The metal-sorption capacity of clay minerals varies among the various minerals and is based on the density of negative charges on the clay surface).
- Calcium carbonate (amorphous, calcite).

Parameters that Control the Metal Forms

Environmental conditions control the sorption of metals. One of the major factors influencing metal speciation is the acidity (pH) of the soil. An increase in pH changes the solid-solution partitioning of cations towards the solid phase, and hence the mobility and availability of cations generally decreases. Another controlling factor is the available amount of sorption sites related to the cation-exchange capacity of a soil and the amount of competitively sorbed cations, especially calcium. High binding coefficients and nonlinear adsorption of metals are typical features that tend to increase over time due to increased chemical binding, precipitation, and inclusion of metals into solid matrices (aging). Aging is also impacted by most of the factors affecting metal speciation.

When many cations compete for the same sorption sites, the solid-solution partitioning of cations shifts towards the solution phase, and hence the mobility and availability of cations generally increases. Metal partitioning over the different sorption phases is assumed to be in equilibrium. Depletion of one of the metal species may occur, mostly the free metal ion activity because it reflects the chemical reactivity of a metal and is rapidly taken up by organisms. Disequilibrium due to depletion may lead to a new equilibrium situation. The time in which a new equilibrium is established depends on the total dissolved metal concentration and the concentration and nature of the ligands present in the solution. The release of free ion (Me^{2+} or $Me^{2+}(H_2O)$), replenished from metals bound to inorganic ligands in the solution (e. g. MeOH, $MeCl_2$), requires only seconds, whereas the release of metals from the solid phase towards the solution phase takes days rather than hours. In conclusion, total metal concentrations in soil include non-bioavailable forms. All loosely-bound metal species in the soil are in equilibrium with each other, however equilibration time depends on the nature of the ligand present.

To summarize, the main factors affecting metal speciation and interaction with biota include:

- Oxidation potential—redox conditions.
- Salinity.
- Competing ions.
- Acidity (pH).
- Nature of sorbent phases and their surface areas.
- Surface site densities.
- Colloid formation.

Biological Availability

Metals in the solution phase reflect the species being chemically most available and are likely to be of most importance for uptake by organisms. However up to now, no consistent relationship has been found between any metal species and either bioaccumulation or toxicity. This is because biological availability is a physiologically driven uptake process. The biologically available metal fraction is the fraction actually taken up by organisms. The magnitude of metal accumulation depends on the metal supply of the soil and the demand of soil organisms for metal uptake. Which metal species in the soil can be taken up by organisms is organism-specific and influenced by the possible uptake routes. Quantification of exposure routes of metals for terrestrial invertebrates is difficult and cannot yet be done accurately (Belfroid and Van Gestel 1999). From an ecological point of view, two metal uptake routes, or a combination of them, may be envisaged for soil invertebrates. Firstly, metal uptake via the permeable external surfaces was distinguished. The direct source of importance of this uptake route is metals in pore water. Secondly, metal uptake via the oral route was distinguished. Metal uptake via the oral route includes possible modification of metal speciation by gut conditions. This route includes uptake via drinking, soil and food ingestion. Via drinking, metal uptake is indirectly from pore water, possibly following modification of the pore water depending on gut conditions. Upon soil and food ingestion the metal uptake is indirectly from solid phases, possibly following modification by gut conditions. When focusing on bioaccumulation, problems around metal availability (such as which species are chemically reactive and how fast is metal replenishment) and metal bioavailability (such as which metal species are bioavailable, the contribution of uptake routes, and the physiological need for essential metals) are integrated and overcome.

Toxicological Availability

Toxicological availability is the toxico-dynamic behavior of metals inside organisms. Accumulated metals are distributed throughout the organism's body, and can be sequestrated in a biologically available form or isolated metabolically to be no longer toxicologically available. At cellular level, the internal metal speciation which can be found in an organism is (Vijver et al. 2004):

- Free ionic form or complexed ion species (e. g. $CdCl_2$, $CdCl^+$, $CdCl^{3-}$).
- In the active centre of functional proteins (e. g. hemoglobin, hemocyanine), low molecular weight peptides, in the active centre of enzymes.
- To low molecular weight organic acids (e. g. citrate).
- To metallothionein, to transport proteins (e. g. ferritin), or other sequestration proteins.
- As intracellular granules or extracellular granules.

These biochemical mechanisms serve to prevent the organism against accumulation of reactive metal species, and they might also have an impact on the accumulation level reached in organisms during exposure. In theory, when the storage compartment is inert and an infinitive sink, this will be reflected in linear uptake curves. When the storage compartment has a dynamic equilibrium with the labile compartment and elimination from the storage occurs, a saturation type accumulation curve can be seen. Adverse effects will occur whenever the metal uptake flux exceeds elimination or storage flux, and the metals bioaccumulate in excess over the metabolically required pool or exceed a threshold concentration at the specific site of action.

Annex 3
Impacts of Deficiencies and Overdoses of Metals on Human Health

In this Annex, health effects of some selected metals are described and a few examples of concrete impacts are provided. However it is necessary to remember that the geological background varies very much and has no political borders. Therefore in most cases local health effects of these metals are the same wherever they occur in the world. Arsenic is such an example demonstrating that local poisoning from local drinking water from wells in the forests of Scandinavia has the same effect as in the huge mass poisoning in Bangladesh and West Bengal. Therefore it is not possible to distinguish local effects from global effects.

Iron

Iron can be found in meat, whole meal products, potatoes and vegetables. The human body absorbs iron in animal products faster than iron in plant products. Iron is an essential part of hemoglobin; the red colouring agent of the blood that transports oxygen through our bodies. Iron may cause conjunctivitis, choroiditis, and retinitis if it contacts and remains in the tissues. Chronic inhalation of excessive concentrations of iron oxide fumes or dusts may result in development of a benign pneumoconiosis, called siderosis. No physical impairment of lung function has been associated with siderosis. Inhalation of excessive concentrations of iron oxide may enhance the risk of lung cancer development in workers exposed to pulmonary carcinogens. A more common problem for humans is iron deficiency, which leads to anaemia. A man needs an average daily intake of 7 mg of iron and a woman 11 mg; a normal diet will generally provide all that is needed.

Copper

Copper is naturally present in food, drinking water and all environmental compartments. Copper is an essential element and adverse effects are related to deficiencies as well as overdoses.

The concentration of copper in the body is strictly and efficiently regulated by homeostatic mechanisms. Systemic effects ensue but the capacity of the homeostasis is exceeded. The major control mechanism is gastrointestinal absorption and biliary excretion into faeces. Liver has an important role in the maintenance of the copper homeostasis. The failure to maintain homeostasis may lead to adverse effects resulting either from deficiency or excess. Copper deficiency causes more and far severe adverse health effects than copper toxicity (WHO, 1998 and SCHER, 2008).

At least 12 major proteins require copper as an integral part of their structure (WHO, 19984). Specific adverse consequences from copper deficiency in humans have been observed in measures of cardiovascular function, bone metabolism, lipid levels, and immunological parameters indicative of impaired immune function (Copper risk assessment report, 2007).

Effects of Cu deficiency in animals have also been extensively studied in several parts of the world because it is a problem mainly for sheep and cattle production. Copper supplementations to animal feed are common practice: pigs, cattle, chicken farms as well as fish farms (SCAN, 2003).

Effects from excess after single doses have been observed in humans as nausea and other gastrointestinal irritation effects due to high copper concentration in drinking water (above the WHO drinking water limit of 2 mg/l). After repeated oral dosing at elevated levels, liver, forestomach and kidneys are target organs of copper toxicity (Copper risk assessment report, 2007 and SCHER, 2008).

To cope against copper deficiency, WHO (1998) set a lower safe threshold level for copper at 20 µg Cu/kg body weight/day for adults and at 50 µg Cu/kg body weight/day for children. From the copper Risk Assessment, no conclusive Deficiency Effect Level (DEL) was derived but dietary intake of 1 mg Cu/day was shown to be sufficient to maintain

the copper balance (Stern, 2007 and SCHER, 2008).

In the copper RA report, a long-term No Observed Adverse Effect Level (NOAEL) value was derived from existing animal studies and allowed to calculate a systemic safe threshold value of 0.16 mg/kg body weight/day (or 0.041 mg/kg body weight as internal dose (25 % gastro-intestinal absorption)). For a person of 70 kg this would correspond to an upper limit of 11.4 mg/person/day for ingested copper (Cross, 2007 and SCHER, 2008). A 10 mg/person/day as upper safe value of was also concluded by several other independent national and international commissions (IOM, 2001; WHO 2004 and 2008).

Zinc

Zinc is a trace element that is essential for human health. When people absorb too little zinc they can experience symptoms of zinc deficiency e. g.: a loss of appetite, decreased sense of taste and smell, slow wound healing and skin sores. Zinc-shortages can even cause birth defects. An important effect of zinc deficiency is the reduction in immune response, leading notably in children to increased frequency of mortality through infectious disease (Zinc investigators' collaborative group, 1999, 2000; Brooks et al 2005; Shankar et al 2000). Zinc deficiency is a major health problem at a global scale: it has been estimated by FAO that approximately one third of the world's population lives in countries that have a high risk of zinc deficiency (IZiNCG 2004). For this reason, major efforts are being undertaken by the world community to fight zinc deficiency in developing countries (WHO-UNICEF 2004).

Zinc deficiency can be a danger to unborn and newborn children (Samuelson et al., 2011). Diabetes presents one example of the use of geochemistry in medical geology. Childhood diabetes is almost exclusively of the insulin-dependent type (type1). A case control study in Sweden was designed comparing zinc contained in biogeochemical samples from different areas. The results showed that a high water concentration of zinc was associated with a significant decrease in risk. This provides evidence that a low groundwater content of zinc, which may reflect long-term exposure through drinking water, may be associated with later development of childhood onset diabetes.

Although humans can handle proportionally large concentrations of zinc, too much zinc can still cause major health problems, such as stomach cramps, skin irritations, vomiting, nausea and anemia. Very high levels of zinc can damage the pancreas and disturb the protein metabolism, and cause arteriosclerosis. Extensive exposure to zinc chloride can cause respiratory disorders.

Aluminium

Aluminium is one of the most widely used metals and also one of the most common elements in the earth's crust. Aluminium may be leached from the ground under acidic conditions, like in connection with acid rain, and have harmful effects on local organisms. Human intake of aluminium is predominantly through food, both due to natural content and in some countries also through food additives used to preserve food. Less than 0,1 % is normally absorbed from the stomach and intestines, the rest passing through. There are no health effects associated with normal intake of aluminium in food or water. People on specific medications will take in larger quantities of aluminium. Workers employed in aluminium production may experience respiratory problems, usually linked to some of the substances released during production.

Aluminium can cause problems for kidney patients when it enters the body during kidney dialyses. This condition is now well recognised and prevented through control of aluminium concentration in the water used.

The Joint Expert Committee on Food Additives (JECFA), an UN WHO/FAO body has recently (June 2011) revised the Provisional Tolerable Weekly Intake limit (PTWI) for aluminium to 2 mg/kg body weight/week.

Nickel

Nickel is a compound that occurs in the environment at different levels, dependent on location. Some foodstuffs naturally contain small amounts of nickel. Chocolate and oats are known to contain higher quantities than some other food. Some plants are known to accumulate nickel and as a result the nickel uptake from these plants could be significant. In summary, Humans may be exposed to nickel by breathing air, drinking water, eating food or smoking cigarettes. Skin contact with nickel-releasing items – may also result in nickel exposure, but uptake by the dermal route is negligible and would not result in significant systemic exposure. In small quantities nickel may be essential to humans, although this is difficult to demonstrate given the pervasiveness of low levels of nickel exposure. Allergic reactions such as skin rashes, can occur as a result of prolonged and intimate exposure with nickel-releasing items, mainly from jewelry.

Inhalation exposure to high levels of nickel compounds found during the processing and refining of sulfidic nickel ores has resulted in higher chances of development of lung and nose cancer. Exposure to nickel carbonyl can cause several immediate effects (e. g. headaches, weakness, nausea, vomiting, etc.) as well as delayed effects (e. g., pneumonia, respiratory failure, cerebral edema, death, etc.). This compound is used in the Mond nickel refining process and exposure is strictly controlled. A few case reports of asthma associated with exposure to water soluble compounds exist. Adverse reproductive developmental effects have been observed in rats orally exposed to high levels of nickel sulfate. However, studies of female refinery workers in Russia have not shown adverse reproductive effects to be associated with nickel exposures.

Nickel compounds have been listed by the National Toxicology Program (NTP) as known human carcinogens while nickel metal is listed as being reasonably anticipated to be carcinogenic. The International Agency for Research on Cancer (IARC) has listed nickel compounds within group 1 (there is sufficient evidence for carcinogenicity in humans) and nickel metal within group 2B (agents which are possibly carcinogenic to humans). OSHA does not regulate nickel as a carcinogen. Only certain nickel compounds have been demonstrated to be carcinogenic, and carcinogenicity is restricted to the inhalation route of exposure. A recently conducted animal study demonstrated that nickel metal was not carcinogenic by the inhalation route of exposure. This result is consistent with the lack of evidence of increased respiratory cancer risks in workers with predominant nickel metal exposures.

Chromium

People can be exposed to chromium through breathing, eating or drinking and through skin contact with chromium or chromium compounds. The level of chromium in air and water is generally low. In drinking water the level of chromium is usually low as well, but contaminated well water may contain the dangerous chromium(VI); hexavalent chromium. For most people eating food that contains chromium(III) is the main route of chromium uptake, as chromium(III) occurs naturally in many vegetables, fruits, meats, yeasts and grains. Various ways of food preparation and storage may alter the chromium contents of food. Chromium(III) is an essential nutrient for humans and shortages may cause heart conditions, disruptions of metabolisms and diabetes. But the uptake of too much chromium(III) can cause health effects as well, for instance skin rashes.

Chromium(VI) is known to cause various health effects. Some health problems that are caused by chromium(VI) are skin rashes, upset stomachs and ulcers, respiratory problems, weakened immune systems, kidney and liver damage, alteration of genetic material, carcinogenicity, dermatitis, asthmatic bronchitis, bronchospasms and edema. The health hazards associated with exposure to chromium are thus dependent on its oxidation state. The metal form is of low toxicity.

Lead

Lead can enter the human body through uptake of food, water and air. Foods such as fruit, vegetables, meats, grains, seafood, soft drinks and wine may contain significant amounts of lead. Cigarette smoke also contains small amounts of lead. Lead can enter (drinking) water through corrosion of pipes. This is more likely to happen when the water is slightly acidic. That is why public water treatment systems are now required to carry out pH-adjustments in water that will serve drinking purposes. Lead can enter a foetus through the placenta of the mother. Because of this it can cause serious damage to the nervous system and the brains of unborn children. For as far as we know, lead fulfils no essential function in the human body; it can merely do harm after uptake from food, air or water.

Lead can cause several unwanted effects, such as disruption of the biosynthesis of haemoglobin and anaemia, rise in blood pressure, kidney damage, miscarriages and subtle abortions, disruption of nervous systems, brain damage, declined fertility of men through sperm damage, diminished learning abilities of children, behavioural disruptions of children, such as aggression, impulsive behavior and hyperactivity

Fortunately, lead in the environment has strongly declined in recent years. This has been also observed in marine species. The concentration of lead in fish and blue mussel in the Baltic Sea has shown a decreasing trend since the early 1980's. The main reason is obviously to be found in the successful measures, which have been taken in order to lower emissions from industries. Another important reason is the increasingly restricted legislation by authorities, which has resulted in an increased use of unleaded gasoline in cars. The average level of lead in blood of both children and adults fits very well to the amount of used lead. Both correlates have shown a significant decline from late seventies. We know that low lead levels negatively influence processes of heme synthesis. In slightly higher amounts, Pb may cause alterations in the central nervous system. Monitoring of Pb levels in children at risk is thus very important.

One important factor in the effects of lead is the speciation and mode of occurrence. An excellent example of this can be seen in Sweden and Greece. In both countries there are ancient mining areas which have been mined for more than 1000 years: Falun in Sweden, Lavrion in Greece. Both these areas have been mined for lead. The total soil lead contents in the cities are in both cases extremely high. However the uptake of lead into vegetables and people are almost zero in Falun and in Lavrion the uptake is extremely high causing several diseases, mental effects, etc. and the blood lead contents in children are normally very high. The reason for this is that although the total lead contents in soils are the same, the lead is not bioavailable in Falun and is bioavailable in Lavrion. This result shows that the bioavailability, bioaccessability and geoavailability must be taken into account looking at the health effects of metals in the environment.

Tin

Tin is mainly applied in various organic substances. The organo-tin compounds are the most dangerous forms of tin for humans. Despite the dangers, they are applied in a great number of industries, such as the paint industry and the plastic industry, and in agriculture through pesticides. The number of applications of organic tin substances is still increasing, despite the fact that we know the consequences of tin poisoning.

The effects of organic tin substances can vary. They depend upon the kind of substance that is present and the organism that is exposed to it. Triethyltin is the most dangerous organic tin substance for humans. Humans can absorb organo-tin compounds through food and breathing and through the skin.

The uptake of organo-tin compounds can cause acute effects as well as long-term effects. Acute effects are eye and skin irritations, headaches, stomachaches, sickness and dizziness, severe sweating, breathless-

ness and urination problems. Long-term effects are depressions, liver damage, malfunctioning of immune systems, chromosomal damage, shortage of red blood cells, brain damage (causing anger, sleeping disorders, forgetfulness and headaches)

Mercury

Metallic mercury is used in a variety of household products, such as barometers, thermometers and fluorescent light bulbs. The mercury in these devices is trapped and usually does not cause any health problems. However, when a thermometer breaks a significantly high exposure to mercury through breathing will occur for a period of time while it vaporizes. This can cause harmful effects, such as nerve, brain and kidney damage, lung irritation, eye irritation, skin rashes, vomiting and diarrhoea.

Mercury has a number of effects on humans, that can be simplified into the following main effects: Disruption of the nervous system, damage to brain functions, DNA damage and chromosomal damage, allergic reactions, resulting in skin rashes, tiredness and headaches, negative reproductive effects, such as sperm damage, birth defects and miscarriages. Damaged brain functions can cause degradation of learning abilities, personality changes, tremors, vision changes, deafness, lack of muscle coordination and memory loss. Chromosomal damage is known to cause mongolism.

Mercury compounds were the causes of several serious early environmental hazards. Over a period in the 1960's the concentrations of mercury in fish in Swedish lakes increased and fishing in many lakes was outlawed. The reason is that during the period when there was a deposition of mercury, pools of mercury were built up in the soils. From these pools mercury can become mobile (methylation of mercury) and once more affect living organisms. In 50 % of the Swedish lakes (40 000 lakes) pikes have mercury contents exceeding 0.5 mg/kg which is the limit recommended by Codex Alimentarius (United Nations).

Large amounts of mercury are used for artisanal gold mining in several developing countries. Mercury is used during gold mining to dissolve gold dust in sand, thereby forming amalgam. Pure gold is then produced by heating the amalgam so that mercury evaporates and is emitted to the air, leaving the pure gold behind. In the Amazon alone, some two thousand tonnes of mercury have been emitted in this way during the two latest decades. Most of this mercury has been imported from Europe. The fish in the gold mining areas get increased levels of mercury, thereby poisoning the local population, whose staple food is fish. The gold miners are also exposed to mercury vapour, especially when amalgam is heated. The mercury emissions to the air contribute to the global burden of mercury. There is a law in Brazil against using mercury for gold mining. In spite of this, the gold miners are the main contributors to mercury emissions in Brazil.

Cadmium

Cadmium accumulates in the human body, especially in the kidneys. According to current knowledge, kidney damage (renal tubular damage) is probably the critical health effect, both in the general population and in occupationally exposed workers. The accumulation of cadmium in the kidney (in the renal cortex) leads to dysfunction of the kidney with impaired reabsorption of, for instance, proteins, glucose, and amino acids. It is estimated that 1 percent of all smoking women in Sweden with low body iron levels may experience adverse kidney effects due to cadmium load. Both human and animal studies indicate that skeletal damage (osteoporosis) may be a critical effect of cadmium exposure. Lung changes primarily characterised by chronic obstructive airway disease may follow high occupational exposure. Early minor deterioration in ventilatory function may progress, with continued cadmium exposure, to respiratory inadequacy. An increased mortality rate from obstructive lung disease has been seen in workers with high exposure in the past. Other effects of cadmium exposure are: disturbances in calcium metabolism, hypercalciuria and formation of stones in the kidney.

Arsenic

The public health concern for environmental exposure to arsenic has been widely recognized for decades. However, recent human activities such as drilling for water in arsenic containing aquifers have resulted in even greater arsenic exposures and the potential increase for chronic arsenic poisoning on a worldwide basis. This is especially the case in China, Taiwan Province of China, Thailand, Mexico, Chile, and India. The sources of arsenic exposure vary from burning of arsenic-rich coal (China) and mining activities (Malaysia, Japan) to the ingestion of arsenic-contaminated drinking water (Taiwan Province of China, Philippines, Mexico, Chile).

The groundwater arsenic contamination in Bangladesh and the West Bengal Delta of India has received the greatest international attention due to the large number of people potentially exposed and the high prevalence of arsenic-induced diseases (Table A3.1). Recent estimates suggest that as many as 20 to 30 million people are at risk from drinking arsenic-contaminated water in Bangladesh, which is obtained from the millions of tube wells that appear to be contaminated with naturally occurring arsenic. Several epidemiological studies have documented the global impact of arsenic contamination and the characterization of the sources of exposure.

Table A3.1

Some selected examples of arsenic poisoning from drinking water worldwide. In addition to these are for example Argentina, New Zealand, Brazil, Ghana, Zimbabwe, Japan, Chile, France, UK, Sweden (Data from Selinus et al., 2005)

Country or region	Year of discovery	Contents in groundwater (µg As/L)	Number of people at risk for cancer
Taiwan Province of China	1950	10 – 1820	200 000
Chile	1971	900 – 1040	437 000
Hungary	1774	10 – 176	220 000
Bangladesh	1980s	< 1 – 4700	100 000 000
India, West Bengal	1980s	< 10 – 3900	1 000 000
Thailand, Ronpibool	1980s	1 – 5000	1000
China, Xinjiang	1980s	1 – 8000	100 000
Argentina	1981	100 – 1000	2 000 000
Mexico	1983	10 – 4100	400 000
Peru	1984	500	250 000
USA	1988	10 – 48000	?
China, Inner Mongolia	1990	1 – 2400	600 000
Bolivia	1997	No data	20 000
Vietnam	2001	1 – 3050	Millions
Romania	2001	10 – 176	36 000
Nepal	2002	-456	?

The ingestion of As by humans can cause a variety of disorders, including skin lesions (e. g., hyperpigmentation, melanosis, keratosis), respiratory system problems (e. g., chronic cough, shortness of breath, bronchitis), nervous system effects (e. g., neuropathy, neurobehavioral, weakened memory, lower IQ, decreased attention), cancers of different organs (e. g., skin, lung, bladder), and reproductive effects (e. g., pregnancy complications, fetus abnormalities, premature deliveries, reduced birth weight). There are, in addition, potential links to heart disease and diabetes, but further evidence is needed to support these relationships. Approaches available to document chronic As exposure include analysis of As levels in drinking water, and measurement of urinary, nail, hair and blood As levels (biological monitoring). It has been shown that even low level As-exposures may affect human health, with greater effects in malnourished people. Recent evidence also implicates ethnic origin as a potential variable when determining As effects. It is becoming clear that a drinking water quality guideline of 50 µg/L As is not protective, and while guidelines have decreased (to 25 µg/L in Canada and 10 µg/L USA and WHO), attempts to lower them to ≤ 5 µg/L (Canada) must be encouraged. Because groundwater can contain high levels of As, most groundwater sources used for drinking water should be tested for As. If total As concentrations are above 5 µg/L, then it is suggested that biological monitoring should be carried out. This includes measuring As levels in urine, blood, toenails and hair.

Perhaps the single most characteristic effect of long-term oral exposure to inorganic arsenic is a pattern of skin changes. These include a darkening of the skin and the appearance of small lesions on the palms, soles, and torso. Chronic arsenic exposure from oral ingestion and inhalation has been associated with a variety of internal cancers involving the gastrointestinal tract, urinary bladder, lung, liver, and kidney. Research has also pointed to significantly higher standardized mortality rates for cancers of the bladder, kidney, skin, and liver in many areas of arsenic pollution.

Chronic arsenic toxicity due to drinking of arsenic-contaminated groundwater has been recently reported from many Asian countries. Of these, the catastrophic health problems caused by arsenic in the well waters of Bangladesh and West Bengal, India have been front page stories in newspapers, on television, and in scientific journals. Although estimates as to how many people are at risk vary, there is no question that it runs into the tens of millions in Bangladesh alone, and in West Bengal it is suspected that about 6 million people are exposed to arsenic-contaminated drinking water above the 50 ppb As level. This situation has been called the "greatest mass poisoning in history". What is not often reported is that the tens of millions of people exposed to arsenic in Bangladesh represent only a portion of the people who are at risk worldwide. Dangerously high levels of arsenic have been reported in water supplies of communities in Argentina, Austria, Brazil, Canada, China, Ghana, Greece, Hungary, Iceland, India, Japan, Korea, Malaysia, Mexico, Inner Mongolia, Nepal, Romania, Taiwan Province of China, Vietnam, Zimbabwe, and the U.S.

Cobalt

As cobalt is widely dispersed in the environment humans may be exposed to it by breathing air, drinking water and eating food that contains cobalt. Skin contact with soil or water that contains cobalt may also enhance exposure. Cobalt is not often freely available in the environment, but when cobalt ions are not bound to soil or sediment particles, the uptake by plants and animals is higher and accumulation in plants and animals may occur.

Cobalt is a part of vitamin B12, which is essential for human health. The total daily intake of cobalt is variable and may be as much as 1 mg, but mostly it will pass through the body unadsorbed, except that in vitamine B12. Ruminants require cobalt for growth and vitality and therefore ionic cobalt supplementation may be useful in veterinary practice.

However, too high concentrations of cobalt may damage human health. When we breathe in too high concentrations of cobalt through air we experience lung effects, such as asthma and pneumonia. Health effects that are a result of the uptake of high concentrations of cobalt are vomiting and nausea, vision problems, heart problems and thyroid damage. Health effects may also be caused by radiation of radioactive cobalt isotopes. This can cause sterility, hair loss, vomiting, bleeding, diarrhoea, coma and even death. This radiation is sometimes used with cancer-patients to destroy tumors. These patients also suffer from hair loss, diarrhea and vomiting. Cobalt dust may cause an asthma-like disease with symptoms ranging from cough, shortness of breath and dyspnea to decreased pulmonary function, nodular fibrosis, permanent disability, and death. Exposure to cobalt may cause weight loss, dermatitis, and respiratory hypersensitivity. The International Agency for Research on Cancer (IARC) has listed cobalt and cobalt compounds within group 2B (agents which are possibly carcinogenic to humans). ACGIH has placed cobalt and inorganic compounds in category A3 (Experimental animal carcinogen – the agent is carcinogenic in experimental animals at a relatively high dose, by route(s), histologic type(s), or by mechanism(s) that are not considered relevant to worker exposure.) Cobalt has been classified to be carcinogenic to experimental animals by the Federal Republic of Germany.

Molybdenum

With regard to effects of increased Mo-levels on humans, there are several studies that have described some adverse effects on people that are chronically exposed to elevated levels of molybdenum (liver dysfunction of workmen chronically exposed in a Soviet Mo-Cu plant, and signs of gout among inhabitants of Mo-rich areas of Armenia). The relevance and reliability of the conclusions made in these studies, however, are questionable.

There is a specific phenomenon that is specifically associated to ruminants, and which is generally known as molybdenosis. Molybdenosis is found only in ruminants such as cattle, deer and sheep, and is caused by molybdenum induced copper deficiency. It is not found in non-ruminants. Effects in cattle correspond with symptoms observed when dietary copper is deficient e. g. diarrhoea, alopecia (loss of hair), achromatrichia (change in hair colour), reduced milk yield and loss of body weight. In short, molybdenosis is copper deficiency (hypocuprosis), caused by the formation of insoluble copper – thiomolybdate complexes that can be formed in the "unique ecosystem" of the rumen of ruminants. Individual experimental studies with cattle have demonstrated that toxicity symptoms related to molybdenum-induced copper deficiency are either reduced or totally disappear after the addition of adequate copper to the diet (Clawson et al., 1972). Also in field studies, toxicity symptoms in cattle associated with an increased intake of molybdenum either reduced or disappeared simply by addition of supplementary copper. Smolders and Buekers (2009) conducted an in depth review of the Cu:Mo ratios at which molybdenosis is observed in cattle, and concluded that a dietary Cu-Mo ratio of 1.30 was sufficiently protective against molybdenosis for cattle. Available literature data on molybdenosis for other ruminants (field data on sheep, deer) confirmed that molybdenosis in these animals only occurred at a Cu-Mo ratio well below 1.30 (i. e., between 0.07 and 0.8).

Molybdenosis has not been observed in non-ruminants as their gastro-intestinal system does not involve the conditions and the micro-organisms found in the rumen of ruminants. Nonetheless, molybdenosis is a well-recognised phenomenon that has been observed in the field, and that requires proper assessment. The onset of molybdenosis is highly dependent of the dietary copper level, its bioavailability to the ruminant and the dietary Cu:Mo ratio. Through the addition of copper to the diet, however, the occurrence of copper deficiency (i. e., molybdenosis) can be prevented.

An illustrative example of the complexity of diagnosing trace element imbalances in animals, especially wild animals, is the disease in moose (Alces alces L.) appearing in an area in Southwest Sweden from about 1985. Affected animals showed a number of symptoms if they were found alive. Behavioral disturbances with apathy and pathological locomotion, loss of appetite, diarrhoea, emaciation, discoloration and loss of hair and opacities in the cornea and lens of one or both eyes were described in sick animals. In the dead animal post mortem examinations revealed lesions of the mucosa on the gastro-intestinal tract like oedema, hyperemia, hemorrhage and erosive lesions. The heart was dilated and flabby and myocardial lesions were seen macroscopically. The gastro-intestinal changes indicated a viral etiology of the disease but other findings do not support this and still no virus have been detected that could be responsible for the disease. An indication of the ethiology was found in measurements of trace elements in livers and kidneys from yearling moose sampled all over Sweden during the normal hunting periods in 1982, 1988, 1992 and 1994. The results showed that from 1982, before the outbreak of the disease, to later samplings the hepatic concentrations of Se and especially Mo increased in the affected area whereas Cu, Cd and some other elements decrease in concentration. These results were different from the neighboring areas during the same period. The plausible explanation for this discrepancy in the fact that the Alvsborg county was heavily limes to counteract the effects of acid rain that had caused damage to local forest and aquatic ecosystems. The increase in soil pH after liming however, altered the bioavailability of various trace elements, and as such may have altered the Cu:Mo ratio in soil, surface waters and grass down to a level below the "safe" threshold value. The hypothesis that the liming-induced effect on trace metal bioavailability resulted in hypocuprosis/molybdenosis, is supported by the fact that the majority of symptoms and pathological signs found in the moose could be explained by decreased activity of Cu-containing enzymes.

Other Cu-deficiency problems that are related to low Cu:Mo ratio's have earlier been suspected and reported from North America in moose (Alces alces gigas) in Alaska and from Africa in Grant's gazelle (Gazelle granti) in the Rift valley in Kenya.

Annex 4
Applications of Metals in Society

The most important applications of the metals considered in this report are listed in the table below (main source: USGS).

Table A4.1
Applications of the metals

Metal	Most important applications
Fe	98 % is forged into steel, used in construction, transportation, machinery and equipment, cans and containers, a wide variety of consumer products
Al	transportation (automobiles, airplanes, trucks, railcars, marine vessels, etc.); packaging (cans, foil, etc.); construction (windows, doors, siding, etc); consumer durables (appliances, cooking utensils, etc.); electrical transmission lines; machinery
Cu	power transmission and generation; building wiring; telecommunication; electrical and electronic products; industrial machinery; consumer and general products
Zn	coating, galvanising, alloys (bronze and brass) in construction materials; stabiliser, pigment and micronutrient
Pb	industrial and transport (SLI) batteries, ammunition, lead sheet, pigments and stabilizers
Cr	stainless steel and non-ferrous alloys; plating of metals, pigments, leather processing, catalysts, surface treatments, and refractories
Ni	In stainless and ferrous and non-ferrous alloys and superalloys, and in electroplating. Used in transportantion, construction, machinery, electrical equipment, household appliances.
Sn	coatings, alloys, solder
Hg	dentistry, switches and lighting, industrial applications such as in production process of PVC
Cd	batteries, pigments, coatings, stabiliser
As	wood preservative, pesticide
Au	jewelry, electronics, financial reserves
PGM	jewelry; catalytic converters; industrial catalysts; electronics and electronic equipment; fiberglass; LCD screens; dentistry
Mo	alloying agent in steel, cast iron, and superalloys, also added to chromium, columbium (niobium), manganese, nickel, tungsten, or other alloy metals; chemical applications, including catalysts, lubricants, and pigments
Co	rechargeable battery electrodes; superalloys; airbags in automobiles; catalysts for the petroleum and chemical industries; cemented carbides (also called hardmetals) and diamond tools; corrosion- and wear-resistant alloys; drying agents for paints, varnishes, and inks; dyes and pigments; ground coats for porcelain enamels; high-speed steels; magnetic recording media; magnets; steel-belted radial tires

Annex 5
Ore Grades and Ore Grade Declines

Historically, the long-term trend in the grades of ores processed has declined for numerous metals, often substantially in the first half of the twentieth century and more slowly in recent decades, depending on the metal. In general, the synthesis of extensive production statistics remains relatively uncommon, although a range of recent papers have published data on trends for copper, uranium, gold, nickel and platinum group metals of varying historical lengths. There are a range of factors which need to be considered in understanding the drivers behind ore grade decline, as these are crucial in any projection of the likely future trends in ore grades.

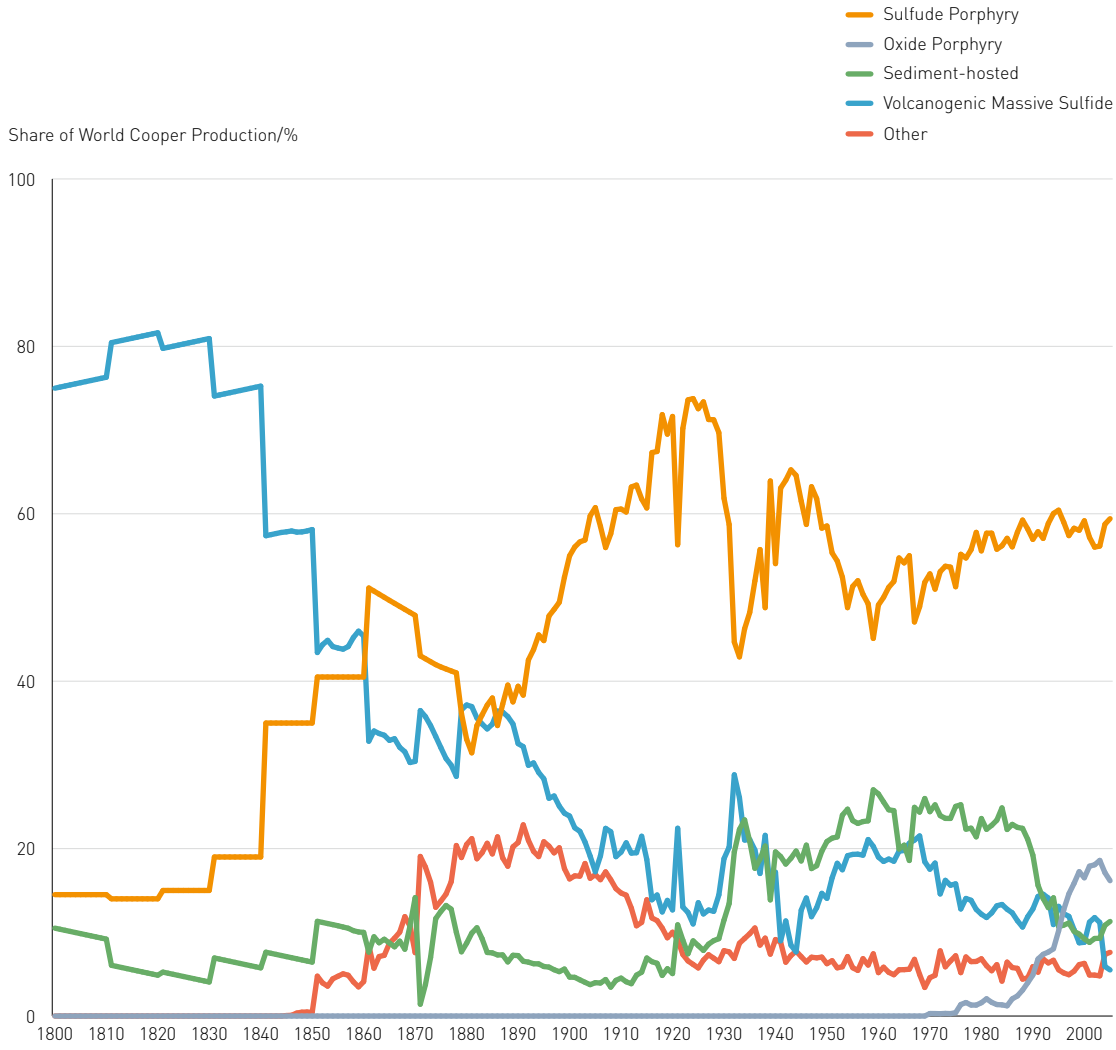
The ore grades processed at any given are a complex function of available technology, prevailing prices, demand-supply balances, ore types, ongoing exploration success or sometimes even social or environmental constraints. In general, growing demand, improving technology and exploration success has continued to ensure reliable and relatively cheap supply (in real terms). This has allowed the gradual lowering of cut-off grades, the grade at which it is economic to process ore, and a substantial expansion of annual global production.

Taking copper as a common example, this has led to a shift away from smaller but high grade deposits types towards giant porphyry copper ores which are substantially lower in grade, as shown in Figure A5.1 (Gerst, 2008). This shift was also crucially facilitated by the advent of flotation technology early in the twentieth century, which allowed the production of a high grade Cu concentrate for smelting rather than having to smelt the entire (lower grade) ore, which not only made Cu metal cheaper but reduced pollution burdens.

by the rise of lower grade but more extensive sulfide ores from the 1890s (e.g. Mt Lyell, Cobar and Mt Morgan mines). The temporary increase in ore grade in the late 1920s is due to the closure of uneconomic low grade open cut mines in preference for high grade underground mines to survive the depressed global Cu market – but with the revival of the Cu market from the early 1930s, the large open cut mines extracting low grade ore (~0.6 – 1 % Cu) were re-opened and Australian average grades declined accordingly. In

Figure A5.1

Changing ore types for copper mining (Gerst, 2008)



Some long-term data sets on Cu ore grade over time for some countries is shown in Figure A5.2. For Australia, the mid-1800s was dominated by rich, near surface Cu oxide ores (e.g. Burra and Peak mines), followed

the 1950s, Cu mining was begun at Mt Isa based on high grade ore (~3 % Cu), leading to a sustained ore grade increase to ~2 % Cu in Australia. From the late 1990s, however, a range of significant but lower grade Cu mines

were developed, leading to a gradual decline in recent ore grades approaching near historic lows of ~0.7 % Cu. Although 'high grade' Cu deposits can still be found (e. g. DeGrussa, WA), these are invariably much smaller in contained Cu than their larger but lower grade counterparts. In general, the grades of most remaining Cu deposits are of similar or lower grades to current producing mines, suggesting that, if production is to be maintained or increased, ore grades as mined and processed are unlikely to increase again in the future but will very gradually decline, albeit at a much slower rate than the 1800s and early twentieth century. Similar histories are important in understanding the evolution of Cu mining and ore grades in the USA, Canada and elsewhere around the world. That is, the intersection of demand, technology and exploration.

For comparison, ore grade trends are shown for gold in Figure A5.3, nickel in Figure A5.4, uranium in Figure A5.5 and platinum group metals in Figure A5.6. For gold, the decline in ore grade is about an order of magnitude over the past century, from about 20 g/t Au around 1900 to between 1 – 3 g/t Au by 2010. The past 30 years has seen a major expansion in world gold mining to record levels based on a sustained higher gold price (especially in real terms) as well as the new process technology of carbon-in-pulp, which allows extremely efficient use of cyanide to extract the gold – combined, this has facilitated a major lowering in ore grades (see Figure A5.3). The long-term declines in Ni grades is less pronounced than copper or gold, but still significant for some countries (e. g. New Caledonia). Of perhaps greater importance is the increasing shift to more complex Ni

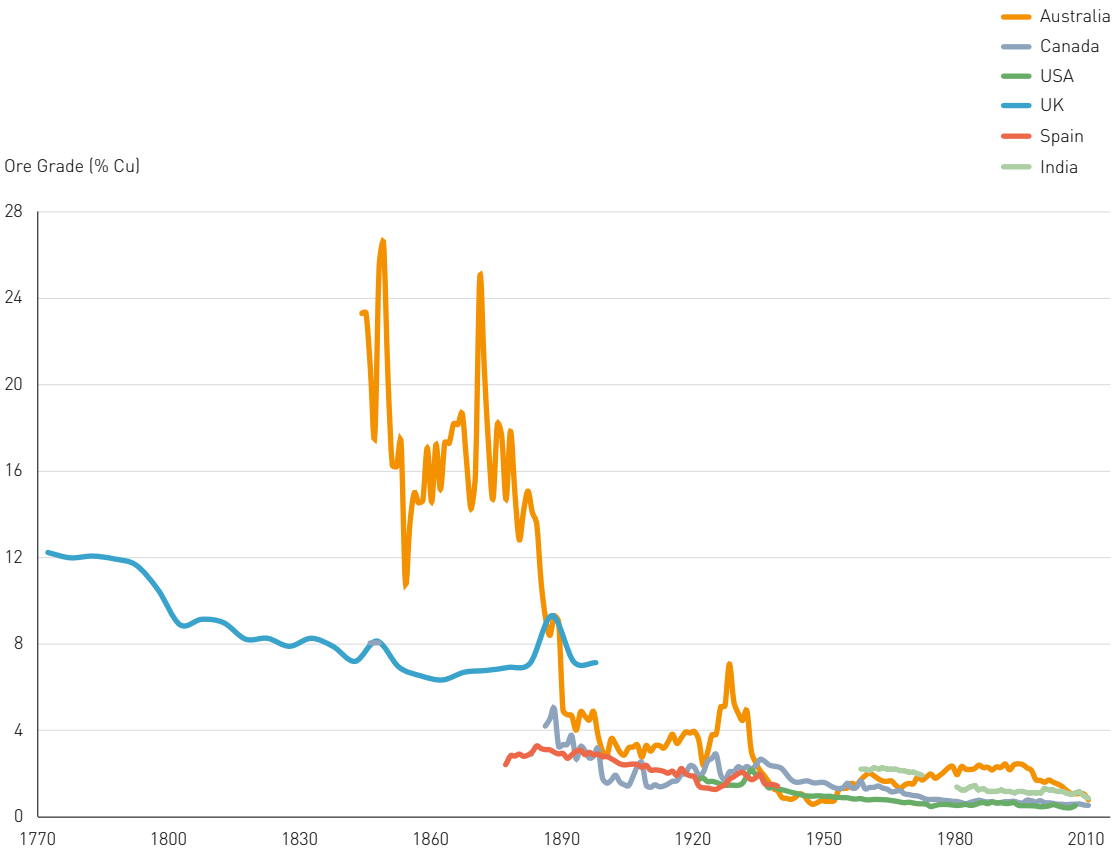


Figure A5.2

Long-term trends in processed copper ore grades for select countries (data from Crowson, 2012; Mudd, 2010a, Mudd, 2010b; Ruth, 1995; USBoM, var.; USGS, var.)

laterite ores, which require more intensive processing than their sulfide cousins. The global trends in U ore grades are typically a very gradual decline, allowing for the relative production from the countries shown in Figure A5.5, although Canada is the exception – its average U ore grade increased from the 1980s due to the rich deposits being developed in Saskatchewan (~0.5 – 20 % U_3O_8) and the closure of the low grade (~0.1 % U_3O_8) Elliot Lake field in Ontario in 1996. There are still numerous low grade U deposits across Canada, and if these are included in future U supply, ore grades will gradually decline (depending on the sequence of new mines and their respective grades). In Australia, most deposits are low grade (~0.02 – 0.3 % U_3O_8), dominated by the super-giant Olympic Dam Cu-U-Au-Ag-REE resource at ~0.03 % U_3O_8. The past decade has also seen gradual ore grade declines for many PGE companies and their respective mines, often related to ore types and mine configurations being developed, such as Platreef versus Merensky reefs in the Bushveld Complex (see (Mudd, 2012).

Figure A5.3

Long-term trends in processed gold ore grades for select countries (data from CMSA, 2010; Craig & Rimstidt, 1998; Machado & Figueiroa, 2001; Mudd, 2007; Natural Resources Canada, var., including updated data for Australia to 2010)

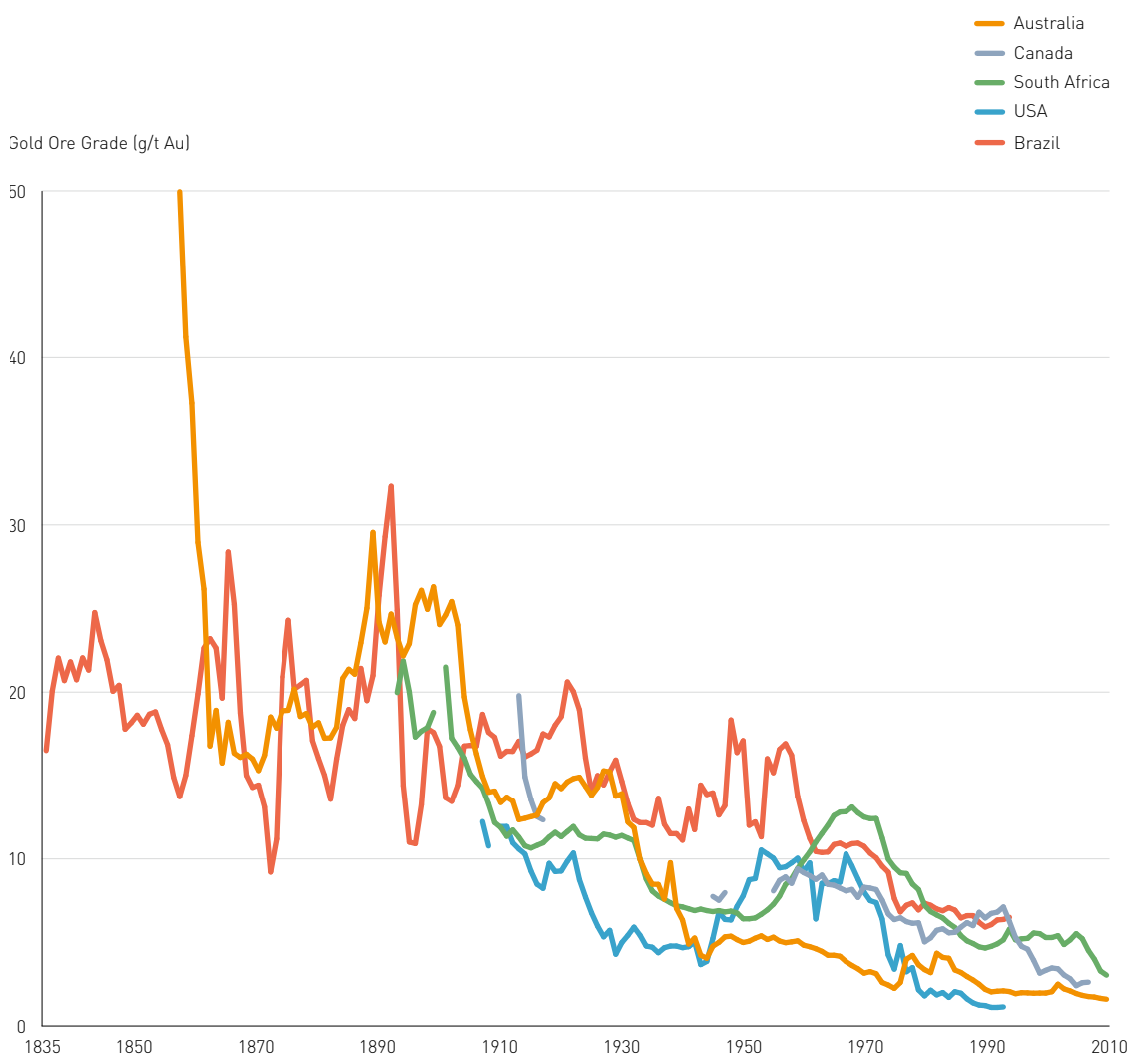


Figure A5.4

Long-term trends in processed nickel ore grades for select countries (data from Mudd, 2010b)

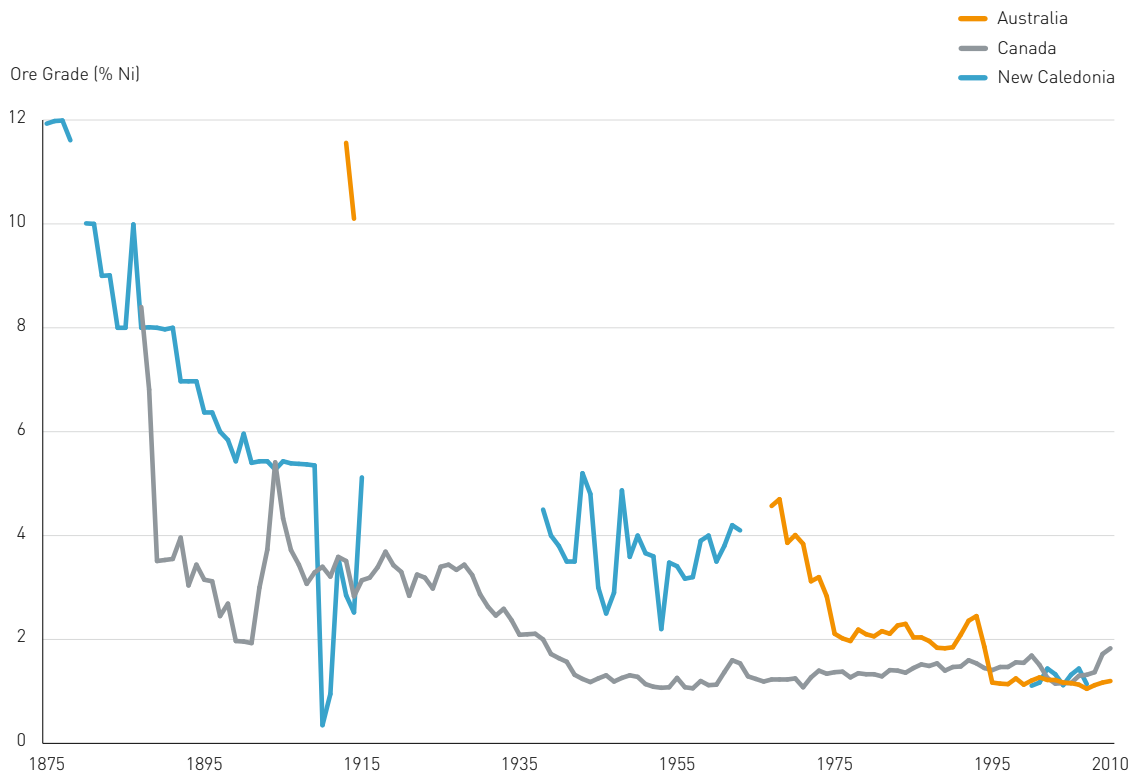


Figure A5.5

Long-term trends in processed uranium ore grades for select countries (data updated from Mudd and Diesendorf, 2008; Mudd and Diesendorf 2010) (note logarithmic scale for ore grade)

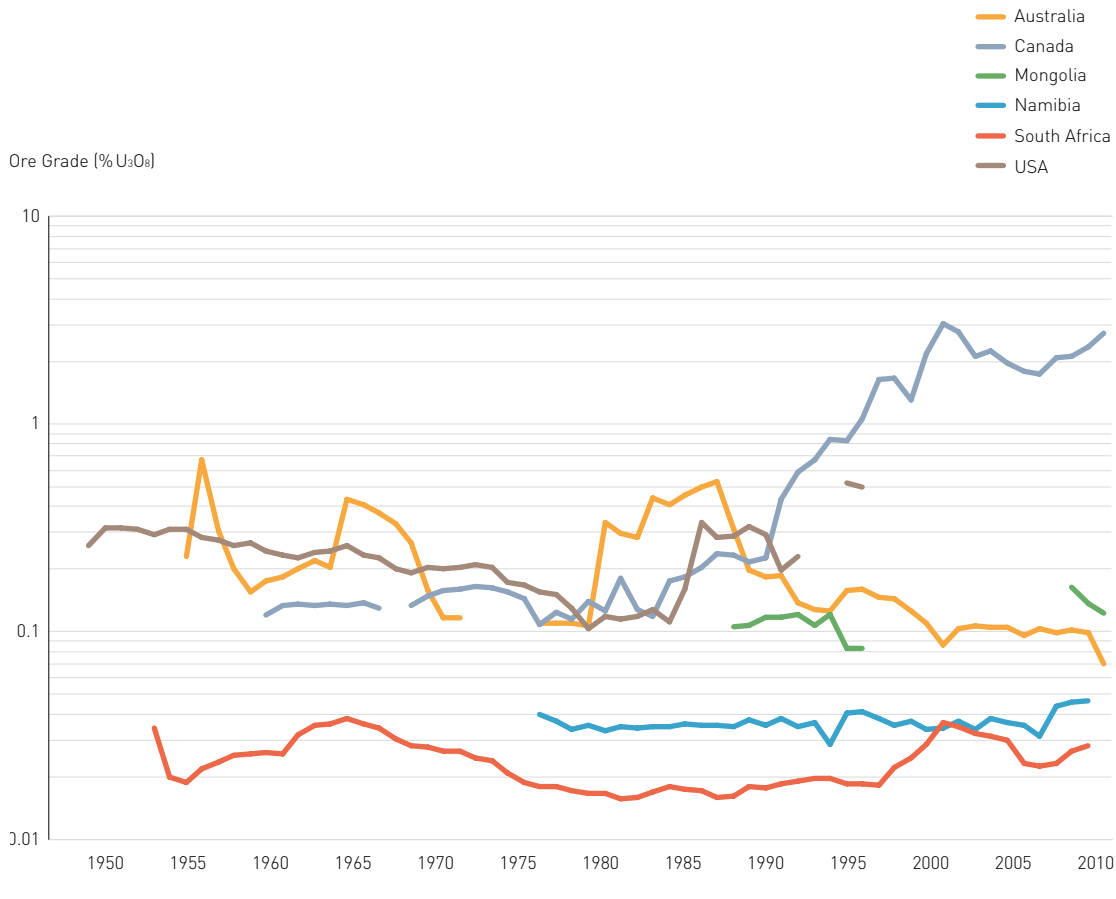


Figure A5.6

Recent trends in processed platinum group element (PGE) ore grades for select companies (Mudd, 2012)

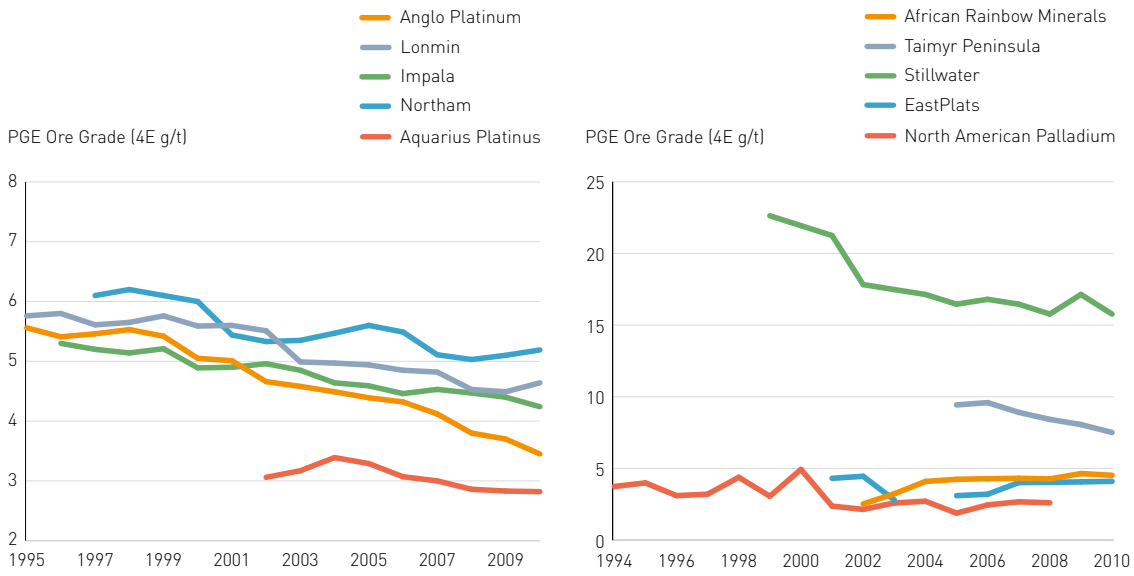
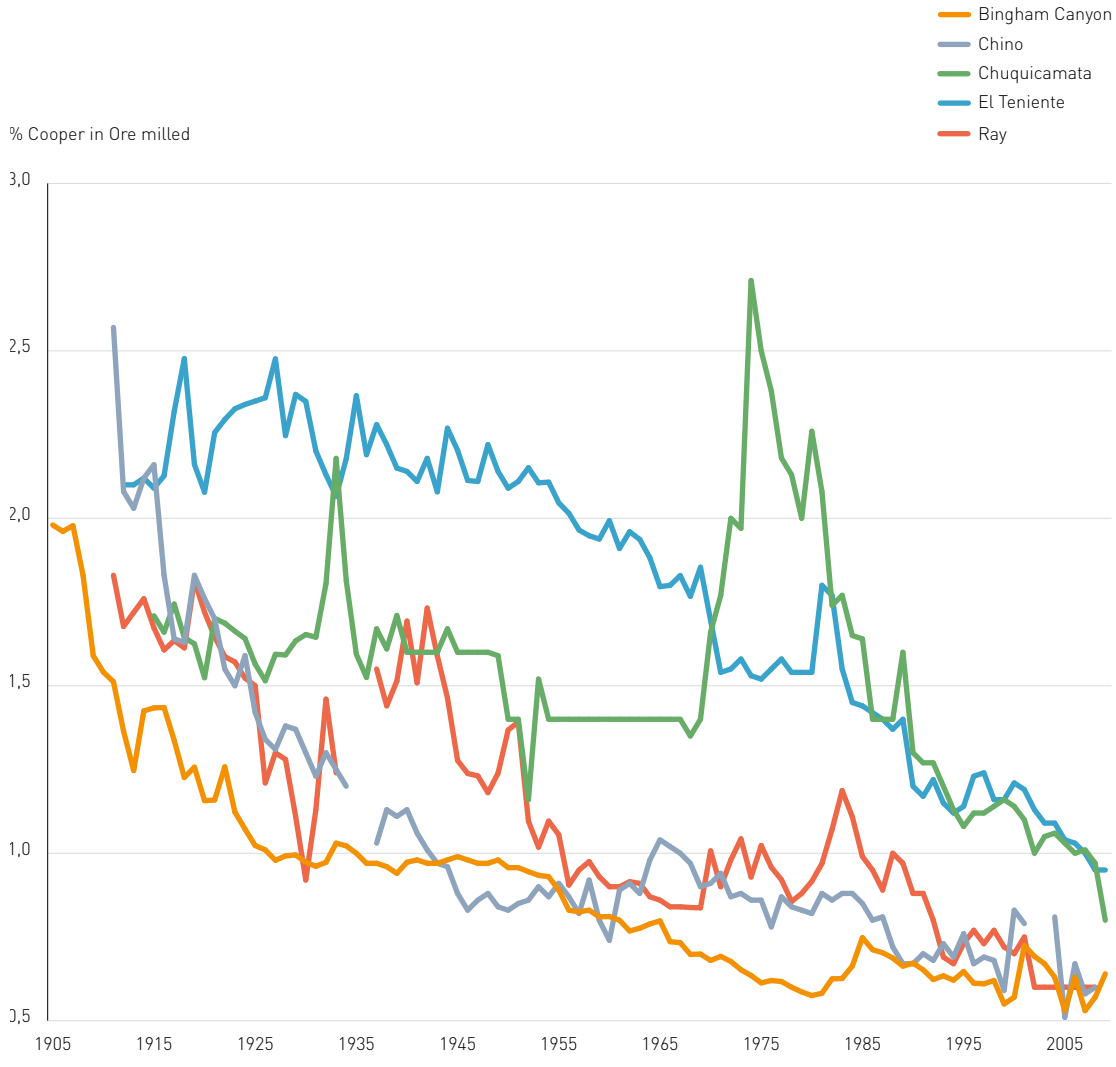


Figure A5.7

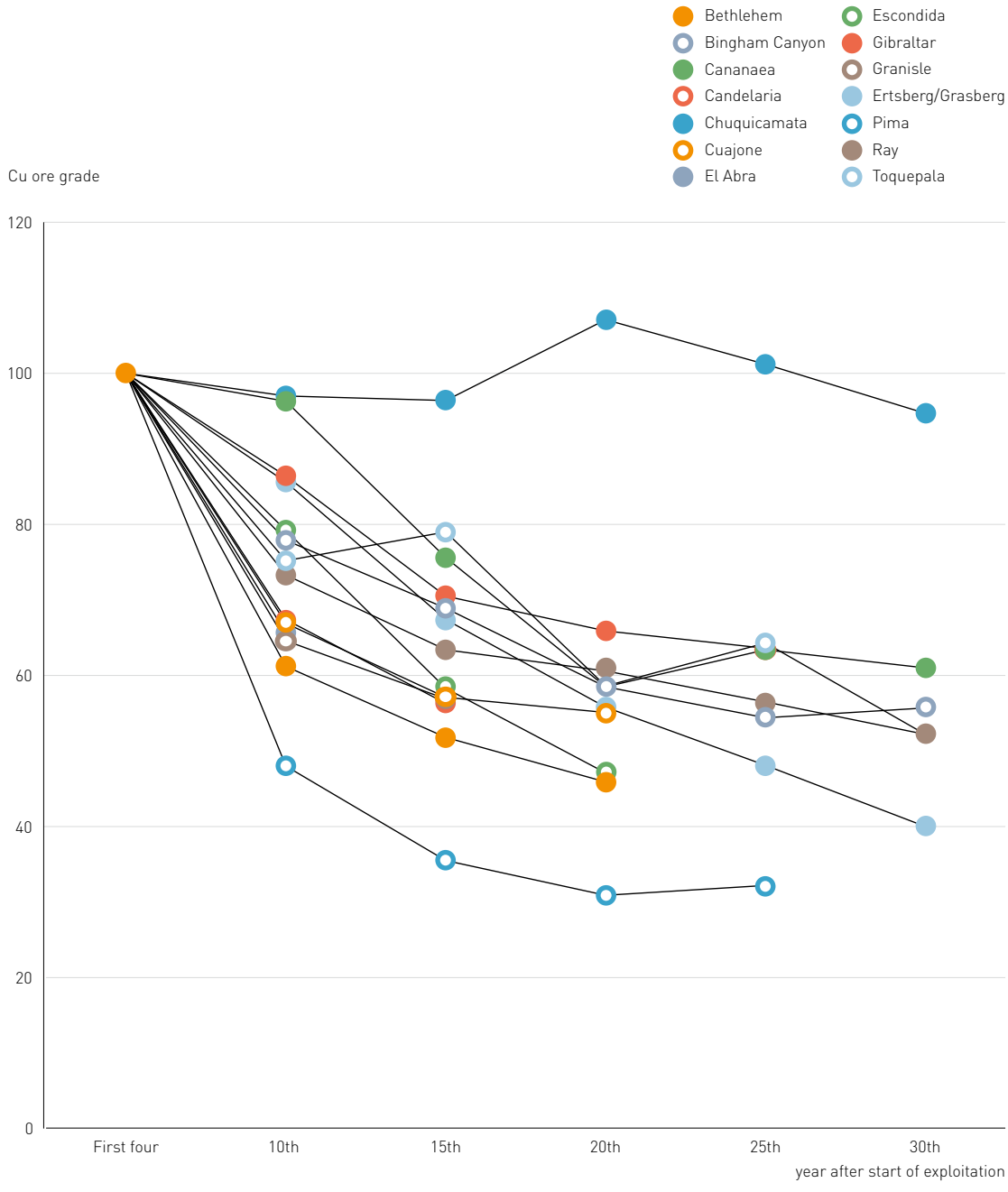
Long-term trends in ore grades at some giant Cu mines (Crowson, 2012)



For copper, a recent paper by (Crowson, 2012) includes a remarkable range of data on Cu mining and ore grades for select mines and fields around the world. Some century-old Chilean and USA Cu mines are shown in Figure A5.7, with relative trends in ore grades over 30 years from initial production for several large Cu mines shown in Figure A5.8.

Figure A5.8

Approximate relative trends in Cu ore grades over 30 years from initial production for some major mines (adapted from Crowson, 2012)



Annex 6
Life Cycle Assessment Methodology

A6.1
General Aspects

Life Cycle Assessment (LCA) is a comprehensive life cycle approach that quantifies ecological and human health impacts of a product or system over its complete life cycle. The term "products" is taken thereby in a very broad sense – including physical goods as well as services. The main applications of LCA are e. g. the analysis of the origins of problems related to a particular product, the comparison of improvement variants of a given product, the design of new products, or the choice between a number of existing comparable products. Within the basic principle of this method, the following steps can be identified:

- Compiling the inventory of relevant inputs and outputs of a defined system.
- Evaluating the environmental impacts associated with these inputs and outputs.
- Interpreting of the results of the inventory analysis and the impact assessment in accordance with the goal of this study.

According to the standards 14040 and 14044 of the International Organisation for Standartization, ISO (ISO, 2006a and ISO, 2006b), four phases – as shown in Figure A6.1 – are distinguished within an LCA study:

- **Goal and scope definition:** The scope, including system boundary and level of detail, of an LCA depends on the subject and the intended use of the study. The depth and the breadth of LCA can differ considerably depending on the goal of a particular LCA (ISO 2006b).
- **Inventory analysis:** It is the second phase of LCA. It is an inventory of input/output data with regard to the system being studied. It involves the collection of the data necessary to meet the goals of the defined study. (ISO, 2006b). More in Chapter 6.
- **Impact assessment:** It is the third phase of the LCA. The purpose of this third step is to provide additional information to help assess a product system's inventory results so as to better understand and evaluate the magnitude and significance of the potential environmental impacts related to the inventory data collected in the 2nd step (ISO, 2006a and ISO, 2006b). More in Chapter 6.
- **Interpretation:** It is the final phase of the LCA. Here, the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations (ISO, 2006a).

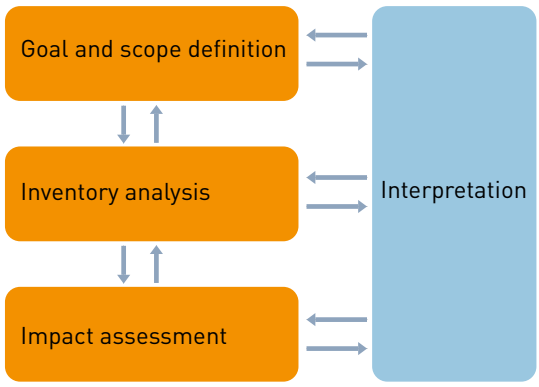


Figure A6.1

The LCA framework according to the ISO 14040/14044 series (ISO, 2006a)

According to the respective ISO standards (ISO, 2006a and ISO, 2006b), LCA is a relative and iterative approach, based on transparency and comprehensiveness. Relative, as an LCA is always structured around a functional unit that defines what is examined. All further activities then take place relative to this functional unit. Iterative, as shown in Figure A6.1, all steps are related to each other (i. e. each step is using the outcomes of the other steps) and thus, only passing several times across the various steps results in the end in comprehensiveness. As almost all life cycles of products include processes that occur all over the world, a high-quality, global environmental inventory database is mandatory

to ensure sound and credible results of LCA studies.

In relation to the topic of this report – i. e. the production of various metals – the goal and scope of the therefore relevant LCA studies is the examination of the impacts of the production of a specific amount (e. g. 1 kg or 1 tonne) of either of the metals covered by this report – produced out of the respective ore, or via an adequate recycling procedure, out of appropriate scrap. As soon as not only the production, but a complete life cycle of a metal for a specific use context is taken into account, the goal & scope step has to ensure that all functionalities of the metal for this context are taken into account and adequately covered by choosing an appropriate functional unit as well as the system boundaries.

A6.2
Life Cycle Inventory (LCI)

As mentioned above, this is the second phase of LCA, resulting in an inventory of input/output data with regard to the system being studied. Input data are energy and material amounts consumed in the various process steps, from the extraction of the metal-containing ores, across the various beneficiation and concentration steps, up to the final supply of one unit (i. e. one kg, one tonne) of a metal to the (global) metal market. On the output side, the amount of emissions to air, water and soil, the amount of waste water and waste, is recorded as detailed as possible for the same process steps as the above mentioned input data.

In relation to the topic of this report – i. e. the production of various metals – a critical element can be identified on the input side. Then in both cases (i. e. production of primary metals out of ores, resp. production of secondary metals out of scrap), complex systems have to be calculated as ores as well as scrap often represent a mixture of various metallic compounds – and thus, allocation issues get important. Dubreuil et al. (2010) reports that representatives from ferrous and non-ferrous metal groups agreed on a "consensus mapping presentation of a general allocation approach and the identification of harmonized metrics". The developed approach distinguishes between four different cases (called "recycling map models"); each of them representing another, typical life cycle of a metal. A table in Dubreuil et al. (2010) gives some example for each of the four types – table that is shown here in Table A6.2.

Table A6.1

Table with Metal recycling loop type examples (Dubreuil et al., 2010)

Type 1 Closed metal loop	**Type 2** Alloy loop	**Type 3** Transfer to another metal pool	**Type 4** Metallurgical re-separation
Steel scrap is recycled by a minimill where it is remelted and formed into semi-products.	Stainless steel alloys are retained in a distinct metal pool. Constituents include iron, chromium, nickel and other elements.	Nickel in low-alloy steel is recycled into the steel loop, where it is retained in dilute fractions in the steel pool.	Gold and platinum group metals are retained in copper-rich metallic fractions during electronic equipment recycling. At the copper smelter, these other metals are separated and refined.
Steel scrap is recycled by an integrated mill where the recycled metal is blended with primary metal coming from the blast furnace into the basic oxygen furnace.	Aluminum-magnesium alloy used for beverage cans is recycled as a distinct pool. The purity and properties of the alloy are managed and preserved.	Chromium coating on steel is recycled into the steel loop, where it is retained in dilute fractions in the steel pool.	Zinc used for galvanizing follows the steel onto which it is coated. During steel recycling, zinc is separated to electric arc furnace dust, which is treated to remove cadmium. Zinc is then recovered in an Imperial Smelting Furnace.
Copper in applications where it is nearly pure is recycled back to semi-fabricators, where it is remelted and reformed into semi-products.	Brass is a copper-zinc alloy that is collected and recycled to retain alloy properties.	Due to inefficiencies in physical separation, copper particles are entrained with the steel recycling flow. Once melted, copper cannot be removed economically from the steel.	

However, so far there are no generally accepted, accurate allocation factors available for an application of these four above described models – hence, as mentioned in Dubreuil et al. (2010), "important work needs to be done" to achieve such factors. But despite this lack, several LCA and/or LCI studies about the here examined metals exist and are published; using their own, specific allocation factors. More details can be found in Chapter 6, describing in details the available LCI data sources.

A6.3
Life Cycle Impact Assessment (LCIA)

In the Life Cycle Impact Assessment (LCIA) phase, the third step of the ISO framework, the emissions and resource data collected in the preceding LCI step are translated into indicators that represent environment and health impacts as well as resource scarcity. This is based on factors which represent the impact per unit emission or resource consumption. These factors are generally calculated using models (European Commission, 2010b); however, over the last two to three decades a broad variety of such LCIA factors has been developed and published. A, still not complete, overview of this broad variety of LCIA factors can be found e. g. in the ecoinvent database; as the developers of this database try to publish for the user a clear guidance how to use the various LCIA factors/methods in combination with the data from the ecoinvent database; described in the report from Hischier et al. (2010).

In the framework of the International Reference Life Cycle Data System (ILCD) handbook – a series of technical documents that provide detailed guidance on all the steps required conducting a Life Cycle Assessment (LCA) – the European Commission's Joint Research Centre (EC-JRC) started in 2010, after a thorough analysis of the existing approaches (European Commission, 2010a and 2010b) a public consultation phase on recommended methods for the Life Cycle Impact Assessment. A first draft of a report with recommended LCIA factors was distributed in the LCA community and a workshop was held in Brussels in October 2010.

In relation to the topic of this report – i. e. the production of various metals – important indicators among the huge amount of various LCIA indicators available in a variety of LCIA methods (for a recent overview see e. g. European Commission, 2010a) are the Resource Depletion, the Global Warming Potential (GWP) – or alternatively the Cumulative Energy Demand (CED) – as an indicator for the energy intensity of a process, the Acidification Potential (AP) and/or the Ecotoxicity Potential (ETP), both representing the releases of highly acid substances into the environment. In some publications (e. g. Norgate et al., 2007) you still can find also indicators for the amount of waste produced – like e. g. the Solid Waste Burden (SWB); although there are nowadays data available for different waste treatment activities in order to avoid this kind of indicator; and include instead the total amount of emissions occurring in these treatment activities into the overall amount of emissions across the life cycle. According to the report from the ILCD team about recommended LCIA factors (European Commission, 2011– [not yet published AND NOT TO BE CITED!]), the following modelling is recommended for these above mentioned single impact assessment factors:

- **Resources Depletion:** For the resource depletion topic, the report recommends using the 2004 update of the factors for the depletion of abiotic resources reported in the EDIP 97 LCIA method, described in Hauschild and Wenzel (1998), resp. in Hauschild and Potting (2005). This is a model that takes into account fossil fuels and minerals, and it represents the person-reserve, meaning the quantity of the resource available to an average world citizen. For the calculation of the characterisation factors, the amount extracted is divided by the global production of the reference year (2004) and weighted according to the economically viable reserves of this material.

- **Global Warming Potential (GWP):** For the GWP, the recommendation favourites the "default" 100 year baseline model for greenhouse gases, according to the IPCC report from 2007 (IPCC, 2007). The IPCC factor is used in all LCIA methods that take into account GWP – although not all of the methods use the latest version of the IPCC report. Among the three perspectives (20, 100 and 500 years), the 100 year baseline is commonly used; this is also the time horizon used e. g. for the Kyoto protocol or further policy work in the area of climate change.

- **Acidification Potential (AP):** For the AP, the European Commission is suggesting to use the so called "Accumulated Exeedance", developed by Seppälä and co-workers. This method does not only take into account the dispersion of an emission in the atmosphere, but also the sensitivity of the ecosystem receiving the (additional) deposition due to the emission (Seppälä et al., 2006), and uses this method to calculate the European country-dependent characterisation factors. The atmospheric transport and deposition model to land area and major lakes/rivers is determined using the EMEP model – a detailed model for long-range transport of air pollutants in Europe – combined with a European critical load database for sulphur and nitrogen depositions in Europe. However, so far not much LCA software tools have integrated this approach for a practical application.

- **Ecotoxicity Potential (ETP):** For the ETP, the recently developed, common international framework for toxicity categories (Rosenbaum et al., 2008) has been used. This approach results from a consensus building effort amongst related modellers and, hence, the underlying principles reflect thus common and agreed recommendations from these experts. The model accounts for all important parameters in the impact pathway as identified by a systematic model comparison within the consensus process. The model addresses the freshwater part of the environment problem and includes the vital model elements in a scientifically up-to-date way. USEtox has also been set up to model a global default continent. In USEtox, a distinction is made between interim and recommended characterization factors, reflecting the level of expected reliability of the calculations in a qualitative way. Ecotoxicological characterisation factors for 'metals', 'dissociating substances' and 'amphiphilics' (e. g. detergents) are all classified as interim in USEtox (Rosenbaum et al. 2008).

In case of the **Cumulative Energy Demand (CED)**, the European Commissions doesn't recommend any factor (resp. is indirectly recommending dealing with these resources similar as with mineral/metallic resources). The consumption of fossil fuels is also part of the above described ARD factor for the resource depletion. In the same time, CED analysis has a rather long tradition; and the indicator has been created – as reported e. g. in Hischier et al. (2010) – already in the early seventies after the first oil price crisis (Boustead and Hancock, 1979, Pimentel 1973).
In the same time, CED is widely used as a screening indicator for environmental impacts (Hischier et al., 2010). For this report, the definition for the CED from the ecoinvent database, based on the respective document from the German Industry Association (VDI) has been used. However, opposite to the ecoinvent database that shows the various factors of the CED in an non-aggregated form; for the purpose of this study, all these values have been aggregated into one single number – the "Total Cumulative Energy Demand". More details about this issue can be found in Hischier et al. (2010).
A specific issue in LCIA is aggregation. Most LCA studies end up with a number of indicators on different environmental impacts, either at midpoint level or at endpoint level. A next possible step is aggregating them all into one indicator for environmental performance. This step requires normalisation and weighting. The weighting step is subjective and (therefore) controversial. The ISO guideline for LCA states that weighting is not permitted in case of comparative studies. LCA researchers are hesitant to apply this step at all, because of the subjectivity of its nature. In many cases, there is no need for it. Sometimes there is, and then various options exist for attributing weights to specific impact categories. Political (stakeholder) weighting and (scientific) panel weighting are two options.

It should be noted that some LCIA methods have an inherent weighting. These come up with single scores that have a weighting procedure behind them that is invisible for the user.

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Abbreviations and Acronyms

ACGIH	American Conference Of Industrial Hygienists
AMD	Acid Mine Drainage
AP	Acidification Potential
AR	Aqua Regia
ARD	Abiotic Resource Depletion
ASM	Artisanal And Small-Scale Mining
BAT	Best Available Technology
BEV	Battery Electric Vehicles
BF	Blast Furnace
BIW	Body-In-White
BL	Baseline
BLM	Biotic Ligand Model
BOF	Basic Oxygen Furnace
BREF	Best Available Technique Reference Notes
C	Concentration
CASM	Communities And Small-Scale Mining
CCS	Carbon Capture Storage
CED	Cumulative Energy Demand
CLRTAP	Long-Range Transboundary Air Pollution
CML	Institute Of Environmental Sciences Of Leiden University
CRT	Cathode Ray Tubes
CSIRO	Commonwealth Scientific And Industrial Research Organisation
DEL	Deficiency Effect Level
DfE	Design For Environment
DfR	Design For Recycling
DNA	Deoxyribonucleic Acid
DRI	Direct Reduced Iron
EAA	European Aluminium Association
EAF	Electric Arc Furnace
EC50	Half Maximal Effective Concentration
ECI	European Copper Institute

EEE	Electric And Electronic Equipment
EFF3	Standard Efficiency
Eh	Activity Of Electrons
ELCD	European Life Cycle Database
EoL	End-Of-Life
E-PRTR	European Pollutant Release And Transfer Register
EQC	Environmental Quality Criteria
ETP	Ecotoxicity Potential
EU	European Union
FAO	Food And Agriculture Organisation Of The United Nations
GER	Gross Energy Requirement
GHG	Greenhouse Gas
GWP	Global Warming Potential
HC5	Hazardous Concentration For 5 % Of The Species
HPAL	High-Pressure Acid Leaching
HPGR	High Pressure Grinding Rolls
IARC	International Agency For Research On Cancer
IC	Integrated Circuit
ICE	Internal Combustion Engine
ICT	Information And Communication Technology
IEA Blue Map	Mix According To Shell Blue Map Scenario, Including Fossil Fuels As Well As Renewable Energy Sources
IED	Industrial Emissions Directive
ILCD	International Reference Life Cycle Data System
IMOA	International Molybdenum Association
IPCC	Inter-Governmental Panel On Climate Change
IPP	Integrated Product Policy
IRP	International Resource Panel
ISO	International Organization For Standardization
ISP	Imperial Smelting Process
IZA	International Zinc Association

JECFA	Joint Expert Committee On Food Additives
JRC	Joint Research Centre
K-G index	Klee-Graedel Human vs. Nature Dominance Index
LCA	Life Cycle Assessment
LCDs	Liquid Crystal Display
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCT	Life Cycle Thinking
LW	Lightweight
MFA	Material Flow Analysis/Accounting
MPC	Maximum Permissible Concentration
msPAF	Multiple Substance PAF
NOAEL	No Observed Adverse Effect Level
NOEC	No Effect Concentration
NPI	National Pollutant Inventory
NPRI	National Pollutant Release Inventory
NRA	No Risk Area
NTP	National Toxicology Program
OCEE	Optimal Concentration Range Of Essential Elements
OEM	Original Equipment Manufacture
OSHA	United States Occupational Safety And Health Administration
PAF	Potentially Affected Fraction
PC	Personal Computer
PEC	Predicted Environmental Concentration
PGM	Platinum Group Metal
pH	Potential Hydrogen
PM	Particle matter
PM10	Particle matters of 10 micrometers or less
PNEC	Predicted No Effect Concentration
PSU	Power Supply Unit
PTWI	Provisional Tolerable Weekly Intake Limit
PWB	Printed Wiring Board
RARs	Risk Assessment Reports

RE	Rare Earths
REACH	Registration, Evaluation, Authorisation, And Restriction Of Chemical Substances
RMC	Roasted Molybdenite Concentrate
SD	Standard Deviation
SETAC	Society Of Environmental Toxicology And Chemistry
SFA	Substance Flow Analysis
SHG	Special High Grade
SLC	Super Light Car
SMD	Surface Mount Device
SSD	Species Sensitivity Distribution
ssPAF	Single Substance PAF
StEP-Initiative of UN	Solving The E-Waste Problem
SWB	Solid Waste Burden
SX/EW	Solvent Extraction/Electrowinning
TGD	Technical Guidance Document
TRI	Toxic Release Inventory
TSL	Top Submerged Lance
UNECE	Nited Nations Economic Commission For Europe
UNEP	United Nation Environment Programme
USA	United States Of America
US-EPA	United States Environmental Protection Agency
USSR	Union Of Soviet Socialist Republics
WBCSD	World Business Council For Sustainable Development
WEEE	Waste Electrical And Electronic Equipment
WFD	Water Framework Directive
WHO	World Health Organization
WtoE	Waste-To-Energy

Units

cm	centimetre (10^{-2} metres)
CO_2-eq	carbon dioxide equivalents
g	gram
Gg	gigagram (10^{9} gram)
GJ	gigajoule (10^{9} joules)
GL	gigalitre (10^{9} litres)
GWh	gigawatt hour (10^{9} watt hour)
kg	kilogram (10^{3} gram)
kL	kilolitre (10^{3} litre)
km	kilometre (10^{3} metre)
kt	kilotonne (10^{9} gram)
kWh	kilowatt hour (10^{3} watt hour)
J	joule
L	litre
Ln	natural logarithm
Log	logarithm
mg	milligram (10^{-3} gram)
MJ	megajoule (10^{6} joules)
mm	millimetre (10^{-3} metres)
Mt	megatonne (10^{12} gram)
PJ	petajoule (10^{15} joules)
ppb	part-per-billion
t	tonne (10^{6} gram)
TWh	terawatt hour (10^{12} watt hour)
vkm	vehicle kilometre
y	year
µg	microgram (10^{-6} gram)
µm	micrometre (10^{-6} meter)

Chemical Abbreviations

CH_3Hg^+	methyl mercury
Ag	silver
Al	aluminum
$Al(OH)_3$	aluminium hydroxide
AL_2O_2	aluminium oxide
As	arsenic
Au	gold
Be	beryllium
Cd	cadmium
$CdCl_2$	cadmium chloride
Co	cobalt
CO_2	carbon dioxide
Cr	chromium
Cr(VI)	hexavalent chromium
Cu	copper
Cu_2FeSnS_4	stannite
$CuFeS_2$	chalcopyrite
Dy	dysprosium
Fe	iron
$Fe(O_2H)$	hydrous iron oxides
Fe_3S_4	iron sulfide
FeO	iron oxide
FeS	iron sulfide
FeS_2	iron disulfide
Ga	gallium
Ge	germanium
HCFC	hydrochlorofluorocarbon
HFC	hyrdofluorocarbon
Hg	mercury
HgS	cinnabar
HNO_3	nitric acid

In	indium
Ir	iridium
$MeCl_2$	methylene chloride
MeOH	methanol
Mg	magnesium
Mn	manganese
MnO_2	oxides of manganese
Mo	molybdenum
Nd	neodymium
Ni	nickel
NiMH	nickel metal dydride
NOx	nitrogen oxide
Pb	lead
PP	polypropylene
PE	polyethylene
PVC	polyvinyl chloride
PCB	polychlorinated biphenyl
Pd	palladium
Pr	praseodymium
Pt	platinum
Rh	rhodium
Sb	antinomy
Sc	scandium
Se	selenium
SIO_2	silicon dioxide
Sn	tin
Sn^{2+}	tin stanious
SnO_2	cassiterite
SO_2	sulfur dioxide
SOx	sulfur oxide
SS	stainless steel
Ta	tantalum
Ti	titanium

Tl	thallium
TOC	troodos ophiolite complex
U_3O_8	triuranium octoxide
V	vanadium
W	tungsten
Y	yttrium
Zn	zinc

International Resource Panel

As our economies have grown, so has the use of materials and resources. In an increasingly globalised economy, the challenge for policy-makers is to streamline actions for ensuring a more sustainable management of resources, both renewable and non-renewable. There are existing measures such as policies on climate change and biodiversity that tackle certain aspects of the global resource issues. However a holistic approach to resources management is needed to better identify their interlinkages and gaps in a systemic way.

The establishment of the International Resource Panel, or Resource Panel for short, is a first step towards addressing this need. Hosted at UNEP, the Resource Panel was officially launched in November 2007 to provide the scientific impetus for decoupling economic growth and resource use from environmental degradation.

The objectives of the Resource Panel are to provide independent, coherent and authoritative scientific assessments of policy relevance on the sustainable use of natural resources and in particular their environmental impacts over the full life cycle as well as to contribute to a better understanding of how to decouple economic growth from environmental degradation.

This work builds on and contributes to other related international initiatives, including the 10-Year Framework of Programmes on Sustainable Consumption and Production (10YFP) and the Green Economy Initiative.

Global Metal Flows Working Group

Economic development is deeply coupled with the use of metals. The growing demand for metals implies a permanent pressure on the resource base. Metals are resources that have a high value and in principle can be easily reused and recycled. Reuse and recycling activities of metals on a global scale can contribute to closing the loops, turn waste into resources, and are expected to thereby reduce environmental impacts, safeguard the availability of metals, minimize metal prices, and promote meaningful and safe jobs for poor people in developing countries.

The Global Metal Flows Working Group aims at contributing to the promotion of reuse and recycling of metals and the establishment of an international sound material-cycle society by providing scientific and authoritative assessment studies on the global flows of metals. Expected results include revealing potentials for increasing the resource efficiency of metal flows at the national and international level.

About the UNEP Division of Technology, Industry and Economics

The UNEP Division of Technology, Industry and Economics (DTIE) helps governments, local authorities and decision-makers in business and industry to develop and implement policies and practices focusing on sustainable development.

The Division works to promote:

> sustainable consumption and production,
> the efficient use of renewable energy,
> adequate management of chemicals,
> the integration of environmental costs in development policies.

The Office of the Director, located in Paris, coordinates activities through:

- **The International Environmental Technology Centre** - IETC (Osaka, Shiga), which implements integrated waste, water and disaster management programmes, focusing in particular on Asia.
- **Sustainable Consumption and Production** (Paris), which promotes sustainable consumption and production patterns as a contribution to human development through global markets.
- **Chemicals** (Geneva), which catalyzes global actions to bring about the sound management of chemicals and the improvement of chemical safety worldwide.
- **Energy** (Paris and Nairobi), which fosters energy and transport policies for sustainable development and encourages investment in renewable energy and energy efficiency.
- **OzonAction** (Paris), which supports the phase-out of ozone depleting substances in developing countries and countries with economies in transition to ensure implementation of the Montreal Protocol.
- **Economics and Trade** (Geneva), which helps countries to integrate environmental considerations into economic and trade policies, and works with the finance sector to incorporate sustainable development policies.

UNEP DTIE activities focus on raising awareness, improving the transfer of knowledge and information, fostering technological cooperation and partnerships, and implementing international conventions and agreements.

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A key question that relates to the very broad and intensive use of metals is whether society needs to be concerned about long-term supplies of any or many of them. This is a many-faceted question that cannot be answered quickly or unequivocally. To address it, the Global Metal Flows Working Group envisions a series of six reports, of which this is the third one addressing environmental risks and challenges of anthropogenic metals flows and cycles.

This report, compiled by a group of international experts, focuses on the impact of metals on the environment as well as on their life cycle energy use. Currently, primary metals production is responsible for 7–8% of the total global energy use as well as for severe local environmental impacts. The report suggests to apply best available techniques and to increase recycling of metals, which not only requires significantly less energy per kg metal produced than primary production but also helps decreasing the overall local impacts of mining. However, even if recycling rates are increased, rising global demand for many metals will remain a huge environmental challenge in the next decades worldwide.

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United Nations Environment Programme
P.O. Box 30552 Nairobi, Kenya
Tel.: ++254-(0)20-762 1234
Fax: ++254-(0)20-762 3927
E-mail: uneppub@unep.org

UNEP

For more information, contact:
Resource Panel Secretariat
UNEP DTIE
Sustainable Consumption
and Production Branch
15 rue de Milan
75441 Paris CEDEX 09
France
Tel: +33 1 44 37 14 50
Fax: +33 1 44 37 14 74
E-mail: resourcepanel@unep.org
www.unep.org/resourcepanel

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