Managing raw materials scarcity:
safeguarding the availability of geologically scarce mineral resources for future generations

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safeguarding the availability of geologically scarce mineral resources
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Het beheer van schaarse grondstoffen:
waarborgen dat geologisch schaarse delfstoffen beschikbaar blijven
voor toekomstige generaties
(met een samenvatting in het Nederlands)

Proefschrift

ter verkrijging van de graad van doctor aan de Universiteit Utrecht op gezag van de rector magnificus, prof. dr. G.J. van der Zwaan, ingevolge het besluit van het college voor promoties in het openbaar te verdedigen op maandag 17 oktober 2016 des middags te 4.15 uur

door

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geboren op 20 november 1948 te Hunsel

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ABBREVIATIONS

3R	Reduce, Reuse, Recycle
Ag	Silver
Al	Aluminum
As	Arsenic
ASEAN	Association of South East Asian Nations
Au	Gold
Ba	Barium
Be	Beryllium
Bi	Bismuth
Cap	Capita
Cd	Cadmium
CDR	Common but Differentiated Responsibilities
Co	Cobalt
Cr	Chromium
Cu	Copper
EAF	Electric Arc Furnace
EC	European Commission
EFRA	European Flame Retardant Association
EGR	Extractable Global Resources
EHS	Environment, Health and Safety
ENMOD-convention	Convention on the prohibition of military or any hostile use of environmental modification techniques
EoL	End-of-life
ETS	Emission Trading Scheme
EU	European Union
Fe	Iron
G	Gram
Ga	Gallium
GDP	Gross Domestic product
Ge	Germanium
GFRP	Glass Fiber Reinforced Plastics
Hg	Mercury
IAEA	International Atomic Energy Agency
IMOA	International Molybdenum Association
In	Indium
Kt	Kiloton
Li	Lithium
LIBS	Laser Induced Breakdown Spectroscopy
ME	Material Efficiency
Mg	Magnesium

Mn	Manganese
Mo	Molybdenum
Nb	Niobium
Ni	Nickel
OECD	Organization of Economic Cooperation and Development
OPEC	Organization of Petroleum Exporting Countries
OSPAR Convention	Oslo-Paris Convention on the Protection of the Marine Environment of the North-East Atlantic
P- value	Significance
Pb	Lead
PCB	Polychlorinated biphenyl
PET	Polyethylene terephthalate
PMG	Platinum Group Metals
PSS	Product Service Systems
PVC	Polyvinyl chloride
RB	Reserve Base
Re	Rhenium
REDD	Reducing Emissions from Deforestation and Forest Degradation
REE	Rare Earth Elements
Sb	Antimony
Se	Selenium
Sn	Tin
Sr	Strontium
Ta	Tantalum
Ti	Titanium
TNO	Technisch Natuurwetenschappelijk Onderzoek (Dutch for Technical Scientific Research)
U	Uranium
UNESCO	United Nations Educational, Scientific and Cultural Organisation
UNEP	United Nations Environmental Program
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
USD	United States Dollar
USGS	United States Geological Survey
V	Vanadium
W	Tungsten
WEEE	Waste Electronic and Electrical Equipment
WTO	World Trade Organization
Zn	Zinc
Zr	Zirconium

Chapter 1

Introduction

1.1   DEVELOPMENT OF MINERAL RESOURCES USE

Mineral resources are the physical foundation of society. Prehistoric ages are named after mineral resources: Stone Age, Bronze Age, and Iron Age. Without mineral resources there would be no wealth or progress. Since the beginning of the 20th century the use of mineral resources has been increasing faster than ever before. (See Figure 1-1).

For a long time in history, stone, wood, iron, copper, and tin were the main raw materials for buildings, transport, tools, and weaponry. Wood is a renewable resource. In practice, stone can be considered as a non-exhaustible resource as well, because of its abundance.

From the industrial revolution of the 18th century onwards, the use of non-renewable re-sources increased quickly. This was the result of a continuous search to improve the proper-ties of materials: more strength, lower weight, better corrosion resistance, higher (or lower) conductivity of electricity and heat, lower costs, etc. The industrial revolution coincided with a technological revolution. Technology development worked as a self-reinforcing flywheel, resulting in an accelerating sequence of new discoveries. New elements were identified (e.g. cobalt in 1737, zinc in 1746, nickel in 1751, tungsten in 1783, magnesium and aluminum in 1808). New applications were developed (crucible steel in 1765, stainless steel in 1912, aluminum production in 1890, super alloys in 1947). (Ashby, 2009).
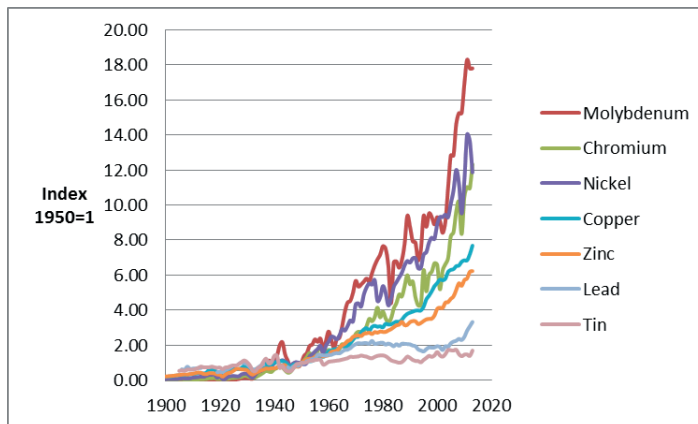
Figure 1-1 Global production of commodities. Derived from USGS, 2014

Gradually, the dependence of humanity on non-renewable mineral resources has increased: from a total dependence on non-exhaustible materials to a near-total dependence on ex-haustible resources (Ashby, 2009).

The GDP of the average world citizen in 2013 was about 10,000 USD at current prices and the GDP of the average Northern American was about 53,000 USD (United Nations Statistics Division, 2015). Let us assume that the GDP of the average world citizen by 2100 will have increased to the same level as that of the average American in 2013. This means an annual

growth of about 3%, which does not seem unrealistic considering the global GDP growth in the (recent) past. Given the expected increase of the world population from 7 billion now to about 9 billion in 2100, the global GDP in 2100 would be about 7 times higher than in 2013. Since the use of mineral resources – to a certain degree – is correlated with GDP growth, it can be expected that the demand for mineral resources will grow accordingly.

Will the earth be able to continue bearing such growth? Will there be enough mineral resources to sustain a worldwide infrastructure and a pattern and level of consumption as present in the United States at this moment? Despite new discoveries it is clear that reserves of mineral resources are declining. Many mines in the USA and in Europe have closed, as ore grades have declined. In the US the copper grade of mined copper ore has declined from more than 2% in the early part of the 20th century to 0.5% today and the iron grade in iron ore from 60% to 20% (Tilton, 2003). Australia, still an important mineral-producing country, is going in the same direction (Prior et al. 2012). Hence, given the assumed demand increase, the issue may no longer be *whether* the reserves of mineral resources in the earth's crust will still be sufficient for future generations, but *when* the scarcest resources will be depleted. The next question is whether or not humankind would need to anticipate a situation of serious geological scarcity of a number of mineral resources. Not anticipating on depletion of certain mineral resources may lead to a situation in which the scarcest resources will finally become so expensive that in the future the scarcest minerals and the services provided by them will hardly be attainable anymore for poor nations and poor people. That situation might contribute to a further increase of the economic inequality between nations and between people and also of the danger that nations might consider the use of force to protect or gain access to the resources. In his book *"The looting machine"*, Burgis (2015) gives a frightening picture of the existing hunt for minerals in Africa already going on today. He reports on *"the systematic theft of Africa's wealth by warlords, tycoons and smugglers"*. Diamond (2004) warns of a collapse of our civilization, because it is hardly imaginable that the earth could support bringing all world citizens to the same level of wealth as the citizens of the industrialized world.

1.2 LIMITS TO GROWTH?

The question is when the extraction of a mineral resource can be called "sustainable". The Brundtland definition for sustainable development is relevant in this context: *"Sustainable development is the kind of development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* (World Commission on Environment and Development, 1987). Although this definition has been widely embraced, it does not provide an operational framework for the extraction of mineral resources.

There are three types of limits connected to the increasing use of mineral resources:

- Environmental limits. These limits are due to the uncontrolled dissipation of minerals in the environment resulting in direct threats of toxicity of the receiving land, water and air or indirect threats for biodiversity.
- Criticality limits. Industrialized economies can be seriously damaged when the supply of a certain mineral resource is disrupted. The extent, to which a society is dependent on the supply of a mineral, is called criticality. Criticality limits are determined by e.g. substitutability, the number of suppliers, the geopolitical situation, and the relative importance of the mineral for the economy of a country.
- Geological scarcity. This concept is related to the potential depletion of mineral resources. This thesis focuses on geological scarcity.

Thinking and warning about scarcity of resources and its consequences is not new. In 1798, Malthus predicted that continuous population growth could pace out the production capacity of fertile land, which then would lead to mass death from hunger, epidemics, and wars for resources. The only solution he saw was "moral restraint" by poor people who know that they cannot support a family. Later, Malthus' pessimistic view on the limited resources for an increasing world population was followed by influential essays from Ricardo (1817) and Mill (1848). In his publication Ricardo includes mineral scarcity as a factor limiting population growth. Mill, however, recognizes the possibilities of new technology for increasing the productivity of exploiting land and other resources.

At the end of the 19th century there was a broad concern about resource availability, especially in the USA. This was reflected by the so-called Conservation Movement that was active between 1890 and 1920 (Tilton and Coulter, 2001). The origin of the concern about scarce resources was especially connected to the fast industrialization and the development of vast wilderness areas. President Theodore Roosevelt was one of the prominent members/supporters of the conservation movement. The Conservation Movement promoted the wise use of resources, which entailed using renewable resources in place of nonrenewable resources, more abundant nonrenewable resources in place of less abundant nonrenewable resources and recycled products in place of primary resources (Tilton and Coulter, 2001)

After World War II, new concerns about the long-term availability of resources emerged in connection with the substantial resource use related to the reconstruction. In the USA, this led in 1952 to the creation of the President's Material Policy Commission (or Paley Commission, after its chairman). One of the spinoffs of the work of this Commission was the sponsoring of organizations and studies on growth and scarcity. A very influential book in this framework was published by Barnett and Morse (1963). Their findings and views on the relation between economic growth and depletion of nonrenewable resources stood in sharp contrast with the views thus far, namely that technology development had completely compensated for increasingly scarce nonrenewable resources and could be expected to do so in the future as well. The strong potential of technology development to solve scarcity problems was also emphasized in books by Maurice and Smithson (1984) and Diamandis and Kotler (2012). In

1979, a number of scientists reconsidered and nuanced Barnett and Morse's vision (Smith, 1982). In 1972, Meadows et al. published their book *Limits to Growth* for the so-called Club of Rome.

In contradiction to Barnett and Morse, they came to the conclusion that per capita food and industrial output would collapse as a result of exhaustion of mineral resources by 2050. In 1992, Meadows and his co-authors updated their advice to the Club of Rome (Meadows et al., 1992), basically confirming their original point of view.

The above described differences of views on geological scarcity of mineral resources reflect the discussion between the so-called resource optimists and resource pessimists. The resource pessimists support the so-called fixed stock paradigm: the earth is finite and so the amount of mineral resources is finite as well, but demand will not stop growing so it is only a matter of time before supply can no longer meet demand. Resource pessimists include Meadows et al. (1972 and 1992), Kesler (1994), Diederen (2009) and Bardi (2013).

The resource optimists support the so-called opportunity cost paradigm. The optimists do not deny that mineral resources will deplete gradually, but they have a strong belief that humanity will be able to cope with the effects of depletion. When demand outpaces supply, the costs will rise and – simultaneously – so will the pressure to find substitutes or alternatives for the depleted mineral. When the real price for a mineral commodity is rising, society has to consider what to give up for obtaining an additional ton of that scarce commodity. According to the resource optimists, the market will automatically solve the problem. Moreover, most mineral resources are not destroyed by using them, such as is the case for oil, natural gas and coal. To a certain extent, recycling and reuse are possible. Finally, the total geological stock is enormous. It will always be possible to extract minerals, although the costs will be considerable. Many resource optimists can be found in the mining industry and linked institutions (Hodges (1995), Gunn (2011), Simon (1980 and 1981), Adelman (1990), and Beckerman (1995), and also Maurice and Smithson (1984) and Diamandis and Kotler (2012)).

Resource pessimists and resource optimists both acknowledge that mineral resources are exhaustible. The difference between them is that the optimists trust that humankind will timely find a clever solution for the replacement of depleting resources by substitutes, as has always been the case thus far. The pessimists are of the opinion that humanity should not deliberately deprive future generations of scarce resources.

1.3   RESEARCH OBJECTIVE AND RESEARCH QUESTIONS

Which mineral resources are really scarce from a geological point of view and which mineral resources are less scarce or not scarce. How do we define *"geologically scarcity"*? If humanity wants to act rationally in connection with geological scarcity, then a distinction needs to be made between scarce, less scarce, and non-scarce mineral resources. Following the Brundt-

land definition of sustainable development, the sustainable level of extraction of scarce mineral resources needs to be determined, in view of the interest of future generations. Furthermore, geological scarcity needs to be distinguished from other causes of scarcity, such as scarcity resulting from geopolitics (such as economic boycotts), or scarcity that is deliberately caused by monopolists or oligopolists, or scarcity due to incidental events such as strikes, accidents, etc.

Once a definition has been formulated of the sustainable extraction rate of a mineral resource, it becomes possible to determine whether, on the basis of the definition, the current extraction and use of the primary material needs to be reduced and, if so, by how much. The use of a mineral resource can be reduced by substitution by another resource, by a higher material efficiency, or by technology that uses less scarce materials and by increasing the material efficiency and the recycling rate in which the primary resource is applied. The question is whether, with a combination of these approaches, it is technically and financially feasible to achieve the required reduction of the extraction of geologically scarce mineral resources. If this is the case, what could then be the mechanism to achieve such an extraction reduction in practice? Would the price mechanism of the free market system not be adequate enough to automatically, timely, and sufficiently reduce the consumption of mineral resources long before they become really scarce? If this is not the case and the creation of an international agreement on the conservation and sustainable use of geologically scarce mineral resources is advisable, the question would be on which normative principles such an agreement could be based and what the key elements of such an agreement would be.

The objective of the research presented here was to enable soundly-based recommendations to be made on whether humankind needs an international agreement on the conservation and sustainable use of geologically scarce mineral resources and, if so, to identify the key elements of such an agreement.

The main research question was: What are the concrete objectives, the time framework, the technical steps and the policy approach needed to achieve a sustainable level of extraction of geologically scarce mineral resources? The sub- questions were:
-   What does geological scarcity mean, which mineral resources are geologically scarce and how can the concept of sustainable rate of extraction be made operational?
-   What technical options are available for making extraction sustainable from the point of view of prevention of depletion?
-   What is the role of the price mechanism of the free market system in view of geological scarcity of mineral resources?
-   Is there a normative justification for an international agreement on the conservation and sustainable use of mineral resources?
-   What are the key elements of an international agreement on the conservation and sustainable use of mineral resources?

The character of the study is necessarily interdisciplinary. To obtain the required results, geological and technical information needs to be combined with insight from economics, law, and political sciences.

1.4   OUTLINE OF THE THESIS

In chapter 2 we will investigate the concepts of geological scarcity and sustainable extraction. Which mineral resources can be said to be geologically scarce? Does the extraction of these minerals need to be reduced to be sustainable and if so, by how much? In chapters 3 to 6 we will explore for four scarce mineral resources (antimony, boron, molybdenum, and zinc) whether a combination of substitution, material efficiency and recycling is technically and economically feasible, i.e. can such a combination of measures realistically lead to a sufficient reduction of the use of these minerals? In chapter 7 we will investigate whether it is certain that the price mechanism of the free market system will automatically and timely lead to such reduction of the extraction of geologically scarce mineral resources that sufficient resources are retained for future generations. In chapter 8 we will explore which normative principles from existing international environmental legislation would also be applicable to an international agreement on the conservation and sustainable use of geologically scarce mineral resources. In chapter 9 we will formulate, analyze, and discuss the key elements of an effective international agreement on the conservation and sustainable use of geologically scarce mineral resources. Chapter 10 contains the conclusions of our research.

REFERENCES

Adelman, M.A., 1990, Mineral depletion, with special reference to petroleum. Rev. Econ. Stat. 72(1)1-10

Ashby, M.F., 2009, Materials and the Environment, Eco-informed material choice, Butterworth-Heineman Publications

Bardi, U., 2013, Plundering the Planet, In: 33rd report for the Club of Rome

Barnett, H., Morse, C., 1963, Scarcity and Growth, the economics of natural resource availability, Baltimore, MD: Johns Hopkins University Press, for Resources for the Future

Beckerman, W., 1995, Small is stupid, London, Duckworth

Burgis, T., 2015, The looting machine, Warlords, tycoons, smugglers and the systematic theft of Africa's wealth, Harper Collins Publishers

Diamandis, P.H., Kotler, S., 2012, Abundance, The future is better than you think, Free Press, New York

Diamond, J., 2005, Collapse, North Point Press

Diederen, A., 2009, Metal minerals scarcity: a call for managed austerity and the elements of hope, TNO

Gunn, G., 2011, Mineral scarcity – a non-issue? British Geological Survey

Hodges, C.A., 1995, Mineral resources, Environmental issues and Land use, 1995, Science 268, 5215, 1305-12 (new series)

Kesler, S.E., 1994, Mineral resources, Economics and the Environment, New York, Macmillan

Malthus, T. 1798, An essay on the principles of population

Maurice, C., Smithson, C.W., 1984, The doomsday myth, 10,000 years of economic crises, Hoover Institu-
    tion Press, Stanford University

Meadows, D.H. et al, 1972, The limits to growth, New York, Universe Books

Meadows, D.H. et al, 1992, Beyond the limits, Post Mills, VT, Chelsea Green Publishing

Mill, J.S., 1848, Principles of Political Economy

Prior, T., Giurco, D., Mudd, G., Mason, L., Behrisch, J., 2012, Resource depletion, peak minerals and the
    implications for sustainable resource management, Glob. Environ. Change 22,577-587

Ricardo, D., 1817, Principles of political economy and taxation

Simon, J.L., 1980, Resources, population, environment: an oversupply of false bad news, Science 208,
    1431-1438

Simon, J.L., 1981, The ultimate resource, Princeton, NJ, Princeton University Press

Smith, K., 1979, Scarcity and growth reconsidered, Resources for the Future Inc. John Hopkins Press, Ltd
    London

Tilton, J.E., Coulter, W.J., 2001, Manuscript for the workshop on the long-run-availability of mineral com-
    modities, sponsored by Mining, Minerals and Sustainable Development Project and Resources for
    the Future, Washington DC, April21-23

Tilton, J.E., 2003, On borrowed time? Assessing the threat of mineral depletion, Miner. Energy-Raw Mater.
    Report, 18(1), 33-42

United Nations Statistics Division, 2015, National Accounts

United States Geological Survey, 2014, Historical Statistics for Mineral and Material Commodities in the
    United States

World Commission on Environment and Development (Brundtland Commission), 1987, Our common
    future

Chapter 2

Metal scarcity and sustainability, Analyzing the necessity to reduce the extraction of scarce metals[1]

ABSTRACT

There is debate whether or not further growth of metal extraction from the earth's crust will be sustainable in connection with geologic scarcity. Will future generations possibly face a depletion of specific metals? We study whether, for which metals and to what extent the extraction rate would need to be reduced in order to be sustainable. To do so, we propose an operational definition for the sustainable extraction rate of metals. We have divided 42 metals in 4 groups according to their geologic scarcity. Applying the proposed sustainability definition to the 17 scarcest metals, shows that for almost all considered metals the global consumption of primary resources needs to be reduced to stay within sustainable limits as defined in our analysis. The 8 geologically scarcest metals are antimony, bismuth, boron, copper, gold, molybdenum, rhenium and zinc.

KEYWORDS

Sustainable extraction
Geologic scarcity
Minerals depletion

2.1 INTRODUCTION

The extraction and consumption of metals has increased along with economic development. For consumables, communication and infrastructure, a growing range and quantity of metals is essential. Since more than 100 years, global demand of metals increases exponentially (Krausmann, 2009). There is debate whether or not further growth of metal extraction from the earth's crust will be sustainable in view of the limited extractable quantities of these metals in the earth's crust. Will technology improvements be able to keep pace with decreasing ore grades and rising energy costs, as has been the case thus far (Skinner, 2001; Bardi 2013; Bleichwitz 2010)? In this paper we will investigate whether, for which metals and to what extent, extraction rates need to be reduced to prevent that access to certain metals and their services will become extremely costly for future generations. The result is important for governments, the manufacturing industry and society to focus strategic and economic efforts on the most relevant metals.

This paper does not discuss sustainability with respect to the environmental impacts of mining, processing, manufacturing, using and disposing of materials leading to a possibly harmful dissipation of metals in the environment, and other environmental impacts.

2.2 BACKGROUND

The most influential definition of sustainability was formulated in 1987 by the so-called Brundtland Commission in their report *"Our common future": "Sustainable development is the kind of development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* (World Commission on Environment and Development, 1987). Since then, governments, politicians, scientists and representatives from industry try to make the Brundtland sustainability definition operational. In a period of only two years after the Brundtland sustainability definition was published, about 140 variously modified definitions of sustainable development emerged (Johnston et al, 2007).The same authors estimate that by 2007 some 300 different elaborations of the concept of sustainability and sustainable development existed in the domain of environmental management and associated disciplines. This demonstrates that the Brundtland sustainability definition has been interpreted in many different, even contradictory, ways.

Despite the extensive discussion on sustainability, the concept is hardly or not concretely operationalized for the extraction of primary resources. Several authors (Hansson (2010), White (2013), Medveçka and Bangerter (2007) Goodland (1995) and van den Bergh (2010)) plead for the formulation of an operational definition that can be used at a technical level to enable bringing sustainability into practice. We found only a single concrete approach proposed by Graedel and Klee (2002). This approach assumes that an extraction rate of a

metal is sustainable, if a world population of 9 billion people can be provided of sufficient quantity of that metal for a period of 50 years.

How much of a resource is extractable? In technical terms all is extractable. But whether or not extraction at a certain moment in time is economically feasible depends on a combination of factors; the most important being ore grade, depth, location and the willingness to pay for the extracted material (e.g. Tilton and Coulter (2001), Tilton (2003) and Allwood et al (2011)). It is therefore important to differentiate between reserves and potentially extractable resources. According to the United States Geological Survey (2012b):

- Reserves are that part of the reserve base that could be economically extracted or produced at the time of determination.
- The reserve base is that part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality thickness, and depth.
- Identified Resources are resources whose location, grade, quality, and quantity are known or estimated from specific geologic evidence. Identified resources include economic, marginally economic, and sub-economic components.
- Resources: A concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible.

Part of the world has not yet been intensively explored because of political instability or topographical inaccessibility. Resources may lie beneath a cover of rocks and are so deep that the prospecting technology presently in use cannot yet detect them (Skinner, 2001). Many problems arise when digging deep into the earth due to the increasing temperature and rock pressure. In theory, these resources are available, albeit at considerably higher exploitation costs.

However, it has never been investigated, what fraction of the various metals in the earth crust can be realistically mined. Exploration is expensive and therefore has a relatively short time horizon. Mining companies concentrate exploration on the highest concentrations in a deposit and not on the lower-sub-economic grades. Therefore, an estimate of the extractable global resources has to be made on theoretical grounds. Nevertheless, such estimates are essential to determine the sustainable extraction rate of metals.

The (future) demand for primary resources can be substantially reduced by increasing product life times and the end of life recycling rate of products, both reducing the use of a resource per unit of service delivered (material efficiency), and by substitution. Recycling, material efficiency and substitution will be fostered by rising primary resource prices.

2.3   METHODOLOGY

First, we investigate the concept of scarcity. The lower the ratio between economically extractable metal ores and the (expected) demand for those ores, the higher the geological scarcity. Secondly, we investigate what fraction of a metal in the earth's crust can be considered as extractable. We subdivide metals according to geological scarcity. We will do this by comparing the extractable global resources of 42 metals and groups of metals (including Rare Earth Elements (REE) and Platinum Group Metals (PGM)) with the 2010 extraction rates provided by USGS (2012a). Thirdly, we formulate an operational definition for the sustainable extraction rate of metals. The operational definition needs to be such that the question *"whether extraction reduction is needed, for which metals, how urgent and to which extent?"* can be answered. We apply our definition for the sustainable extraction rate of metals to the geologically scarcest metals. For each investigated metal, this will clarify whether or not the current extraction rate is sustainable and – if not – to what degree the extraction rate needs to be reduced to be sustainable. Finally, we carry out a sensitivity analysis to investigate the robustness of the results.

2.4   SCARCITY AND EXTRACTABLE RESOURCES

2.4.1   Three types of scarcity

After Gunn (2011) there are three types of scarcity:
- Absolute (geologic) scarcity because of depletion of resources
- Temporary scarcity, because supply cannot match demand due to various causes, e.g. geopolitics, accidents, weather conditions, monopolies, strikes.
- Structural scarcity of companion metals. Companion metals are metals that are contained in ores of major carrier metals and are not produced independently, but become concentrated in the production of the carrier metal at a level that isolation becomes economically justified. They are by-products. The additional revenues of these companion metals may be small, compared to the total operation and do not provide sufficient incentives to expand the extraction of the carrier metal just. Therefore, supply of the companion metals will not necessarily be fostered by rising prices, and remains limited by the extraction rate of the carrier metal.

According to Gunn:
o   Major carrier metals are: Cr, Mn, Fe, Al, Mg, Ti, Sn, Ni, Cu, Pb, and Zn.
o   Co- and by products with a dedicated production and exploitation infrastructure are: Ag, Au and Mo
o   All other metals are by-products of carrier metals with little or no dedicated infrastructure

We investigate geologic scarcity of metals and how metals can be divided in groups of increasing scarcity. Geologic scarcity of a metal depends on how fast the metal is extracted

(extraction rate) compared to the availability of (economically) extractable ore in the earth's crust (Gunn, 2011). Scarcity reflects the tension between availability of and demand for resource, and is expressed by Equation 1.

$$S_c = A_v/E \qquad \qquad \text{(Eq. 1)}$$

Where:

S_c = geological scarcity, expressed in the number of remaining years until the depletion of extractable resources

A_v = extractable resources (tons). We will use the Global Extractable Resources as defined by the UNEP International Resource Panel (2011a); see section 2.4.2 below.

E = annual extraction rate (tons/year), based on USGS data (USGS, 2012a).

2.4.2   Extractable Global Resources (EGR)

What fraction of a metal in the earth's crust can be realistically mined? Table 2-1 provides enrichment factors of a number of metals in ores compared to the crustal occurrence of those metals. For many of the metals with a low crustal occurrence, enrichment factors of 100-10000 are normal, whereas for the metals with a higher crustal occurrence, the enrichment factors are much lower: typically 1-100.

Table 2-1 Typical ore grades and enrichment factors for some metals. The ore grades are derived from Rankin (2011), the upper crustal occurrence data are from UNEP (2011a).

	Typical minimum ore grades (ppm)	Upper crustal occurrence (ppm)	Enrichment factor (rounded)
Geochemically abundant metals			
Aluminum	320000	80000	4
Iron	250000	35000	7
Titanium	100000	4100	20
Geochemically scarce metals			
Nickel	10000	44	200
Copper	5000	25	200
Zinc	40000	71	600
Gold	4	0.0018	2000
Lead	40000	17	2000
Tin	50000	5.5	9000

According to Steen and Borg (2002), typical differences in extraction costs between extraction from common rocks and from ores are:

- between 10 and 100-fold for cobalt, chromium, copper, nickel and zinc
- between 100 and 1000-fold for lead and tin
- more than 1000-fold for cadmium and tungsten

These differences in costs are important as these reflect the economic implications of deple-tion of metal ores. But the depletion of metal ores has not only economic consequences. In parallel, it is also negative for energy and water use, waste production and the landscape. According to Skinner (2001), supported by Phillips(1977), van Vuuren et al ((1999) and Tilton (2003), the distribution of grade (weight percentage) and tonnage of the *major (*or abundant) elements (i.e. those present at average concentration levels in the earth's crust >0.1 % or 1000 ppm) is normal bell shaped, whereas most of the *minor* (or scarce) elements (i.e. average con-centration in the earth's crust is < 0.1% or 1000 ppm) are bi-modally distributed (see Figure 2-1). The right part of the bimodal curve represents the *minor* element's ores. The supposed bimodal distribution of the *minor* elements explains the relatively high enrichment factors of these elements compared to the relatively low enrichment factors of the *major* elements with a (supposed) modal distribution.
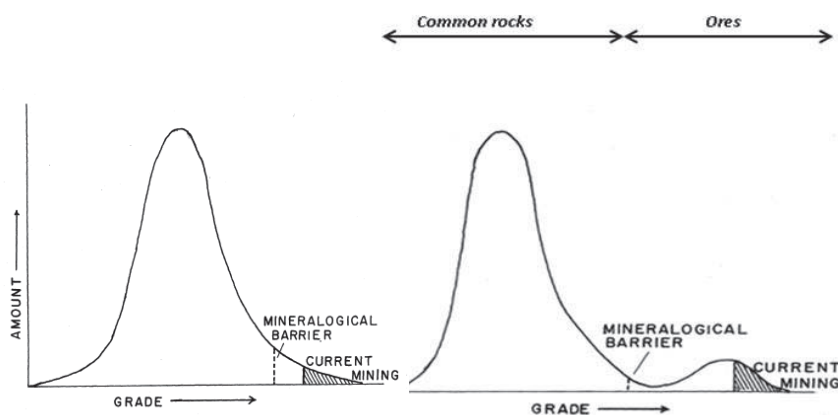
Figure 2-1 Grade and tonnage distribution of major elements (>0.1 weight %) in the earth's crust, left fig-ure, and minor elements (<0.1 weight %), right figure (after Skinner, 2001). The distribution is log normal.

The total amount of a metal outside of the richer deposits (in all common rocks of the earth's crust) is huge compared to the amount of a metal in ores. The limit-grade between extract-ability and non-extractability is not fixed, as it depends on the willingness of the market to pay for the metal. Gold is extracted until much lower grades than zinc, because the market is willing to pay more for gold than for zinc. This limit-grade, which moves over time, is called the "*mineralogical barrier*". Several scientists have tried to determine the order of magnitude of the limit grade. According to Skinner (1976), the total quantity of copper that occurs in deposits with grades above the mineralogical barrier would be between 0.01 % and 0.001 % of the total quantity of copper in the crust. On the basis of data on the distribution of known deposits of minerals, Rankin (2011) makes plausible that the combined size of ore deposits of a particular metal is directly proportional to the crustal occurrence of the metal. This leads to the conclusion that, if the total mineral deposit of one metal can be determined, the mineral deposits of all other metals in the earth's crust can be calculated as well, by comparing their crustal occurrence to the crustal occurrence of the metal with known total deposits. So, if

(according to Skinner, 1976) the quantity of copper deposits above the mineralogical barrier would be a maximum of 0.01 %, than this would also be the case for other metals. In line with Skinner (1976), also Rankin (2011) and Erickson (1973) use the range of 0.01 % - 0.001 % of the total amount of a metal in the crust as starting point for estimates to calculate extractable deposits. Using a tectonic-diffusion model for the movement of copper deposits in the earth's crust, Wilkinson and Kesler (2007) came to the somewhat divergent conclusion that copper deposits above the mineralogical barrier could be as high as 0.1 % of the total amount of copper in the crust. However, in line with Skinner and Rankin, the UNEP International Resource Panel (2011a), consisting of a broad panel of raw material scientists, proposes 0.01% of the total amount of a metal in the top 1 km of the continental part of the earth's crust as a reasonable estimate for the upper limit for the *Extractable Global Resources.* The UNEP International Resource Panel (2011a) has compared the USGS Reserve Base (RB) estimates with the Extractable Global Resources according to the 0.01 % definition. The EGR/RB ratios vary considerably: mostly between 1 and 100 with an average of 35, except for gold, copper and lead, where the EGR/RB ratio is < 1. UNEP (2011a) draws the conclusion that the estimate of 0.01 % of the total amount of a metal available in the top 1 km of the earth's crust can indeed be considered as a rough upper limit for the Extractable Global Resources. Considering this, we assume that 0.01 % is a reasonable upper limit for the amount of extractable metal deposits and will use the Extractable Global Resources definition of the UNEP International Resources Panel (2011a) as basis for our calculations. Only if the EGR is lower than the Reserve Base as provided by the US Geological Service, i.e. for copper, gold and lead, we correct the EGR for these three metals to 2.5 times the USGS RB. The factor 2.5 is based on Rankin (2011, p 303), who compared the results of an assessment of undiscovered deposits of gold, silver, copper, lead and zinc in the USA with the EGR/RB ratio.

We will test the robustness of our results by also assuming a five times higher amount of available resources (i.e. 0.05 % of the total amount of the metal in the top 1 km of the continental part of the earth's crust).

2.4.3   Sub-division of metals in scarcity groups

Based on the corrected UNEP data on the EGR and recent extraction data from USGS we have calculated the potential depletion period for every metal after 2050 (Table2-2). By deducting the expected total extracted quantity of the metal between 2010 and 2050 from the EGR (and neglecting thus far extracted amounts) we estimate for each metal the remaining available geological stock by 2050.

Table 2-2 Remaining lifetime (after 2050) for exploitation of metals until depletion[2]

Metal	Extraction in 2010 (*1000 ton) (a)	Yearly extraction in 2050. yearly growth 3 % (*1000 tons) (b)	Approximate total extraction between 2010 and 2050 (*1000 tons) (c)	Extractable Global Resources according to UNEP (2011a) (million tons) (d)	Remaining available resources in 2050 (million tons) (e)	remaining years after 2050 until depletion (f)
Li	28.1	92	2200	800	800	8700
Be	0.205	0.67	16	120	120	180000
B	834	2727	65000	600	535	200
Mg	5760	18789	450000	530000	530000	28000
Al	41000	133744	3200000	3200000	3200000	24000
Ti	3836	12512	300000	170000	170000	14000
V	57.6	188	4500	4300	4300	23000
Cr	5925	19328	470000	3300	2800	150
Mn	4865	15870	380000	24000	24000	1500
Fe	1218824	3975848	96000000	1400000	1300000	330
Co	89.5	292	7000	680	670	2300
Ni	1590	5187	130000	1800	1700	320
Cu	15900	51866	1300000	1000	6200	120
Zn	12000	39144	940000	2800	1900	47
Ga	0.182	1	14	680	680	1100000
Ge	0.118	0	9.3	64	64	170000
As	40	130	3100	60	57	440
Se	2.12	7	170	2000	2000	290000
Sr	405	1321	32000	14000	14000	11000
Zr	600	1957	47000	7600	7600	3900
Nb	62.9	205	4900	480	480	2300
Mo	242	789	19000	60	41	52
Ag	23.1	75	1800	20	18	240
Cd	21.1	69	1700	39	37	540
In	0.609	2	48	20	20	10000
Sn	265	864	21000	220	200	230
Sb	167	545	13000	8	-5.1	-9.4
Ba	4616	15056	3650000	22000	22000	1400

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2   The corresponding table in the original publication contained 2 errors (regarding the 2010 extraction of respectively boron and zirconium). The corrections have been added to the original publication. For boron this happened in Resour. Conserv. Recycl. 101 (2015) 212-13 and for zirconium in Resour. Conserv.Recycl. 113(2016)165

Table 2-2 Remaining lifetime (after 2050) for exploitation of metals until depletion (continued)

Metal	Extraction in 2010 (*1000 ton) (a)	Yearly extraction in 2050. yearly growth 3 % (*1000 tons) (b)	Approximate total extraction between 2010 and 2050 (*1000 tons) (c)	Extractable Global Resources according to UNEP (2011a) (million tons) (d)	Remaining available resources in 2050 (million tons) (e)	remaining years after 2050 until depletion (f)
REE total	133	434	10000	6700	6700	15000
Ta	0.681	2	54	40	40	18000
W	68.8	224	5400	80	75	330
Re	0.047	0	3.7	0.016	0.012	80
PGM total	0.396	1	31	1.9	1.9	1400
Au	2.56	8	200	0.072	0.049	5.8
Hg	2.25	7	180	2700	2700	370000
Tl	0.01	0.03	0.79	30	30	920000
Pb	4140	13505	330000	680	3400	250
Bi	8.9	29	700	5.2	4.5	160
U	54.6	178	4300	430	430	2400

(a) from USGS (2012a);

(b) calculated with the assumption of an annual growth of the extraction with 3% between 2010 and 2050;

(c) calculated by summing the estimated annual extraction tonnages between 2010 and 2050;

(d) represents the Extractable Global Resources as suggested by the UNEP International Resource Panel (2011a);

(e) is calculated by subtracting (c) of this Table (total extraction between 2010 and 2050) from (d) (the total Extractable Global Resources). In this calculation we have increased the Extractable Global Resources of copper (Cu), gold(Au) and lead(Pb) to 2,5 times the USGS Reserve Base figure, because for these 3 metals the UNEP-EGR figures are lower than the USGS Reserve Base;

(f) calculated by dividing (e) by (b).It is supposed that from 2050 the extraction rates will stay stable

Assuming that the extraction rate remains stable after 2050, it can be calculated how many years remain after 2050 until the EGR of the various metals would be depleted. The result is presented in Table2-2. The remaining number of years after 2050 until depletion is an indicator for the sustainability of the extraction or, in other words, of the geologic scarcity of a specific metal. The lower the number, the scarcer the metal is. Table2-2 enables us to divide the metals in scarcity groups. We distinguish 4 scarcity groups:

Very scarce	Extractable Global Resources depleted before 2050
Scarce	Extractable Global Resources depleted within 100 years after 2050
Moderately scarce	Extractable Global Resources depleted between 100 and 1000 years after 2050
Not scarce	Depletion time of Extractable Global resources > 1000 years after 2050

We now can sub-divide the metals in geologic scarcity groups. See Table 2-3.

Following should be noted:

- A number of the above metals are carrier metals, others are companion metals. Main carrier metals are aluminum, magnesium, manganese, titanium, chromium, copper, iron, nickel, lead, tin and zinc. (Gunn 2011). A number of metals like for instance gold, molybdenum and antimony have dedicated production facilities, and are co-products as well. The rest of the metals in Table 2-3 are companion metals. The extraction rate of these companion metals is directly dependent on the extraction rate of the carrier metals. This phenomenon may cause that the actual scarcity of companion metals may differ from the one expected on the basis of their average geological occurrence, due to the different extraction rate of the carrier metal. However, in our view this will probably not have an essential influence on the gross long term availability of the companion metal. If a companion metal is extracted at a higher rate than supposed in Table2-2, the price will probably decline. As a result the companion metal will not be fully exploited and still be available for later extraction (e.g. mine wastes and tailings). If a companion metal is extracted at a lower rate than supposed in Table2-2, its price will probably increase and its consumption will likely decrease. In this way it may be conserved.
- The growth of the extraction rate of certain metals (or groups of metals) in the right column of Table 2-3 may be considerably higher than the supposed 3%. The extraction rate of platinum, for instance, was 4.9% over the period 1979-2002 (Gordon et al, 2006). The high growth rate especially applies for a number of metals that are essential for advanced energy and IT technologies, see e.g. Kleijn (2012) and Achzet et al (2011).
- Some of the 17 scarcest metals are easier recyclable than others, making them less scarce. The categorization of Table 2-3 is based on present recycling rates. However, further recyclability of selected metals may be much more promising than for other metals, which would facilitate the reduction of extraction and primary production.

Table 2-3 shows that there are relatively few scarce metals from a geologic point of view: antimony, gold, molybdenum, rhenium and zinc. Of course metals could move to another scarcity column (scarcer or less scarce). This depends on whether society is willing to further increase extraction or – just the opposite – reduce extraction to reduce the environmental impact of mining, or keep the metals available for future generations. For example, metals in the right column may become scarcer than assumed in Table 2-3, if demand would increase due to growing use of new technologies.

2.5 OPERATIONALIZATION OF THE SUSTAINABILITY CONCEPT FOR METAL EXTRACTION

The main question in this paper is for which metals – if at all – reduction of the current extraction rate would be needed and to which extent in order to remain sustainable. The following three factors determine the sustainability of the extraction rate of metal ores:

- The extractable global resources
- Continuity over a long period of time
- Inter- and intra generational responsibility

Table 2-3 Division of metals in groups according to geologic scarcity. The depletion periods are after 2050. It is assumed that the extraction increases annually by 3 % until 2050 where after it stabilizes.

Very scarce (EGR depleted before 2050)		Scarce (EGR depletion time <100 years after 2050)		Moderately scarce (EGR depletion time between 100 and 1000 years after 2050)		Not scarce (EGR depletion time >1000 years after 2050)	
Sb	Antimony	Au	Gold	Ag	Silver	Al	Aluminum
		Mo	Molybdenum	As	Arsenic	Ba	Barium
		Re	Rhenium	B	Boron	Be	Beryllium
		Zn	Zinc	Bi	Bismuth	Co	Cobalt
				Cd	Cadmium	Ga	Gallium
				Cr	Chromium	Ge	Germanium
				Cu	Copper	Hg	Mercury
				Fe	Iron	In	Indium
				Ni	Nickel	Li	Lithium
				Pb	Lead	Mg	Magnesium
				Sn	Tin	Mn	Manganese
				W	Tungsten	Nb	Niobium
						PGM	Platinum Group Metals
						REE total	Rare Earth Elements
						Se	Selenium
						Sr	Strontium
						Ta	Tantalum
						Ti	Titanium
						Tl	Thallium
						U	Uranium
						V	Vanadium
						Zr	Zirconium

2.5.1   The extractable global resources

This subject has been elaborated in section 2.4, see Table2-2.

2.5.2   Continuity over a long period of time

The Brundtland definition, and most other sustainability definitions, refers to future generations. Their needs should not be compromised by the behavior of previous generations. Based on the precautionary principle, humanity should keep sufficient economically accessible reserves of every metal available to ensure that future generations retain access to the (potential) services offered by the metal, and get sufficient time to adapt to unavailability, if necessary. Per definition "sustainability" implies a long time period, ideally eternally. Theoretically, the sustainable extraction of a metal ore is even impossible, since metal ores are not renewable. Stopping further extraction, would require a 100% closed cycle to be achieved through recycling and

reuse. This seems to be difficult to achieve in practice. Some material (dissipative) losses are inevitable. Therefore, we try to approximate the concept of "sustainability" to find an approach that is practically feasible, yet also satisfies the long term objective of meeting the needs of future generations. A period of 50 years as proposed by Graedel and Klee (2002), so just two generations ahead, is – in our view - insufficient to be considered sustainable. In our view the length of such a time period – for an acceptable approximation of sustainability- should cover at least centuries, given current rates of technology development. We propose a period of 1000 years in order to simulate a situation of quasi-perpetuity. If humanity can continue extracting a metal at a certain rate during a period of 1000 years without serious scarcity problems, than we can define this extraction rate as sustainable. We realize that the 1000 year period is arbitrary. However, an order of magnitude smaller period, such as for instance 100 years, would be, in our opinion, too short to simulate sustainability, and to satisfy the long term goal that future generations are ensured a sufficient supply of economically accessible resources. A sustainability period of 100 years would allow just a few generations to deplete a substantial part of the extractable resources, which might make it more difficult for future generations to adapt. On the other hand, an order of magnitude longer period, e.g. 10,000 years, seems unnecessarily long. Because of the arbitrary character of the supposed 1000 year period, we will carry out sensitivity analyses using periods of 200 and 500 years.

2.5.3   Inter- and intra-generational responsibility

According to the Brundtland definition of sustainable development, both the needs of the present generation and the needs of the future generations need to be met. There should be both inter-generational and intra-generational responsibility. One part of humanity may not deprive another part of humanity from resources nor may the current generation deprive future generations from resources. This starting point leads to the conclusion that an extraction rate of a material can be labeled as sustainable, if such an extraction rate can sustain a situation wherein world citizens in different countries in various parts of the world, (can) have a similar average per capita level of consumption of that material. This is in line with the approach of the United Nations Environmental Program (UNEP, 2011b). According to Krausman et al (2009), 3 % is the approximate average annual growth rate of metals extraction during the 20st century. In practice the growth rate differs per metal. Table 2-4 provides an overview of annual growth rates of five non-ferrous metals (based on Gordon et al, 2006).

Table 2-4 Growth of extraction rates of five metals

Metal	Period	Annual growth rate (%)
Copper	1910-2002	3.3
Zinc	1919-2002	3.2
Nickel	1979-2002	3.8
Tin	1959-2002	1.8
Platinum	1979-2002	4.9

By 2050, a global growth rate of 3% leads to the same result as the so-called *"freeze and catching up"* scenario of UNEP (UNEP, 2011b). In the UNEP scenario, the industrialized countries *freeze* metal consumption at the 2010 level, while developing countries build up to the same average per capita consumption as the industrialized countries by 2050 (*catching up*). According to the medium population growth scenario of the United Nations Department of Economic and Social Affairs (2011), world population will grow to about 9 billion people by 2050 and stabilize at 10 billion people around 2100. For our consumption scenarios we will use 9 billion.

2.5.4 Proposed operational definition of sustainable extraction of metals

Based on the above three factors for the sustainable extraction of metals we can formulate the following operational definition for the sustainable extraction rate of a metal: *The extraction rate of a metal is sustainable, if (1) a world population of 9 billion can be provided with that metal for a period of at least 1000 years assuming that, (2) the average per capita consumption level of the metal is equally divided over the world's countries.*

According to this definition the sustainable extraction rate per capita per year is (Eq.2):

$$SER = EGR/P*T_s,$$
                                                                (Eq.2)

where
SER = Sustainable Extraction Rate per capita (kg/capita/year)
EGR = Extractable Global Resources (kg) (see section 2.4.2).
P = world population (i.e. 9 billion)
T_s = sustainability period (i.e. 1000 years)

2.6   THE SUSTAINABLE EXTRACTION RATE FOR 17 METALS

We will apply our definition to determine the sustainable extraction rate of the 17 scarce metals identified in Table 2-3. The results are presented in Table 2-5. Table 2-5 compares the calculated sustainable extraction rates with the present (annual) per capita use in industrialized countries and in the world as a whole. This enables to calculate whether and to what degree the extraction rate needs to be reduced for each metal to be sustainable for the industrialized countries and globally (as defined above).

We depart from the current situation regarding end-of-life recycling, product life times and substitution of metals by other metals or by alternative services. Current recycling rates, material efficiency and substitution have already implicitly been taken into account in the current extraction rates. The current extraction rates result from the primary resources needed, given the existing end-of-life recycling, material efficiency, and substitution rates. This does not mean that recycling, material efficiency and substitution could or should not be further improved or increased. Future potential does exist (Allwood et al., 2011), but is

Table 2-5 Necessary extraction reduction rates to obtain sustainable extraction rates for 17 scarce metals. Points of departure are a sustainability period of 1000 years and EGRs of 0.01% of the amount in the top 1 km of the earth's crust[3]

	Extractable Global Resources (million tons)	(a) sustainable per capita extraction rate (9 billion people, depletion in 1000 years) (g/cap/year)	(b) present consumption of primary resources in industrial countries (b) (g/cap/year)	(c) present world consumption of primary resources (c) (g/cap/year)	(d) necessary extraction reduction for industrial countries (d) (%)	(e) necessary extraction reduction for average world citizen (e) (%)
Antimony	8	0.9	75	24	99%	96%
Arsenic	60	6.7	29	6	77%	-17%
Bismuth	5.2	0.6	6	1	91%	55%
Boron	600	66.7	595	119	89%	44%
Cadmium	39	4.3	15	3	71%	-44%
Chromium	3300	367	4000	846	91%	57%
Copper (f)	7500	833	11000	2271	92%	63%
Gold (f)	0.25	0.028	3	0.37	99%	92%
Iron	1400000	155556	700000	174000	78%	11%
Lead (f)	3750	417	3000	591	86%	30%
Molybdenum	60	6.7	150	35	96%	81%
Nickel	1800	200	1400	227	86%	12%
Rhenium	0.016	0.002	0.034	0.0067	95%	74%
Silver	20	2.2	25	3	91%	33%
Tin	220	24	250	38	90%	35%
Tungsten	80	8.9	20	10	56%	10%
Zinc	2800	311.1	6000	1714	95%	82%

(a) Extractable Global Resources divided by 9 billion;
(b) See Halada et al (2008). When no data were available, the world average consumption has been multiplied by 5;
(c) Extraction in 2010 (according to USGS data) divided by 7 billion;
(d) 1 – (a)/(b);
(e) 1 – (a)/(c);
(f) For copper, lead and gold a 2.5 * USGS Reserve Base has been taken as starting point instead of the EGR.

currently not realized. We take the current situation as point of departure to calculate the sustainable extraction rate. After determining the reduction in necessary extraction rate of a metal to be sustainable, the next step is to find out how much <u>more</u> recycling, material efficiency and substitution is needed to achieve the goal of a sustainable supply of metals.

The present consumption of the 17 metals in industrialized countries is included in Table 2-5 (mainly based on Halada, 2008). For the metals that no data was provided, we have taken

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3   The figures for boron have been corrected compared to the figures for boron in the original publication. See foot note under Table 2.2

the average annual world consumption per capita multiplied by 5. This is the approximate average difference between the world average consumption and the consumption in industrialized countries as provided by Halada (2008).

The current annual global per capita consumption in Table 2-5 has been calculated by dividing the actual annual extraction rate by 7 billion (people). Then we compare the actual consumption with the sustainable extraction rate. By how much should the actual consumption be reduced to become sustainable? This comparison results the necessary per capita extraction rate reduction for industrial countries and for the world as a whole. The negative figures indicate possible room for growth of the global per capita extraction rate compared to the current global per capita extraction rate of that specific metal.

Based on the calculations we find that for all the considered metals the consumption of primary resources *in industrialized countries* needs to be substantially reduced in order to be sustainable. The necessary reduction percentages are between 56% and 99%. Except for arsenic and cadmium, the *global consumption* of primary material also needs to be reduced in order to become sustainable. Antimony is exceptional. It starts to be very scarce. Its EGR will be depleted well before 2050 if the current extraction rate is maintained. Sustainable extraction of antimony over a period of 1000 years would only be possible if the global extraction rate would be reduced immediately to 4% of the 2010 extraction rate.

The above approach could be considered optimistic, because the existence of coupling mechanisms, e.g. energy scarcity makes metal scarcity worse and vice versa. Similarly, water scarcity makes metal scarcity worse and vice versa. Also, applications of metals in new technologies may create relatively large increases in the future demand of a metal. These factors were not taken into account in the calculations. Finally, the EGRs as point of departure may be too optimistic. However, the approach could also be too pessimistic, because there may be more resources economically extractable than the current EGRs indicate.
It is striking that for the 17 scarcest metals the results are in line with the so-called Factor 10 recommendations of Schmidt-Bleek (2008) recommending that resource use in the industrialized part of the world should be reduced with a factor 10.

Note that extraction reduction of main carrier metals such as chromium, copper, iron, lead, nickel, tin and zinc necessarily leads to a corresponding extraction reduction of companion metals affecting their availability. Of the 17 scarcest metals it concerns As, Bi, B, Cd, Re, Ag and W. Sb, Au and Mo partly have dedicated production facilities, but are also extracted as co- or by-products. This is an important issue for further research.

2.7 SENSITIVITY ANALYSIS

We have tested the sensitivity of the results for various assumptions, and the results are presented in Table 2-6, i.e. a sustainability period of 200 or 500 years (instead of 1000 years), EGRs of 0.02% and 0.05% (instead of 0.01%), and a mining depth of 3 km (instead of 1 km).

Table 2-6 shows that even if we suppose that at the same time all three parameters are more optimistic than originally assumed (the extractable ore 2 times higher than originally assumed, the mining depth three times, and the sustainability period half the one originally assumed), the consumption of primary metal in industrialized countries still needs to be reduced for antimony, copper, gold, molybdenum, rhenium and zinc.

Table 2-6 Sensitivity of necessary extraction rate reduction for varying assumptions[4]

	necessary extraction reduction for industrial countries (1000 years, 0.01 %, top 1km of earth's crust) (%)	necessary extraction reduction for industrial countries (1000 years, 0.05 %, top 1km of earth's crust) (%)	necessary extraction reduction for industrial countries (200 years, 0.01 %, top 1km of earth's crust) (%)	necessary extraction reduction for industrial countries (500 years, 0.02%, top 3 km of earth's crust) (%)
Antimony	99%	94%	94%	86%
Arsenic	77%	-17%	-17%	-180%
Bismuth	91%	55%	55%	-9%
Boron	89%	44%	44%	-34%
Cadmium	71%	-44%	-44%	-245%
Chromium	91%	54%	54%	-10%
Copper	92%	62%	62%	9%
Gold	99%	95%	95%	89%
Iron	78%	-11%	-11%	-167%
Lead	86%	31%	31%	-67%
Molybdenum	96%	78%	78%	47%
Nickel	86%	29%	29%	-71%
Rhenium	95%	74%	74%	36%
Silver	91%	56%	56%	-7%
Tin	90%	51%	51%	-17%
Tungsten	56%	-122%	-122%	-433%
Zinc	95%	74%	74%	38%

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4   The figures for boron have been corrected compared to the figures for boron in the original publication. See foot note under Table 2.2

2.8   CONCLUSIONS, DISCUSSION AND RECOMMENDATIONS

For 17 metals the current extraction is not sustainable. This is due to the geologic scarcity of these metals compared to the current extraction rates. For 15 out of these 17 metals also a reduction of the primary consumption on a global scale is needed. Based on the analysis, the following metals should get the highest priority: antimony, gold, molybdenum, boron, bismuth, zinc, rhenium and copper. On a global scale, the extraction rates of these metals should be reduced by 96% (for antimony) to 63 % (for copper), to become sustainable.

Our operational definition for the sustainable extraction of metals enables to determine, in an easy and transparent way, whether and to what extent extraction rates need to be reduced. Subdividing the metals in 4 groups of increasing (geological) scarcity enables to distinguish a limited number of 17 metals that need attention. Geological scarcity compares the extraction rate of a material with the extractable amounts of that material in the earth's crust. A sensitivity analysis does not change the conclusions essentially.

It is striking that a number of the 8 scarcest metals do not appear in or do not have a prominent position in various recent lists of critical materials, such as the list of critical raw materials for the EU (2010), the risk list of the British Geological Survey (2012) and in a study by the US Department of Energy (2011).

The study departs from current rates of recycling, material efficiency and substitution of scarce metals. To achieve sustainable extraction rates, recycling, material efficiency and substitution rates need to be increased.

It is recommended that further research explores how the extraction rate of scarce metals can be reduced to become more sustainable:
-   Investigating the (technical) opportunities to reduce the consumption of scarce metals, starting with the 8 scarcest metals;
-   Investigate policy options to realize the technical opportunities for these selected metals;
-   Investigate the relationship between scarcity of companion metals and the carrier metals, and the impact on the future availability of companion metals;
-   Improve estimates of the extractable global resources, especially for the scarcest metals identified in this paper

REFERENCES

Achzet B. Reller A. Zepf V. University of Augsburg, Rennie C. BP, Ashfield M. and Simons J. ON Communication, Materials critical to the energy industry, 2011

Allwood J. M. Ashby M F. Gutowski TG. Worrell E. Material efficiency: A white paper, Resources, Conservation and Recycling 2011; 55;362-81

Bardi U. Plundering the Planet, in:33rd report for the Club of Rome; 2013

Bleichwitz R. International economics of resource productivity, Int. Econ. Policy, 2010;7,227-44

British Geological Survey, Risk List; 2012

Erickson RL. Crustal occurrence of elements, mineral reserves and resources, In: USGS , Professional Paper 820, 1973;p21-5

European Commission, Critical raw materials for the EU, Report of the ad-hoc working group on defining critical raw materials; 2010

Goodland R. The concept of sustainability, Ann Rev of Ecol Syst 1995;26;1-24

Gordon RB. Bertram M. Graedel TE. Metal stocks and sustainability, PNAS January 31, 2006; 103; 1209-14; no 5

Graedel TE. Klee RJ. Getting serious about sustainability, Environ Sci Technol 2002;36;4; 523-29

Gunn G. Mineral scarcity – a non-issue? In: British Geological Survey, 2011

Halada K. Shimada M. Ijima K. Decoupling status of metal consumption from economic growth, Mater Trans 2008; 49, (3) 411-18

Hansson SO. Technology and the notion of sustainability, Technol Soc, 2010; 32 ; 274-79

Johnston P. Everard M. Santillo D. Robert KH. Reclaiming the definition of sustainability, Env.Sci.Pollut. Res. 2007;14(1)60-66

Kleijn R. Materials and Energy: a story of linkages, University of Leiden, 2012

Krausmann F. Gingrich S. Eisenmenger N. Erb K-H. Growth in global materials use, GDP and population during the 20th century, Ecol Econ 2009; 68; 2696-705

Medveçka J. Bangerter P. Engineering sustainable development into industry: unlocking institutional barriers. In:Rodier"D. Adams W. editors); Sustainable Development, HSE and Recycling, Vol 6, Toronto, Canada, Canadian Institute of Mining, Metallurgy and Petroleum, 2007, p13-26

Phillips WGB. Statistical estimation of global mineral resources, Resour Policy, 1977;3(4) 268-80

Rankin WJ. Minerals, metals and sustainability, CSIRO 2011

Schmidt-Bleek F. Factor 10: the future stuff, Sustain: Sci, Pract & policy, 2008, 4(1) 1-4

Skinner B.J. Long run availability of minerals, keynote talk at a workshop "Exploring the resource base", In Resources for the Future 2001

Skinner BJ. A second iron age ahead? Am Sci 1976; 64, 158-69

Steen B. Borg G. An estimation of the costs of sustainable production of metal concentrates from the earth's crust, Ecological Economist 2002; 42, 401-13

Tilton JE. Coulter WJ. Manuscript for the workshop on the long-run-availability of mineral commodities, In: Mining, Minerals and Sustainable Development Project and Resources for the Future, 2001

Tilton JE. On borrowed time? Assessing the threat of mineral depletion, Minerals &Energy-Raw Materials Report, 2003;18(1),33-42

UNEP International Panel on Sustainable Resource Management, Estimating long-run geological stocks of metals, Working Group on Geological Stocks of Metals, Working Paper, April, 2011a

UNEP International Resource Panel, Decoupling Natural Resource Use and Environmental Impacts from Economic Growth, UNEP, 2011b

United Nations, World Population Prospects, The 2010 Revision, Population Division, Department of Economic and Social Affairs, 2011

US Department of Energy, Critical Materials Strategy (2011)

USGS, Mineral Commodity Summaries 2012a

USGS, Mineral Commodity Summaries 2012, Appendix B, 2012b

Van Den Bergh JCJM. Externality or sustainable economics, Ecol Econ 2010, 69, 2047-52

Van Vuuren, D. Strengers B. de Vries H. Long term perspectives on world metal use- a system-dynamics model, Resour Policy, 1999; 25(4)239-55

White MA. Sustainability: I know it when I see it, Ecological Economics 2013; 86;213-17

Wilkinson BH. Kesler SE. Strüngman Forum Reports; In: Graedel TE. and van der Voet E. Linkages of Sustainability, , 2010, p.122

World Commission on Environment and Development, Our common future, 1987

Chapter 3

Towards a sustainable use of primary boron,
Approach to a sustainable use of primary resources[5]

5   Published as: Henckens M.L.C.M., Driessen P.P.J., Worrell E., 2015, Towards a sustainable use of primary
     boron. Approach to a sustainable use of boron, Resources, Conservation and Recycling, 103,9-18

ABSTRACT

The sustainable use of raw materials does not only concern the environmental impacts of their production and consumption, but also the intergenerational distribution of access to the raw material or the services provided by that material. From this sustainability perspective, current generations should not deprive future generations from economically accessible ores, but they have the responsibility to assure that a sufficient quantity of enriched deposits of primary materials continues to be available for future generations.

Comparing the extraction rate of different primary materials to their current use, some materials are scarcer than others. Elements like aluminum, magnesium, titanium and vanadium are relatively abundant and cannot be considered critical from a geological point of view. From a point of view of availability for future generations, action is not really urgent for these elements. However, other elements, like antimony, rhenium, gold, zinc and molybdenum are relatively scarce from a geological perspective. The current extraction rate of these elements is not sustainable.

Boron is also a relatively scarce element, comparing the current extraction rate to the geological availability. The accessible ores may be depleted within two hundred years. This may affect future generations negatively in securing services provided by boron. Therefore, we investigated whether the use of primary boron could be reduced to a sustainable level) without losing any of the services currently provided by boron. In this framework we have designed a generally applicable approach for investigating whether and to what extent a combination of substitution, material efficiency and recycling could reduce the use of a primary material to a sustainable level.

Keywords
Sustainable use of primary boron, Substitution, Material efficiency, Recycling

3.1 INTRODUCTION

The extraction and consumption of minerals has increased along with economic development. For consumables, communication and infrastructure, a growing range and quantity of minerals is essential. Global demand of minerals increases exponentially. There is debate whether or not further growth of mineral extraction from the earth's crust will be sustainable in view of the limited extractable quantities of these minerals in the earth's crust. Henckens et al. (2014) proposed an operational definition for the sustainable extraction of raw materials: *The extraction rate of a material is sustainable, if a world population of 9 billion can be provided with that material for a period of at least 1000 years, assuming that the average per capita consumption level of the material is equally divided over the world's countries.* Using this definition a (non-exhaustive) list of 15 geologically scarce materials has been identified. Boron is one of the materials that are relatively scarce from a geological point of view. In this paper we introduce an approach to assess the technical opportunities to (substantially) reduce mining of primary resources, and use this approach to assess whether a sustainable reduction of boron mining would be possible, without losing any of the services currently provided by boron. We first introduce the approach consisting of substitution, material efficiency improvement and/ or recycling. This is then applied to boron. We end with discussion and conclusions.

3.2 METHODOLOGY

In an interpretation of the 3R approach (Reduce, Reuse, Recycle), there are three main technical options to reduce the consumption of raw materials:
-    Substitution of the material by suitable alternatives in selected applications.
-    Reduced or more efficient use of the material.
-    Increased recovery and recycling of the material.
The first step of our methodology is to develop a general approach for determining whether or not a reduction, required for sustainability, of the application of a primary resource is technically feasible by systematically exploring the opportunities and limitations of each of the above reduction options. The objective of the approach is not to determine the optimal mix of substitution, material efficiency and recycling for a particular case, from an economic or ecologic point of view. Nor is it the intention to make a technical or policy blue print of reduction measures. In practice the definitions of the three reduction categories may overlap, and may be combined in one innovation, making it difficult to assign the reduction in primary material use to a single category. Often several reduction scenarios may be possible, applying different mixes of the three measures.
The second step of the methodology is to apply the findings of the first step to determine the reduction potential of boron.

3.2.1 Substitution

If substitution of a material is possible, this approach may be seen as an interpretation of the first R of the 3R approach. According to Ziemann and Schebek (2010), five types of substitution can be distinguished (Table 3-1).

Table 3-1 Types of substitution, derived from Ziemann and Schebek (2010)

Substitution type	Explanation
Material substitution	Material A is re-placed by material B
Technological substitution	Reduction of material consumption by technological progress
Functional substitution	Product A is replaced by Product B or service C with the same function
Quality substitution	Product A is replaced by Product A' with a lower, but still sufficient quality
Non-material substitution	A product is replaced by a service with the same function

Four main factors determine the potential for substitution of a material:

1. *The performance of the substitute compared to the original.* An important condition for the adequate applicability of a substitute is that the services, provided by the original product, are maintained. For some uses the performance of the substitute may matter less than for other uses. A 100 % equal performance compared to the original is not always necessary (i.e. quality substitution). Each specific application will have its own requirements.
2. *The environment, health and safety (EHS) properties of the substitute compared to the original.* The environment, health and safety properties of the substitute and the original are supposed to encompass all aspects, from cradle to grave, in all stages from the extraction until the end-of-life stage.
3. *The financial characteristics of the substitute compared to the original.* The (additional) costs of a substitute will depend on its availability, accessibility and technology. While the effect of prices may be a relative factor, it can be a decisive element for substitutability in practice.
4. *The geological availability of the substitute compared to the geological availability of the original.* The aim of our investigation of the possible extraction reduction of a material is to conserve scarce materials for future generations. So substitutes should not be less scarce than the original.

Note that, an application can be so specific that the material can hardly or not be substituted, e.g. the application of boron as micro nutrient in fruit and seed production. In such an application, material efficiency is the only option to reduce primary boron use. Substitution is not applicable in such case and recycling only to a limited extent.

3.2.2 Material efficiency

Material efficiency (or resource productivity) reflects the quantity of services that can be provided by a given amount of a material, e.g. light weighting of packaging may result in

reduced material use to package the same product. Table 3-2 provides a general overview of possibilities for material efficiency increase.

Table 3-2 Overview of possibilities for material efficiency (ME)

ME in production process	Prevention of material loss
	Process optimization
	ME in resources purchase
	Recycling of production waste
ME in products	Light-weight or re-designing products Design for recycling
	Design for re-use and multi-purpose use
	Design for longer use, maintenance, repair, remanufacturing
ME during consumption	Longer use and maintenance
	Reuse
	Shared use

In this paper, recycling of end-of-life products (consumption waste) will be addressed under recycling. Ordoñez and Rahe (2013) make plausible that product designers are not in the first place focused on resources conservation, through design for recycling, reuse, maintenance, repair and waste minimization in general. Hence, potential for material efficiency may exist in many products and applications. According to Allwood (2013), generally, lightweight design, product life time extension and more intensive product use are the most effective means to increase material efficiency. Alternatively, Tukker (2004) explored whether Product Services Systems (PSS; e.g. product lease instead of product ownership) may improve material efficiency. His conclusion is that most types of PSS may have some environmental gains, but generally may not drastically improve material efficiency. According to Tukker most can be expected from PSS with the promise of a functional result. For example, international travel can be substituted by videoconferencing. In this case, the functional result is an adequate meeting with effective communication.

How can the potential effect of material efficiency be quantified? Current literature on material efficiency improvement provides mainly examples for specific materials or products, but no meta-studies exist that provide a general overview of potentials. Based on the variety found in the literature, in Table 3-3, we provide an estimate by ourselves of the order of

Table 3-3 Estimated material efficiency improvement potential range (expert judgment of our own based on literature)

	Estimated material efficiency potential range
ME in production process	1-10%
ME in products	10-50%
ME during consumption(excl. recycling of EoL products	10-50%

magnitude of the improvement potential of various types of measures. The efficiency potential indicates the reduction percentage of material use for providing the same quantity of services compared to the original material use. Considering a specific material, an efficiency potential of 25% means that for providing the same services only 75% of the original quantity of that material would be needed for delivery of the same services.

Although differing for particular materials and products, material efficiency has a large potential. Table 3-3 depicts the wide spread found in the literature for a variety of applications. However, this potential will not always be easily realized in practice. Therefore, if we have no data for specific applications of the materials we study, we assume a conservative (default) material efficiency potential of 10 %, apart from the impact of increased recycling of materials from end-of-life products. However, material efficiency is an important option in case that substitution and recycling are not sufficient to reduce the consumption of a material to a sustainable level. More research may then be necessary for specific materials and applications.

3.2.3 Recycling

The recycling potential of a specific material from a specific product depends on the following factors (Graedel and Erdmann, 2012; Worrell and Reuter, 2014):
-   *Concentration.* The higher the concentration, the higher the recycling potential. As a general rule the concentration should be at least as high as the minimally profitable concentration in virgin ore.
-   *Material composition.* Alloys, composites and laminates of various materials make it difficult to isolate the mono-materials, which may limit (or even inhibit) recycling or result in down-cycling.
-   *Product composition.* The more complex the composition or assemblage of the product, the lower the recycling potential.
-   *Dissipative uses.* Dispersed or dissipative use of materials inhibits the (economic) recoverability of materials.
-   *Contamination.* The more a (waste) product is contaminated, the lower the recycling potential.

The UNEP International Resource Panel (2011a) has made an extensive inventory of the actual and widely varying end-of-life recycling rate of 60 metals on a global scale. The UNEP experts have chosen five ranges of recycling rates (see Table 3-4).

Recycling rates will never be 100 %, as not all material may be recoverable due to the factors discussed above. To enable recycling, an infrastructure needs to be built that may include many stakeholders (e.g. manufacturers, households, waste management companies, recycling traders and processors, local governments), and may also encompass the generation of new (international) markets for recycled material. Building such an infrastructure may be capital and time-intensive, and may be affected by changes in product and material compositions. This may, in turn, affect the implementation of other reduction categories.

Table 3-4 Global average end-of-life recycling rate for 60 metals (from UNEP, 2011)

Current global average EoL recycling rates				
<1 %	1-10%	10-25%	25-50%	>50%
As	Hg	Cd	Ir	Ag
B	Sb	Ru	Mg	Au
Ba		W	Mo	Co
Be				Cr
Bi				Cu
Ga				Fe
Ge				Mn
Hf				Nb
In				Ni
Li				Pb
Os				Pd
Sc				Pt
Se				Re
Sr				Rh
Ta				Sn
Te				Ti
Tl				Zn
Y				
Zr				
Lanthanides				

Yet, recycling is a core element of primary resource use reduction and material efficiency. Recycling will always be a part of the portfolio of measures to sufficiently reduce primary resources use.

3.2.4   Combining the potentials: evaluation and conclusion

The results of the different categories are not additional, as they may affect each other, or may result in double counting. Hence, the analysis of the reduction potential needs to assume a certain order of analyzing the different categories.

We propose a method consisting of three consecutive steps (see also Figure 3-1):
(1) investigate the possibilities of substitution
(2) find out, whether and to what extent the remaining quantity of the material requires further reduction, first through material efficiency
(3) investigate further recycling measures on top of what is already being done at the moment.

We use this approach, because substitution may often result in a substantial reduction of the use of a material. This is important because of the large reduction that may be required to achieve sustainable consumption of a number of materials. Theoretically, substitution measures have a 100 % result, and may be achieved by banning certain materials in certain applications. However, practice has shown that bans may be difficult to enforce. If a material is substituted, this may affect the opportunities for material efficiency improvement and/or recycling. Hence, we first need to understand the impacts of substitution on material and
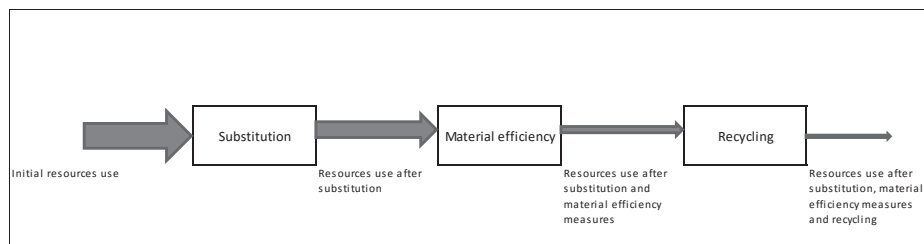
Figure 3-1 Proposed sequence of investigation of measures for a substantial reduction of the use of a geologically scarce material.

production composition to evaluate the need for e.g. setting up a dedicated recycling infra-structure. However, substitution is not a panacea, as the performance of the substitute, as well as economics, should be acceptable and may limit the actual substitution. Also, a scarce material should not be substituted by another scarce material, as that will just relocate the problem for future generations. The substitution should not result in a negative environmen-tal impact compared to the original material, and, finally, as discussed above, substitution policies may not always be effective resulting not only in ineffectiveness, but, in some cases, also in a negative effect on recycling processes.

3.3   BORON: CURRENT APPLICATIONS AND FLOWS

In this section we will apply the approach to boron. Elemental boron is not found naturally on earth. Boron combines easily with oxygen to borates. Its presence in the earth's crust is mostly in borate minerals. More than two thirds of boron reserves are found in Turkey and the USA. Sea water contains about 5 ppm boron, while the average boron concentration in the continental earth's crust is 15 ppm (UNEP, 2011a). On the basis of data from Lyday (2003) and US Geological Survey (2014a and 2014b) boron world production in 2010 is estimated at about 830,000 tons expressed as boron. [6]

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6   This figure is based on the following data:
-    World production (excluding USA) in 2010 is 4080*1000 tons of boron concentrate (all forms)
-    90 % of this amount consists of 4 ores: borax (36.5 % B_2O_3), kernite (51.0 % B_2O_3), calcium borate colemanite (50.8 % B_2O_3) and sodium-calcium borate ulexite (43 % B_2O_3).
-    The content of B_2O_3 in tradable boron oxide ores produced in the USA is about 50 %. We shall assume that this is similar worldwide.
-    From 2005 on, USGS does not provide production figures of boron in the USA. However, on the basis of de data between 1975 and 2005 and the difference between global production in 2005 (including the USA) and global production in 2006 (excluding the USA), the production of boron (all tradable forms) in the USA in 2010 is estimated at about 1300*1000 tons. So the world production of boron (all tradable forms) in 2010 can be estimated at (4080+1300)*1000 tons or

To meet a sustainable level of consumption to enable future generations to keep access to services provided by boron, this volume needs to be reduced by at least 44%, to a maximum of 465,000 tons per year.[7] We start with discussing the current boron applications and flows, followed by a systematic evaluation of the opportunities to reduce current boron use.

3.3.1 Boron applications

Boron and its compounds have many different applications. Nowadays, more than three-quarters of the world's supply of boron is used in glass, ceramics, detergents and fertilizer (US Geological Survey, 2014a). Boron use in different parts of the world is quite divergent, as is shown in Table 3-5. In this analysis we will use the world average (as provided by US Geological Survey).

Glass

Glass represents the most important boron application with an average of 60% globally (US Geological Survey, 2013). Borates improve the thermal shock resistance, increase the aqueous durability and chemical resistance, improve the mechanical strength, provide a higher resistance to devitrification during processing, lower the glass melting temperature (fluxing agent), improve the refining process and formability, and improve optical properties (Borax, 2014). About 90 % of the application of boron in glass is in glass fibre (US Geological Survey, 2013); see Table 3-6.

A smaller part of boron application in glass (about 10 %) is used for borosilicate glass. The applications of borosilicate glass are shown in Table 3-7. Generally, borosilicate glass contains around 5 % B_2O_3.

Ceramics

About 10% of the global boron consumption is used in ceramics (US Geological Survey, 2013). Borates are applied in ceramic glazes and enamels, increasing chemical, thermal and wear resistance. Enamel is a smooth, durable, vitreous coating on metal, glass or ceramics. It is hard, chemically resistant, and scratch resistant, has long-lasting colour fastness, is easy to clean and cannot burn (Fedak and Baldwin, 2005). Enamels are mostly used on steel (Borax 2014). A specific application of boron in ceramics is in light weight armour, in which boron carbide is a key ingredient (US Geological Survey, 2013). The use of borates in the production of ceramic tiles reduces the temperature and energy requirements. Moreover, borates

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5380*1000 tons. About 50 % of this is boron oxide (B_2O_3) or 2690*1000 tons. This matches with 834*1000 tons of boron (B).

7   This figure is calculated as follows. According to UNEP (2011c), the extractable global resources of boron can be estimated at 600 million tons. Hence, according to the definition of the sustainable extraction of minerals, the sustainable per capita extraction rate (9 billion people, depletion in 1000 years) is 66.7 g/cap/year. The present annual per capita consumption of boron is 119 g/cap/year (extraction in 2010 divided by 7 billion people). This means that the necessary reduction is 1-66.7/119 =44 %

Table 3-5 Overview of boron applications.

		World (US Geological Survey, 2014a) 2012 data		USA (Average of the data between 1999 and 2003 (US Geological Survey, 2005)[e]		EU (European Commission, 2013) Year of data is not indicated
Glass		60 %		80%		55%
	Glass wool		*39 %[a]*		*52 %*	
	Fibre glass		*16 %[a]*		*21 %*	
	Borosilicate glass		*5 %[a]*		*7 %*	
Ceramics		10 %		4 %		14 %
Detergents and soaps		4 %		6 %		1 %
Fertilizer		4 %[b]		4%		13 %
Fire retardants		3 %[b]		3%		1 %
Other applications		19 %[c]		3%		16 %
	Chemicals		*8 %[d]*			*7 %*
	Cosmetics, pharmaceuticals and toiletries		*2.5 %[d]*			*2 %*
	Industrial fluids		*2.5 %[d]*			*2 %*
	Metallurgical applications		*6 %[d]*			*5 %*
Total		100%		100%		100%

[a] Global distribution of boron applications in glass is supposed to be similar to the distribution in the USA
[b] Global use of boron in fertilizers and fire retardants is not provided by USGS. The relative global use is supposed to be similar to the use in the USA
[c] Global use of boron in other applications is supposed to be the remainder of total global boron use
[d] Global distribution of boron over the various other applications is supposed to be similar to the distribution in Europe
[e] More recent data (2011) from USGS concerning the use of boron in the USA differ minimally (glass 80 %, ceramics 3%, detergents and soaps 4%, fertilizer 4%, fire retardants plus other applications 9 %), but do not specify the use of boron in fire retardants (USGS,2012)

Table 3-6 Glass fiber applications of boron (Crangle 2012)

Glass fibre applications	Function
Glass fibre textiles	Resistance against corrosion and heat, high strength
Insulation (glass wool)	Thermal insulation and acoustic insulation. Thermal insulation glass wool contains about 4-5 % of boron oxide to aid melting, to inhibit devitrification and to improve the aqueous durability (Lyday, 2003)
Fibreglass reinforced plastics (GFRP or FRP), also called E-glass	Alumino-borosilicate glass with less than 1% alkali oxides E. Fitzer et al. (2008)). Important applications are boats, wind turbine blades, pipes, light weight composite structural components for cars, trucks, trains and aircraft (Borax 2014). The boric oxide concentration varies between 0 and 10 % B_2O_3, but typically between 6 and 10 % boron oxide (Lyday, 2003)

Table 3-7 Borosilicate applications (Borax, 2014)

Borosilicate glass applications	Application examples
Heat resistant glass	Pyrex kitchenware, microwave dishes, laboratory glass
Display screens	LCD screens. This is one of the major boron consuming areas that have grown recently. Generally, flat screen glass contains 11-13 percent boron oxide. The cover glass of touch screens of smart phones and tablets consists of borosilicate glass.
Lighting glass	Head lights, halogen bulbs, fluorescent tubes
Sealing glasses	Tungsten filament lamps, lamps in street lighting, cathode ray tubes
Neutral glasses	Ampoules and vials for medicine for increased chemical resistance
Cosmetic containers	For chemical resistance
Solar glass	Cover glass and substrate glass for photovoltaic cells, and evacuated solar collector tubes
Glass microspheres	Airport runway reflector systems
Other	Optical glass, prisms, lenses, opal glassware, telescope mirror blanks

increase the dry mechanical strength of unfired tiles between 30% and 80% (Lyday, 2003). Ceramic glazes with boron are applied in tiles and tableware (porcelain, china, stoneware and earthenware) (Borax, 2014). By far the largest consumers of boric oxide in ceramics are glazes for wall and floor tiles (Borax, 2014). Wall tiles contain between 3 and 20% of B_2O_3, depending on the firing time and temperature (Borax, 2014). Enamels contain typically 14% B_2O_3.

Fertilizers
Fertilizers represent the third largest application of borates (US Geological Survey, 2013). Boron is a micro-nutrient primarily used in fruit and seed production (US Geological Survey, 2013). Normal plant leaves typically contain 25 to 100 ppm boron (US Geological Survey, 2014a). To sustain boron at this level, it is necessary to supply 1 kilogram per hectare per year (US Geological Survey, 2014a).

Detergents and soaps
The use of borates in detergents and soaps accounts for 4% of world consumption (US Geological Survey, 2012). Borates are used in detergents and soaps as alkaline buffers, enzyme stabilizers, oxygen-based bleaching agents, water softeners, for improvement of surfactant performance, and for soil removal (Borax, 2014). Sodium perborate, in contact with hot water, produces hydrogen peroxide, a very effective bleaching agent. Modern laundry detergents typically contain 15% sodium perborate.

Fire retardants
Zinc borate is used as flame retardant in plastic and rubber applications, in pressed boards, in paper boards, in cellulose-based insulation material, in gypsum board, in cotton batting in matrasses, and in fabrics requiring flame retardant treatment. It forms a glassy coating protecting the surface (EFRA, 2007). Normally, zinc borate is used in combination with other

fire retardants, such as antimony trioxide, aluminium trioxide, magnesium hydroxide or red phosphorus (EFRA, 2007).

Other applications

Boron is used in a multitude of other products, including:

- Chemicals, used as insecticides and for wood preservation, pH – buffer, lubrification, in nuclear power plants as moderator, in semiconductors, air bags and magnets, in abrasives and ballistic vests, electrolytic capacitators, starch adhesives, paints, coatings and printing inks. Anhydrous Borax is used in gold refining as part of flux formulations to dissolve metal oxides.
- Cosmetics (e.g. cosmetic creams, skin lotions, hair shampoos, dyes and gels, bath salts and denture cleaners) (Borax, 2014) and pharmaceuticals. Boric acid is used as an antiseptic and as an antibacterial compound.
- Industrial fluids. According to Borax (2014), borates are used in antifreeze, lubricants, brake fluids, metalworking fluids, water treatment chemicals, fuel additives for the prevention of pre-ignition, in leather tanning as pH-buffer liquid, and in photo developing solutions (pH buffer).
- Metallurgical applications. Addition of boric oxide to steel slags prevents so-called dusty slag, resulting in a stable rock-like material (Borax, 2014). About 15 kg of B_2O_3 is used per ton of slag. Ferro boron in steel increases steel strength.

Developments

- Future boron use (Lyday, 2013) may increase because of application in automotive fuel cells (i.e. sodium borohydride), in cars to replace metal parts with fibre glass reinforced plastics, as well as in batteries (i.e. titanium diboride).

3.3.2   Current boron material flows

A part of the use of boron is dissipative through usage: in detergents and soaps, in fertilizer, in cosmetics and pharmaceuticals, in metallurgical applications, in insecticides, in pH buffer liquids and in lubrication. Based on the relative amounts that are used for these applications, as presented in Table 3-5, we estimate that about 75% of the consumed boron remains in end-of-life products and about 25% is dissipated. According to US Geological Survey (2014 a), current recycling of boron is insignificant. It is estimated that in the boron production phase about 5 % of the extracted boron ends up in waste sludge. See section 3.4.2.

Current boron material flows are represented in Figure 3-2.
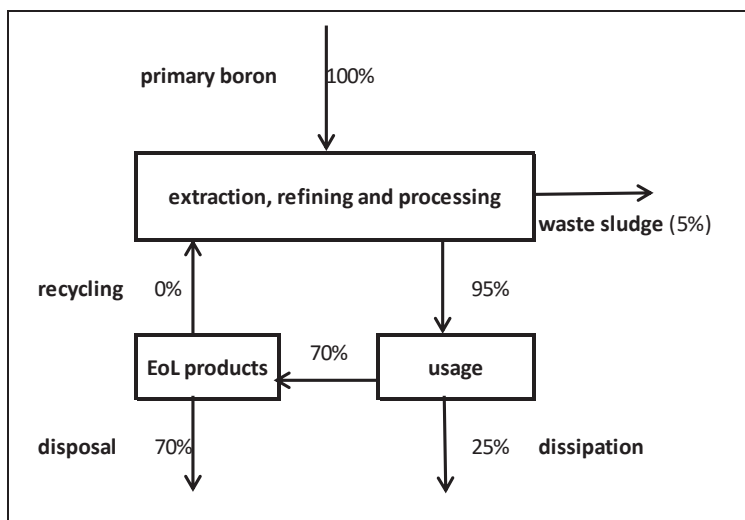
Figure 3-2 Current global boron flows. Global primary boron production in 2010 is estimated at 830 kt B (based on data from the US Geological Survey, 2014 a. 2014b).

3.4 PATHWAY TO SUSTAINABLE BORON USE

3.4.1 Substitution of boron-containing products

Application of boron compounds in products, from which direct human exposure could occur, is under scrutiny because of possible negative effects on human health (Risk and Policy Analysts, 2008), e.g. fertilizer, and detergents and soaps. In the other applications boron is chemically bound and any significant human exposure is improbable. Hence, there is already pressure to substitute certain boron-containing products by less toxic products.

Substitution of boron in glass

- Glass wool can be substituted by various foams, rock wool or natural fibres. Especially rock wool has approximately the same properties as glass wool. Various insulation foams are currently used as an alternative for glass wool, such as expanded poly-styrene, extruded polystyrene and polyurethane. Also natural materials can be used for insulation, such as cellulose and cork. Contrary to glass wool and rock wool, synthetic foams and natural materials have the disadvantage that they are inflammable. There are several new developments in this field such as vacuum insulation panels, gas-filled panels, aerogels and so-called phase change materials. An aerogel is a synthetic porous material derived from a gel, in which the liquid component of the gel has been replaced with a gas. The result is a solid with extremely low density and low thermal conductivity. For a review of the state of the art in this field we refer to the publications of Jelle (2011), Dewick and Miozzo (2002) and Papadopoulos (2005). The conclusion is that in principle it is possible to replace 100% of glass wool for insulation purposes by alternative materials.

- Glass fibres in fibre glass reinforced plastics may be partly substituted by other fibres such as carbon fibre, aramid fibre, high-modulus PE fibre, quartz fibre, basalt fibre, ceramic fibre and natural fibres. Each of these fibres has its specific application area. Glass fibre is the oldest and by far the most common reinforcement in applications used to replace heavier metal parts. Carbon fibre is the most used fibre in high-performance applications. The general performance of natural fibres is not yet as high as the performance of glass fibres, especially because of the hydrophilic nature of natural fibres. However there is quite some development in this area and according to Faruk et al (2014) natural fibres may potentially replace a substantial part of glass fibres in reinforced plastics. The most popular natural fibres are: flax, jute, hemp, sisal, ramie and kenaf (Faruk et al, 2014), while abaca, bamboo, wheat straw, curaua, and rice husk fibres are gaining interest.
  Hence, while substitution of glass fibre by other types of fibre seems possible, we shall conservatively and provisionally suppose that glass fibre in glass fibre reinforced plastics will not be substituted. An additional background for this assumption is the promising recycling potential of glass fibres from GFRPs (see below).
- The substitution of borosilicate glass by a non-boron-containing material seems to be more difficult. Although in some applications glass may be replaced by other materials, we have supposed that for this boron application the substitutability is zero.

The substitution of boron in glass wool (currently one of the key applications of boron) as insulation material is not limited by the substituents' performance, EHS properties, costs or geological availability, as shown in Table 3-8.

Table 3-8 Glass wool substitutability assessment

	Substitutes			References
	Rock wool	Foams	Natural fibers	
Performance	0	0	0	Jelle, 2011; Papadopoulos, 2005
EHS properties	0	-	+	Papadopoulos, 2005
Costs	0	-	-	Papadopoulos, 2005
Geological availability of substitutes	++	0	++	

Performance scale: ++: much better than original; 0: equal to original; - -: much lower than original
EHS scale: ++: much better than original; 0: equal to original; —: very negative compared to the original
Cost scale: ++: much cheaper than the original; 0: equal to original; —: much more expensive than the original
Geological availability: ++: much less scarce than the original; 0: equal to original; — much scarcer than the original

Substitution of boron in ceramics.
According to US Geological Survey (2014a), in enamel, boron may be replaced by phosphates. According to a paper of the European Commission (2010), boron in ceramics is substitutable, but at high costs. We therefore conservatively assume that the substitutability of boron in

ceramics is 0%. However, glass fibre from recycled glass fibre reinforced plastics, may (partly) replace the use of primary boron in ceramics (López et al, 2012).

Substitution of boron in detergents and soaps.
Perborate as bleaching agent in detergents may be replaced by sodium percarbonate and in soaps by sodium and potassium salts of fatty acids (USGS, 2014a). In their use as enzyme stabilizer borates are considered not to be substitutable (Risk and Policy Analysts, 2008). Over the period 2003-2008, the use of sodium perborate in detergents in Western Europe has decreased by around 80%, and has mostly been substituted by sodium percarbonate (Risk and Policy Analysts, 2008). Nevertheless, compared to the use in the USA and the rest of the world, use of perborates in detergents in Europe is still relatively high. In warmer climates sodium perborate performs better than sodium percarbonate (Risk and policy Analysts, 2008). Table 3-9 presents the results of a substitutability assessment of the substitution of perborate in detergents by sodium percarbonate.

Table 3-9 Substitutability assessment of perborate in detergents

	Substitute	Reference
	Sodium percarbonate	
Performance	-	Risk and Policy analysts, 2008
EHS properties	+	Risk and Policy Analysts, 2008
Costs	+	Alibaba, 30-10-2014
Geological availability of substitutes	+	

Performance scale: ++: much better than original;0: equal to original; - -: much lower than original
EHS scale: ++: much better than original; 0: equal to original; —: very negative compared to the original
Cost scale: ++: much cheaper than the original; 0: equal to original; —: much more expensive than the original
Geological availability:++:much less scarce than the original; 0: equal to original;— much scarcer than the original

For the more general functions as alkaline buffer, bleaching agent, water softener, surfactant performance improver and for soil removal, it is hardly imaginable that boron-containing detergents and soaps cannot be partly substituted by non-boron-containing products. It is assumed that the substitutability of boron in detergents and soaps is 50%.

Substitution of boron in fertilizer.
Boron as micro-nutrient cannot be substituted.

Substitution of boron in fire retardant.
There are several alternative fire retardant systems. Zinc borate is typically used as a synergist for other fire retardant systems and is hardly used as a fire retardant on its own. Therefore it is supposed that replacement might be possible, but would decrease the performance of the

applications in which it is used currently. Therefore, we assume that boron compounds can difficultly be substituted in its fire retardant applications.

Substitution of boron in various other applications
-   Chemicals. Some of the boron applications are specific (e.g. lubricants, neutron moderators in nuclear power plants, semiconductors, air bags and magnets, abrasives and ballistic vests, electrolytic capacitators, and gold refining). Other boron applications are less specific and may be easily replaced, such as the application in insecticides and wood preservatives, as pH buffer, in starch adhesives, paints, coatings and printing inks. Nevertheless, we (prudently) assume that only 10% of the boron applications in chemicals are substitutable and 90% is not.
-   Cosmetics and pharmaceuticals. In many cosmetics and in pharmaceuticals, boron applications are not indispensable. Therefore, we assume that at least 25% substitution should be possible.
-   Industrial fluids. Some of the boron applications in industrial fluids are relatively specific (as lubricant, in brake fluids, in metal working fluids, in fuel additives). But others are not specific (as pH-buffer or corrosion inhibitor). We assume that a 25% substitution of boron applications in industrial fluids should be possible.
-   Metallurgical applications. The boron applications in steel production are so specific that it is assumed that substitution is not possible.

The effects for boron substitutability are summarized in Table 3-10.

Table 3-10 Potential substitutability of boron applications. Total boron use is normalized to 100 units.

Main application	Consumption	Sub-application	Consumption of sub-applications	Substitutability	Remaining primary boron use after substitution
	(units)		(units)	(%)	(units)
Glass	60	-Glass fiber in glass wool	39	100%	0
		-Glass fiber in fiber glass reinforced plastics and for high strength textiles	16	0%	16
		-Borosilicate glass	5	0%	5
Ceramics	10		10	0%	10
Detergents and soaps	4		4	50%	2
Fertilizer	4		4	0%	4
Fire retardants	3		3	0%	3
Various	19	-Chemicals	8	10%	7
		-Cosmetics, pharmaceuticals	2.5	25%	2
		-Industrial fluids	2.5	25%	2
		-Metallurgical applications	6	0%	6
Total	100		100	43%	57

Table 3-10 demonstrates that even with conservative assumptions the substitutability of primary boron could be as high as 43% of current use. This means that by substitution only, primary boron consumption can almost be reduced sufficiently to achieve the sustainable level of 56 % of current primary boron use.

The results shown in table 3-10 are not very sensitive for the various assumptions made. If the substitutability of boron in detergents and soaps, chemicals cosmetics and pharmaceuticals and industrial fluids would only be half of the ones supposed here above, then total substitutability would decrease from 43 % to 41 %. The determining factor for total substitutability is the 100 % substitutability of glass wool by other materials.

3.4.2   Material efficiency of boron-containing products

After a 100% substitution of glass wool by other non-boron-containing insulation materials, 50% of boron-containing detergents and soaps by other non-boron-containing detergents and soaps and 15% of boron-containing chemicals, cosmetics, pharmaceuticals and industrial fluids, in principle, additional material efficiency and recycling measures would hardly be necessary to achieve a sufficient reduction of primary boron consumption. Nevertheless, to achieve a robust long-term consumption pattern, taking into account the possibility that new important boron applications might be developed in the future, we have also investigated the opportunities for improved material efficiency and recycling of boron.

We will focus on boron production and the most important boron applications: glass wool, fiber glass and borosilicate glass. Together the applications mentioned represent about 60% of current boron use. More than half of the remaining boron use is dissipative and material efficiency is above all a matter of minimizing use and decreasing losses (e.g. through precision fertilizer application).

-   Boron production.

An important material efficiency opportunity is offered by the recovery of boron contained in borax waste sludge (usually) disposed of at the boron production location in storage ponds. According to Özdemir and Kipcak (2010), and Boncukcuoglu et al (2003) in Turkey, the country with the highest boron reserves in the world, 5% of the extracted boron ends up in the waste sludge. According to Boncukcuoglu et al (2003), it is possible to recover 90% of the boron in the waste sludge by acid leaching followed by precipitation and crystallization. Others (Uslu and Arol, 2004, Kavas, 2006, and Christogerou et al, 2007) studied the possible use of borax waste sludge as an additive in the production of red bricks and in heavy clay ceramics. While this solves the environmental problems of borax waste sludge and reduces the use of other primary materials, this will not contribute to the recovery and efficient use of boron.

-   Glass wool, glass fibers and borosilicate glass.

As far as they are not substituted by other products, demand for glass wool, glass fiber and borosilicate glass can be expected to further increase. Losses of glass wool in construction are estimated at about 5% (Väntsi and Kärki, 2014), providing limited potential for efficiency

improvement. All boron glass applications can potentially be recycled (see section 3.4.3). Therefore, it is important that these boron-containing products are designed in a way that recyclability at the end-of-life stage is facilitated. Further opportunities in this framework may be the potential minimization of glass fiber content in glass fiber containing products, and the potential reduction of losses in the production of glass fiber containing products. Referring to section 3.2.2. we will assume a default material efficiency potential of 10 % after the boron substitution potential has been used.

3.4.3   Recycling of boron-containing products

Recycling of boron in glass wool

Waste glass wool is generated in three ways: construction, renovation and demolition. It is relatively easy to reuse or recycle glass wool from construction sites, because it is not polluted and easily separable. Some glass wool producers offer a take-back scheme for their products (Väntsi and Kärki, 2014). It is possible to return waste glass wool in the glass wool production process. However, the fine particles potentially clog the feeding equipment for air and oxygen of the cupola furnace. To solve this problem it is possible to briquet the waste glass wool using binder materials (Väntsi and Kärki, 2014). Construction waste impurities in the waste glass wool may prevent recycling in the glass wool production process (Väntsi and Kärki, 2014). That is why state-of-the-art selective demolition and sorting are important for an adequate recycling of glass wool. Modern separation techniques are expected to enable achieving reasonable results with separation of mineral wool from a mix of construction and demolition waste. Nowadays, glass wool is still hardly recycled, because recycling costs (including the costs for separation and transport) are usually higher than the costs of the primary raw materials. The main challenges for the reuse of waste glass wool are the voluminous character, making transport relatively expensive, next to the varying composition and availability. Conservatively, we shall assume a glass wool recycling potential of 10 %.

Waste glass wool may be used as a raw material in other products such as in cement and concrete (Shi and Zheng, 2007), in ceramics and in tiles and as an artificial substrate for growing plants (Väntsi and Kärki, 2014). This approach reduces the use of other primary raw materials, but this will not contribute to the sustainable use of boron. In doing so, boron is actually down-cycled and finally dissipated in the environment.

Recycling of boron in glass fiber reinforced plastics

Literature describes three potential recycling methods for glass fibers: chemically, thermally and mechanically. Asmatulu et al (2014) compared the methods, suggesting that chemical recycling offers the highest tensile strength of the recycled fibers (98% of the original strength), while mechanical and thermal recycling result in lower quality fibers (75 % and 50-75% of the strength of virgin fibers respectively). Mechanical recycling consists of cutting and grinding the composite in small pieces, and separating the fibers from the rest of the particles. However, the recovered glass fibers have lost between 18 and 30% of their strength, potentially limiting applicability. Beauson et al (2014), in an investigation of the recyclability

of glass fiber from wind turbine blades, confirm this conclusion. Thermal treatment can encompass pyrolysis and combustion (López et al., 2012a and b, Zheng et al., 2009, Akesson et al., 2012, Asmatulu et al., 2014). The resulting glass fraction cannot be directly reused as glass fiber, but needs reprocessing, because of the relatively low quality mechanical properties. Contrary to this, Mizuguchi et al. (2013) report on a thermal method to decompose glass fiber reinforced plastics yielding the embedded reinforcing fibers in their original form without any noticeable difference between the virgin reinforcing fibers and the recovered ones. In the chemical treatment method, the polymeric matrix is dissolved in organic solvents or strong inorganic acids (see e.g. Liu et al., 2006). Thermal treatment of glass fiber reinforced plastics GFRP therefore may also be oriented to produce high-calorific oils and gases, next to glass for glass-ceramic applications (as glaze) in the building sector. The recycled fiber glass, which can be as much as 99% of the glass fiber in the GFRP, can be used as glazes on tiles and may reduce primary boron use for ceramics glazing (López et al, 2012). Asmatulu et al. (2014) also mention the possibility of "direct structural composite recycling". The concept is that large composite products are cut in smaller-size pieces that can be directly used in small composite products. García et al. (2014) investigated the addition of GFRP waste to micro-concrete. Under specific conditions the addition can be beneficial for the mechanical compressive and bending strength of the micro-concrete. Although the use of other primary materials is prevented in this way, the method will not reduce boron consumption.

Although recycling of glass fiber is still in a developmental stage, research results are promising. Recycling will depend on the costs of recovering and recycling glass fiber containing products versus the costs of primary boron. Conservatively we shall assume a recycling potential of glass fiber from glass fiber reinforced plastics of 25 %.

Borosilicate glass is recyclable, if it is separated from other waste glass. But borosilicate glass cannot be mixed with other glass for recycling, because of its impact on the viscosity of the melt. Recyclability is therefore assumed to be limited. Therefore we shall assume a recycling potential for borosilicate glass of 40 % maximally.

Recycling of boron in ceramics
The majority of boron-containing waste ceramics consists of tiles and sanitary ware in construction and demolition waste. The rest is in broken tableware in municipal waste. Waste composition is complex and overall boron concentration is low. We therefore assume that boron from these waste flows cannot be recycled.

Recycling of boron in other boron applications
The other boron applications are dissipative or are used in quantities and concentrations that are assumed to be too low to be suitable for economical recycling.

Taking the various assumptions into consideration, the overall recycling potential of boron from products that are considered not substitutable for the time being (glass fiber in glass fiber reinforced plastics, and borosilicate glass) is about 12 %.

3.5 CONCLUSION AND DISCUSSION

In general, the consumption of a material can be reduced (1) by substituting the material, (2) by material efficiency and (3) by recycling. Different mixes of substitution, material efficiency improvement, and recycling may be applied. For ease of analysis, we have developed a method that starts with the assessment of the potential for substituting the critical material by suitable alternatives, followed by the opportunities for material efficiency improvement in production and processes of the non-substituted part. After that, the recycling potential of the remainder must be explored. In practice, the potential of the three approaches may influence each other, and an economic approach will contain all three elements. The method excludes a detailed economic analysis.

The approach has been applied to evaluate the opportunities to reduce boron use, as it is one of the elements that may be critical from a (temporal) sustainability perspective. In order to be sustainable, the 2010 extraction of primary boron needs to be reduced by 44 %.

The results of the analysis are represented in Figure 3-3.
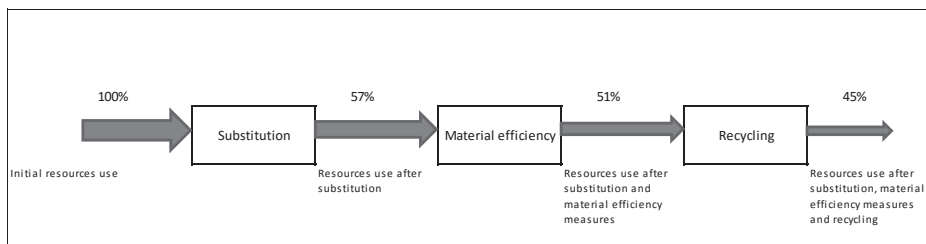
Figure 3-3 Use reduction potential of primary boron with current technologies

The substitutability of current boron applications provides a reduction potential of about 43% of primary boron extraction. The replacement of glass wool by other insulating materials such as rock wool or organic foams and the replacement of boron-containing detergents and soaps by non- boron-containing detergents and soaps are most promising in this respect.

Material efficiency is estimated to have a reduction potential of 10 % of the amount that remains after substitution. The highest potential in this respect is provided by a reduction of boron losses in waste sludge during the production.

Recycling measures can partly replace substitution and/or further decrease the use of primary boron. Most promising in this respect is the recycling of glass fibre from glass fibre reinforced plastics and the separate recycling of borosilicate glass. These recycling measures

are estimated to have a realistic potential of about 12 % of the amount of boron that remains after substitution and material efficiency measures.

The final conclusion is that the total reduction potential for the consumption of primary boron using existing technologies is about 55 %. This is sufficient to make the extraction of primary boron sustainable.

ACKNOWLEDGMENTS

REFERENCES

Akesson, D., Foltynowicz, Z., Christéen, J., Skrifvars, M., 2012 Microwave pyrolysis as a method of recycling glass fiber from used blades of wind turbines. J. Reinf. Plast. Compos. 31, 1136-1142

Alibaba, www.alibaba.com, price sodium perborate, price sodium percarbonate, 30-10-2014

Allwood, J.M., 2013, Transitions to material efficiency in the UK steel economy. Phil.Trans.R.Soc. A 371, 20110577, 28-1-2013

Asmatulu, E., Twomey, J., Overcash, M., 2014, Recycling of fiber-reinforced composites and direct structural composite recycling concept. J. Composite Mater. 48, 593-608

Beauson, J., Lilholt, H., Brondsted, P.,2014, Recycling solid residues recovered from glass-fiber-reinforced composites – A review applied to wind turbine blade materials. J. Reinf. Plast. Compos. 33(16)1542-1556

Boncukcuoğlu, R., Kocakerim, M.M., Kocadağistan, E., Yilmaz, M.T., 2003, Recovery of boron of the sieve reject in the production of borax. Resour. Conserv. and Recycl 37, 147-157

Borax, www.borax.com (2014)

Christogerou, A., Kavas, T., Pontikes, Y., Koyas, S., Tabak, Y., Angelopoulos, G.N., 2009, Use of boron wastes in the production of heavy clay ceramics. Ceram. Int. 35, 447-452

Crangle, R.D. Jr., 2014, Boron, USGS 2012 Minerals Yearbook, September 2014

Dewick, P., Miozzo, M., 2002, Sustainable technologies and the innovation – regulation paradox. Futures 34; 823-840

EFRA, The European Flame Retardants Association, Flame Retardants, Frequently Asked Questions, January 2007

European Commission, Critical raw materials for the EU, report and Annex V of the ad-hoc working group on defining critical raw materials, 2010, European Commission, Enterprise and Industry

Faruk, O., Bledzki, A.K., Fink, H-P., Sain, M., 2014, Progress report on natural fiber reinforced composites. Macromol.Mater.Eng. 299, 9-26

Fedak, D., Baldwin, C.A., 2005, Comparison of Enameled and Stainless Steel Surfaces, Proceedings of the 67th Porcelain Enamel Institute Technical Forum, 45-54

Fitzer, E., Kleinholz, R., Tiesler, H., Stacey, M.H., De Bruyne, R., Lefever, I., Foley, A., Frohs, W., Hauke, T., Heine, M., Jäger, H., Sitter, S., 2008, "Fibers, 5. Synthetic Inorganic". Ullmann's Encyclopedia of Industrial Chemistry. Wiley-VCH Verlag GmbH & Co. KGaA), Weinheim Germany

García, D., Vegas, I., Cacho, I., 2014, Mechanical recycling of GFRP as short-fiber reinforcements in micro concrete, Constr. Build. Mater. 64, 293-300

Graedel, T.E., Erdmann, L., 2012, Will metal scarcity impede routine industrial use? Mater. Res. Soc. Bull. 37 (April), 325-331

Henckens, M., Driessen, P., Worrell, E.,2014, Scarcity and sustainability, Research into the necessity of extraction reduction of scarce metals. Resour. Conserv. Recycl. 93,1-8

Jelle, P.B.,2011, Traditional, state-of-the-art and future thermal building insulation materials and solutions – Properties, requirements and possibilities. Energy Build. 43,2549-2563

Kavas, T., 2006, Use of boron waste as a fluxing agent in production of red mud brick. Build. Environ. 41, 1779-1783

Liu, Y., Meng, L.., Huang, Y., Liu, L.,2006, Method of recovering the fibrous fraction of glass/epoxy composites. J. Reinf. Plast. Compos. 25,1525-1533.

López, F.A., Martin, M.I., García-Díaz, I., Rodriguez, O., Alguacil, F.J., Romero, M., 2012a, Recycling of glass fibers from fiberglass Polyester Waste Composite for the Manufacture of Glass-Ceramic Materials. J. Environ. Protect. 3, 740-747

López, F.A., Martin, M.I., Alguacil, F.J., Ma, Rincón, J., Centeno ,T.A., Romera, M.,2012b, Thermolysis of fiber glass polyester composite and reutilization of the glass fiber residue to obtain a glass-ceramic material, J. Anal. Appl. Pyrolysis 93, 104-112

Lyday, P.A., Boron, US Geological Survey Minerals Yearbook 2003

Mizuguchi, J., Tsukada, Y., Takahashi, H., 2013, Recovery and Characterization of Reinforcing Fibres from Fibre Reinforced Plastics by Thermal Activation of Oxide Semiconductors

Ordoñez, I., Rahe, U., 2013, Collaboration between design and waste management: Can it help close the material loop? Resour. Conserv. Recycl. 72,108-117

Özdemir, M., Kipçak, I.,2010, Recovery of boron from borax sludge of boron industry. Miner. Eng. 23, 685-690

Papadopoulos, A.M. 2005, State of the art in thermal insulation materials and aims for future developments. Energy Build. 2005; 37; 77-86

Risk & Policy Analysts, Assessment of the risk to consumers from borates and the impact of potential restrictions on their marketing and use, final report prepared for the European Commission DG Enterprise and Industry, November 2008

Shi, C., Zheng, K., 2007, A review of the use of waste glasses in the production of cement and concrete. Resour. Conserv. Recycl. 52,234-247

Tukker, A., 2004, Eight types of product Service System: eight ways to sustainability? Experiences from SusProNet. Bus. Strategy and the Environ. 13, 246-260

UNEP International Resource Panel, Recycling rates of metals, a status report, 2011a

UNEP International Resource Panel, Decoupling Natural Resource Use and Environmental Impacts from Economic Growth, 2011b

US Geological Survey, Boron end-use statistics, September 15, 2005

US Geological Survey, Boron Statistics, April 1, 2014b

US Geological Survey, Boron, 2011 Minerals Yearbook, 2013

US Geological Survey, Mineral Commodity Summaries, 2012

US Geological Survey, Mineral Commodity Summaries, Boron, February 2014a

Uslu, T., Arol, A.I., 2004, Use of boron waste as an additive in red bricks. Waste Manage. 24, 217-220

Väntsi, O., Kärki, T., 2014, Mineral wool waste in Europe: a review of mineral wool waste quantity, quality and current recycling methods. J.Mater. Cycles Waste Manage. 16, 62-72

Worrell E. Reuter, M. (Eds.), 2014 1st ed, Handbook of Recycling – State-of-the-Art for Practitioners, Analysts and Scientists, Elsevier, Amsterdam

Zheng, Y., Shen, Z., Ma, S., Cai, C., Zhao, X., Xing, Y., 2009, A novel approach to recycling of glass fibers from non-metal materials of waste printed circuit boards. J. Hazard. Mater. 170, 978-982

Ziemann, S., Schebek, S., 2010, Substitution knapper Metalle – ein Ausweg aus der Rohstoffknapheit? Chemie, Ingenieur,Technik 82,11,1965-1975

Chapter 4

How can we adapt to geological scarcity of antimony? Investigation of antimony's substitutability and of other measures to achieve a sustainable use [8]

8   Published as: Henckens M.L.C.M., Driessen P.P.J., Worrell E., 2016, How can we adapt to geological scarcity of antimony? Investigation of antimony's substitutability and other measures to achieve a sustainable use, Resources, Conservation and Recycling, 108(2016)54-62

ABSTRACT

Antimony is an element that is applied in many useful applications for mankind. However, antimony resources are very scarce, when comparing the current extraction rates with the availability of antimony-containing ores. From an inter-temporal sustainability perspective, current generations should not deprive future generations from extractable ores. The extraction rate of a mineral resource is defined sustainable, if such a rate can be sustained for 1000 years assuming the same consumption per capita in all countries of the world. To achieve a sustainable extraction of antimony, it is necessary to reduce the current extraction with 96 % compared to the primary antimony extraction in 2010. We have investigated whether such an ambitious extraction reduction goal would be technically feasible, without losing any of the current services that are provided by antimony. Reduction of the use of primary antimony can be achieved through (a combination of) substitution, improved material efficiency and recycling. Because the potential of material efficiency and recycling are limited in the case of antimony, the focus is on substitution of antimony in its applications.

The major application of antimony (more than 50 %) is in flame retardants. It appears that about 95 % of antimony in flame retardants can be replaced by other components or systems. Overall, the substitutability of antimony in all its applications is estimated at around 90 %.

The required additional extraction reduction needs to be realized by improved material efficiency and further recycling, especially from the remaining antimony-containing flame retardants and from lead-alloys.

KEYWORDS

4.1   INTRODUCTION

Antimony is an element that is used in many applications that are useful for humanity, e.g. as component in flame retardants, as catalyst to produce polyester, in lead-acid batteries and in lead alloys. However, antimony reserves are very scarce. Comparing the extractable global resources of antimony according to the UNEP approach (2011) with the current pace of extraction of antimony as provided by USGS (2015a), antimony is one of the scarcest mineral resources. According to Henckens et al. (2014) the extractable global resources of antimony are exhausted before 2050 if the antimony extraction rate continues to increase with the current pace. This does not mean that antimony will have disappeared from the earth's crust by that year, but the relatively easily extractable ores will. Further extraction of antimony will then become much more expensive due to e.g. low ore grades, deep mining, remote locations and high energy costs. Seen the utility of antimony for humankind it is therefore important to look at ways to reduce its extraction to a sustainable level, but without losing any of the services currently provided by antimony.

What is the sustainable level of extraction and use of primary antimony?

Henckens et al. (2014) propose the following operational definition for the sustainable extraction of raw materials: *The extraction rate of a material is sustainable, if (1) a world population of 9 billion can be provided of that material for a period of at least 1000 years assuming that, (2) the average per capita consumption level of the material is equally divided over the world's countries.* This approach is based upon four points of departure:

(1) The available amount of extractable ores. According to UNEP (2011), the approximate upper limit of the extractable amount of a mineral resource is 0.01 % of the total amount of that mineral in the top 1 km of the continental part of the earth's crust. This is supported by Erickson (1973), Skinner (1976) and Rankin (2011).

(2) The current extraction rate and the expected future increase of the extraction rate. This can be based on USGS data.

(3) Long-time- availability of sufficient extractable ores for future generations (according to the normative principle of inter-generational equity). What is "long time" in this framework? Theoretically, it should be for eternity, but this is not possible, since ores are not renewable. For practical reasons, Henckens et al. (2014) propose a period of 1000 years as an approximation of quasi-perpetuity. Their argument is that an ore depletion period of 100 years (just a few generations ahead) would be too short a period for sustainable extraction, whereas an order of magnitude longer period of 10,000 years seems unnecessarily long in their view.

(4) The principle right of the citizens of the world on an equitable share of the available mineral resources (according to the normative principle of intra-generational responsibility). In an operational definition for sustainable extraction it would not be justified to depart from the status quo of present inequality. Henckens et al. (2014) therefore propose to depart from the assumption that in 2050, all countries in the world have the same pro capita level of consumption of mineral resources as the industrialized countries at this moment.

According to the 3R approach (Reduce, Reuse, Recycle), there are three main technical ways to reduce the use of primary materials: substitution of the resource in its applications, improved material efficiency and increased recycling. In case a substantial use reduction of a scarce mineral resource is necessary, Henckens et al. (2015) propose to investigate these types of measures in the following sequence: (1) substitution of the resource, (2) material efficiency of the resource's applications remaining after substitution, (3) recycling of the resource from the applications remaining after substitution and material efficiency measures. This approach will result in a specific mixture of the three measures for achieving the required reduction rate. However, in practice, various other scenarios are thinkable as well or economically more optimal.

In this paper we will investigate whether and how it would be possible to reduce the extraction of antimony to less than 4 % of the current extraction at a global scale.
The intention of this investigation is not to make a blue print of measures to be taken, but to demonstrate whether or not a 96 % reduction of the use of primary antimony is feasible at all with current technologies without losing the services provided by antimony.
We will base ourselves on literature data. With regard to the substitutability of antimony in flame retardants and glass we have consulted specialized experts.

4.2   THE OCCURRENCE, EXTRACTABLE AMOUNTS AND SUSTAINABLE EXTRACTION OF ANTIMONY

Since 110 years, China is the main antimony supplier of the world (Tri-star resources, 2015). The main mine is in the province of Hunan in the center of the east part of China. The geological conditions in this area (high porosity karst type area in or nearby active tectonic fault lines) have been favorable for the formation of deposits with a high concentration of antimony, especially stibnite (Sb_2S_3). Both in 2012 and 2013, China had 75 % of the world production of antimony. See Table 4-1 and Figure 4-1.

Figure 4-2 shows that, since 1900 there is a quite steady increase of global antimony production. In recent years, the annual amount of extracted antimony shows relatively large variations, but the production trend is still upward.

Over a period of 113 years, between 1900 and 2013, the average annual production increase was 5.6 %. See Table 4-2 for more details for selected periods.

Based on UNEP (2011) we suppose that the extractable global amount of antimony is 0.01 % of the total amount of antimony in the top 1 km of the continental earth's crust. The extractable global antimony resources, according to the vision of UNEP (2011), are 8 million tons. This is about twice as much as USGS's latest reserve base estimation of antimony in 2009,
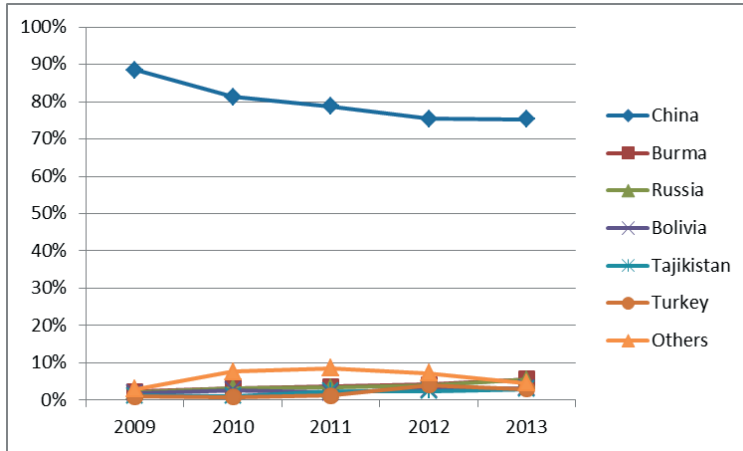
Figure 4-1 Share of antimony production of the main antimony mining countries between 2009 and 2013 (USGS 2015a)
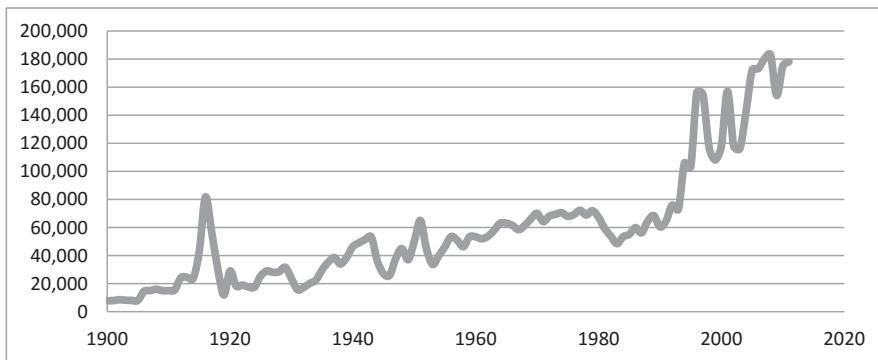
Figure 4-2 Development over time of antimony world production (tons). Derived from USGS (2015b)

which is 4,3 million tons. When we prudently suppose a further average annual increase of the extraction antimony of 3 % from 184,000 ton in 2010 to (a virtual) 545,000 ton in 2050, it can be calculated that the extractable antimony ores will be depleted around 2040. If humanity wants to retain sufficient extractable antimony ores for future generations during a period of 1000 years, global use of primary antimony has to be reduced by 96% from 184,000 tons of antimony in 2010 to a maximum of about 7000 tons per year in the future (Henckens et al., 2014).

Table 4-1 Antimony producing countries (metric tons), USGS 2015c)

	2009	2010	2011	2012	2013
China	140,000	150,000	150,000	136,000	120,000
Canada	64	9,000	10,000	6,000	76
South Africa	2,673	3,239	3,175	3,066	2,400
Bolivia	2,990	4,980	3,947	5,088	5,081
Burma	3,700	5,900	7,000	7,400	9,000
Russia	3,500	6,040	6,348	7,300	8,700
Turkey	1,400	1,400	2,400	7,300	4,600
Tajikistan	2,000	2,000	4,500	4,248	4,675
Australia	1,000	1,106	1,577	2,481	3,275
Kyrgyzstan	700	700	1,500	1,200	1,200
Peru	145				
Mexico	74	71	100	169	294
Total	158,246	184,436	190,547	180,252	159,301

Table 4-2 Global production trends of antimony (USGS, 2015b)

Average annual increase between 1900 and 2013	5.6%
Average annual increase between 1950 and 2013	2.8%
Average annual increase between 1990 and 2013	5.8%
Average annual increase between 2000 and 2013	3.3%

4.3   APPLICATIONS AND FLOWS OF ANTIMONY

The global end uses of antimony in 2010 are presented in Table 4-3. There are two main types of applications of antimony: non-metallurgical applications and metallurgical applications. In the supplementary information we have discussed the various applications in more detail.

A growth area is the use of antimony in glass panels for photovoltaic solar cells (Roskill Consulting Group, 2011). However, on the longer term, the global use of antimony is expected to decline due to its frequent use together with halogenated hydrocarbons or lead. Worldwide, the use of both halogenated hydrocarbons and lead is scrutinized due to environmental and health reasons. Mainly due this reason, in Europe and the USA, application of antimony in flame retardants is lower than in other parts of the world. The problem is that toxic gases may be released by these flame retardants in case of fire and because of the eco-toxic properties of these substances as such. That means that environmental regulations are important determinants for the use of specific flame retardants. Polybrominated biphenyls and polybrominated diphenyl ethers have been banned from the use in electric and electronical equipment by a European Union Directive (June 2011). The application of halogenated hydrocarbons as flame retardants in building cables may be further affected by the European Construction Product Directive (March 2011) requesting testing of acidity, toxicity and smoke properties.

Table 4-3 Estimated global consumption of antimony by end-use in 2010 (tons Sb) (Roskill Consulting Group, 2011)

	tons Sb	%	Main use
Non-metallurgical applications			
Flame retardants	103,500	51.9%	Plastics
PET catalyst	11,400	5.7%	PET
Heat stabilizer	2,600	1.3%	PVC
Glass	1,700	0.9%	Cathode Ray Tubes and solar glass
Ceramics	2,500	1.3%	Construction
Other	1,840	0.9%	Various
Sub total	123,540	61.9%	
Metallurgical applications			
Lead-acid batteries	53,000	26.6%	Automotive
Lead alloys	23,000	11.5%	Construction
Sub total	76,000	38.1%	
Total	199,540	100%	

The EU Directive on waste electrical and electronic equipment (WEEE, 2012) obliges the member states to adopt appropriate measures to minimize the disposal of WEEE in the form of unsorted municipal waste. The minimum recycling targets for various types of WEEE vary between 70 and 85%. In this framework, plastics that contain brominated flame retardants, have to be removed from the separately collected WEEE and to be disposed or recovered in compliance with the EU Waste Directive (2008). Annex VII of the WEEE-Directive prescribes selective treatment for plastic containing brominated flame retardants. This means that these substances are to be removed from collected WEEE and are to be treated separately.

Apart from the environmental concerns on the use of halogenated hydrocarbons in flame retardants, the price plays a role as well. According to USGS (2015a, p19), the flame retardant industry *"began substituting for antimony trioxide in 2011 following a significant increase in price".*

Also the use of antimony compounds as catalyst for the poly-condensation of PET is under discussion because of the migration of small quantities of antimony to food and beverages in PET bottles and PET containers.

The use of antimony in lead-acid batteries is declining as well because of the development of maintenance free batteries without or with much less antimony.

To be able to investigate how the use of primary antimony can be eventually reduced by 96 % we need to analyse the current antimony material flows. Part of the antimony in products is already recycled, reducing the need for primary antimony. Analyzing current antimony re-cycling we will distinguish the recycling of metallic antimony applications from the recycling of non-metallic antimony applications.

Recycling of antimony from metallic applications

The recycling rate of lead-acid batteries is high. This is an important source of secondary antimony. According to Carlin (2006) by 2000, about 95 % of secondary antimony in the USA originated from lead-acid batteries. Thus far, metallic antimony applications are the only source of secondary antimony. This implies that 5 % of secondary antimony results from other antimony-containing scrap of metallic applications (such as lead sheets, pipes, tubes, gutters, etc.). On the basis of these figures, it can be calculated that the recycling rate of antimony from antimony-containing alloys was about 10 % in 2000 in the USA. This low recycling rate of antimony from antimony-containing alloys may be partly explained by the fact that most lead alloys are used in construction and have a long life time. So the recycled amount is relatively small compared to the amount that is newly used. So antimony is accumulating in construction. The life time of batteries is much shorter. A big part of the lead-acid grids from batteries and collected end of life antimony-containing alloys are scrapped and recycled in lead smelters. Thus far, the resulting secondary antimony is mostly used again in lead-acid batteries, although this may change in future with the growing use of low maintenance and maintenance free batteries.

Current recycling of antimony from non-metallic applications

A substantial part of PET bottles is recycled and scrapped. According to Thiele (2009), in 2007 about 24 % of PET in bottles was recycled. In 2007, 72 % of the recycled PET flakes was used in polyester fiber (Noone, 2008), and 10 % was used in bottles again (Thiele 2009). The recycled PET fibers are for instance used in various textiles. According to the same author, in 2007, recycled PET fiber accounted for about 8 % of the world PET fiber production.

For the rest, until now, antimony recycling from most non-metallic uses, such as from flame retardants, heat stabilizers, glass, ceramics and chemicals, is non-existent. Due to the type of use in these non-metallic applications, it is currently not economical, although technically feasible, to recycle the antimony from the end-of –life product. This means that antimony contained in these products will eventually be disposed of in landfills or incinerators.

The data provided in section 4.3 are summarized in Table 4-4.

The data in Table 4-4 result in the antimony flow chart represented in Figure 4-3.

4.4   SUBSTITUTABILITY OF ANTIMONY-CONTAINING PRODUCTS

We will investigate potential measures that would enable the required 96 % reduction of the extraction of primary antimony from the current 74 units in Figure 4-3 to a maximum of 3 units. In this section we will analyze the possibilities for substitution of antimony-containing materials and in the next section material efficiency and recycling measures.

Regarding the substitutability of antimony in flame retardants and in glass we have consulted experts, because these application fields of antimony are both quite specific, compared to the other types of application of antimony. For the expert consultation we have prepared a
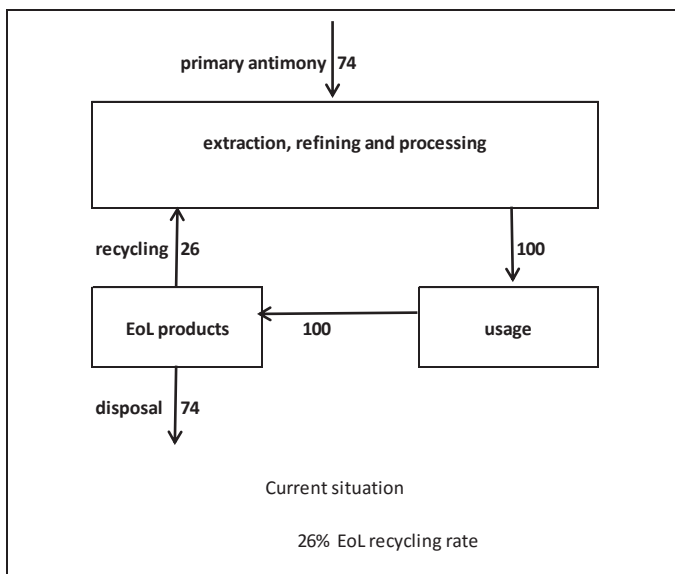
Figure 4-3 Current antimony flows. Current antimony end-usage is normalized at 100 units.

Table 4-4 Current recycling rates of antimony. Antimony end-use is normalized at 100 units. (Roskill, 2011)

	Current distribution of antimony end-use (2010) (Roskill, 2011)	Antimony recycling rate	Reference	Amount recycled	Current use of primary antimony
	Units	%		Units	Units
Non-metallurgical applications					
Flame retardants	51.9	0%		0.0	51.9
PET catalyst	5.7	8%	Thiele (2009)	0.4	5.3
Heat stabilizer	1.3	0%		0.0	1.3
Glass	0.9	0%		0.0	0.9
Ceramics	1.3	0%		0.0	1.3
Other	0.9	0%		0.0	0.9
Sub total					
Metallurgical applications					
Lead-acid batteries	26.6	90%	Carlin (2006)	23.9	2.7
Lead alloys	11.5	10%	Calculated	1.2	10.4
Sub total		*34%*		*25.1*	
Total	**100.0**	**26%**		**26.2**	**74**

list of potential substitutes from the literature. We have asked the experts to indicate for each application:

- Whether 100 % substitution or replacement of antimony would be feasible within 10 years without compromising the required flame retardancy quality

- What the applicability of the combined potential substitutes is (very poor, poor, moderate, good, very good, unknown)
- How the environment, health and safety properties of each potential substituent are compared to the original (very negative, negative, equal, positive, very positive, unknown)
- What the estimated costs of each substituent are (> 200% of original, 120-200 % of original, 80-120 % of original, < 50% of original, unknown)
- Comments, other applications, other substituents

The results are presented in this section. The approach and the results are presented in more detail in the supplementary information.

4.4.1 Substitutability of antimony in non-metallurgical applications

Substitutability of antimony in flame retardants
There is a large variety of flame retardants on the market. The worldwide market share of antimony-containing flame retardants (brominated hydrocarbons or chlorinated hydrocarbons with antimony trioxide) is almost 40 %. See Table 4-5.

Table 4-5 Market shares of various types of flame retardants (volume percent)

Flame retardant	Market share					
	Worldwide 2011 (a)	EU 2006 (b)	Europe, 2007 (c)	United States, 2007 (c)	Asia, 2007 (c)	Worldwide, 2007 (d)
Aluminiumtrihydroxide	40.4%	40%	53%	55%	16%	40%
Halogenated hydrocarbons with antimonytrioxide	39%	30%	21%	20%	67%	38%
Brominated hydrocarbons	19.7%	10%	9%	10%	45%	23%
Antimony trioxide	8.4%	7%	4%	5%	13%	8%
Chlorinated hydrocarbons	11.3%	13%	8%	5%	9%	7%
Organophosphorus	14.6%	18%	16%	12%	8%	12%
Other	5.6%	12% (e)	12%	12%	9%	11%

(a) Townsend Solutions 2012
(b) Cusack, 2007
(c) Keyser, 2009
(d) Based on the assumption that the relative market shares of the various flame retardants worldwide are determined by the use in the USA, Europe and Asia as derived from the data provided by Keyser, 2009
(e)Magnesiumhydroxide 2%, Melamine flame retardants 4 %, other inorganic flame retardants 6%

The Supplementary information provides an overview of the main materials and the applications of these materials in which halogenated flame retardants with antimony trioxide are used, their possible substitutes and replacements. Lassen et al. (1999) provide a detailed overview. The overview makes clear that there are alternatives for halogenated flame retardants.

The consulted experts[9] in the field of flame retardancy have indicated for each application to what extent they estimate that the antimony-containing product can be adequately replaced by a substituent. We have defined *"adequately"* as follows:
- The performance of the substitute compared to the performance of the original, should be adequate, meaning sufficient for the respective application. In this respect we use the following terminology: (1) very poor: antimony can be adequately substituted by alternatives in 0-20% of the uses, (2) poor: antimony can be adequately substituted by alternatives in 20-40 % of the uses, (3) moderate: antimony can be adequately substituted by alternatives in 40-60% of the uses, (4) good: antimony can be adequately substituted by alternatives in 60-80% of the uses, (5) very good: antimony can be adequately substituted by alternatives in 80-100% of the uses
- The environment, health and safety impact should not be negative compared to the original antimony-containing product
- The financial picture connected to the use of a substituent should not be very negative compared to the original antimony-containing product.

Furthermore we have asked the experts whether in their opinion a 100 % substitution of specific antimony-containing flame retardancy systems would be feasible within 10 years without compromising the required flame retardant quality.

Based on the experts' opinions, our conclusion is that at this moment about 55 % of antimony in flame retardants would be adequately substitutable and 95 % within a period of 10 years. About 90 % of the substituting flame retardants are considered to have EHS (Environment, Health and Safety) properties that are equal or positive compared to the antimony-containing original. The costs of more than 50 % of the substitutes are estimated by the experts to be equal or lower than the costs of the original flame retardant with antimony.

The detailed data of the inventory of experts' opinions are included in the Supplementary information.

Substitutability of antimony compounds as catalyst in PET production
Apart from the geological scarcity of antimony, number of other reasons exist to substitute antimony compounds as catalysts in PET production: toxicity for human health and the environment (Shotyk et al. 2006), negative impact on polymer quality (Thiele, 2004), improvable catalytic characteristics (Thiele 2004, Shigemoto et al. 2013).

A number of alternative catalysts are commercially available (Thiele, 2001, Thiele, 2004, Yang 2012, Yang et al. 2013, Butterman and Carlin, 2004, Gross et al., 2010, Furlong, 2014). Most of the alternative catalysts are based on (non-scarce) titanium. Others are based on germanium, zirconium, cobalt, molybdenum, organic materials or enzymes. Molybdenum is also a scarce

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mineral and should be avoided to replace antimony. The other alternative materials mentioned in this section are not considered scarce (Henckens et al. 2014)

Companies like *DAK Amerikas* have included antimony free PET in their sales program. Other companies make publicity for antimony free polyester clothing (for instance McLaren, 2008).

A serious hurdle to overcome is the necessity of adaptation of PET production facilities, when changing to another catalyst. Because of the large volume production of PET, its production facilities have a substantial size and therefore are quite inflexible. In practise change to another catalyst will only be realistic in case of a newly constructed PET plant (Thiele, 2006).

The conclusion regarding the substitutability of antimony in catalysts for the PET production is that antimony is 100 % substitutable in this application.

Substitutability of antimony as heat stabilizer in plastics

Antimony-mercaptide is just one of many heat stabilizers. For an overview it is referred to Markarian (2007) and Babinsky (2006). Antimony-mercaptide is quite insignificant in this market (Butterman and Carlin, 2004).

The conclusion is that antimony's application in heat stabilizers, as far as it is still applied is 100 % substitutable.

Substitutability of antimony in glass

The use of antimony trioxide as fining agent, decolourant and antisolorant can be avoided in melt ovens that are resistant against strongly oxidizing conditions and by using sand with a very low iron and chromium content (Rögels, 2014). In float glass, antimony compounds can be substituted by sodium sulphate. For special glasses, mixtures of various fining agents are used. Antimony sulphide as glass colorant can be replaced by other glass colorants. See Biron and Chopinet (2013). Antimony sulphide in its application of glass colourant is therefore considered to be 100% substitutable.

We have questioned glass experts[10] on the possibilities of substitution of antimony compounds in the various glass applications. On the basis of their reaction, we estimate that an average of 56 % of the applications of antimony in glass is substitutable in the above mentioned ways at this moment. Within a period of 10 years a substitutability of 80 % of antimony in glass is deemed possible by the experts. The detailed results of the expert's opinion on the substitutability of antimony in glass are included in the Supplementary information.

Substitutability of antimony in ceramics

There are many colorants and opacifiers for ceramics on the market available, although it is not clear whether or not exactly the same colour or the same effect can be obtained. Nevertheless we assume that the specific application of antimony compounds in ceramics is not unique, indispensable or non-replaceable and is therefore considered to be 100 % substitutable.

————————

10   Ruud Beerkens of TNO, The Netherlands, Hayo Müller-Simon of the Research Institute of the German Glass Industry (HVG), Germany and Masataka Kawaguchi of Nippon Electric Glass, Japan

Substitutability of antimony in other non-metallurgical uses
Due to the specific character of these applications and the relatively small volume it is assumed that antimony in these applications is not substitutable.

4.4.2   Substitutability of antimony in metallurgical applications

Substitutability of antimony in lead acid batteries
Antimony-containing lead acid batteries can be replaced by antimony-free calcium-calcium lead acid batteries. Antimony free batteries have become the norm in all applications (May, 1992, Toniazzo, 2006, Misra, 2007).

Substitutability of antimony in lead alloys
Rabin (1997) and Roskill Information Services (1997) mention substitute *solders*, without antimony. They contain however bismuth, copper, indium, silver, tin and zinc in various proportions and combinations. Although these metals are less scarce than antimony, most of them are geologically scarce or moderately scarce as well. A mineral resource is defined (1) very scarce, if its extractable ores are depleted before 2050 (like antimony), (2) scarce, if its extractable ores are depleted within a period of less than 100 years after 20150 and (3) moderately scarce, if its extractable ores are depleted within a period of between 100 and 1000 years after 2050 (Henckens et al. 2014). Therefore we assume that substitution of antimony in solder is not possible from a perspective of geological scarcity of the potential substitutes. According to Booser (1992) and Roskill Information Services (1997) many antimony-containing *bearings* have substitutes including alloys of aluminum, copper, tin, zinc, silver, nylon, polyimide, silicon nitride, carbon-graphite, aluminum oxide. Also ball and roller bearings are candidates for selected uses. A part of the substitutes is scarce as well, but another part is not (Henckens et al., 2014). Substitutes for lead-antimony rolled and extruded *alloys* are stainless steels and polymers (Prengaman, 1995)
Substitutes for antimonial lead in *ammunition* for small arms are bismuth-tin alloys (97%/3%), steel and tungsten (Brown, 2001). Bismuth, tin, iron and tungsten are scarce minerals as well, although less than antimony.
In *cable covering*, laminated aluminum and organic polymers are used to substitute lead sheathing of power and communication cables (Prengaman, 1995 and Roskill Information Services Ltd, 1997).
On the basis of the available data it is difficult to provide a quantitative estimation of the substitutability of antimony in its various alloys. More research will be needed. Our prudent first approximation for calculation purposes is that the overall substitutability of antimony in alloys may be in the order of 50 %.

4.4.3   Substitutability of antimony summarized

The conclusion of the sections 4.4.1 and 4.4.2 is that antimony is partly or fully substitutable in many of its applications. The overall substitutability can be estimated at about 90 % of the current antimony end-use. See Table 4-6.

Table 4-6 Antimony substitutability in various applications. Current antimony end-use is normalized at 100 units

	Current distribution of antimony end-use (2010)	Substitutability	Remaining antimony use after substitution
	Units	%	Units
Non-metallurgical applications			
Flame retardants	51.9	95%	2.6
Plastic catalyst	5.7	100%	0.0
Heat stabilizer	1.3	100%	0.0
Glass	0.9	80%	0.2
Ceramics	1.3	100%	0.0
Other	0.9	0%	0.9
Sub total	*61.9*	*94%*	*3.7*
Metallurgical applications			
Lead-acid batteries	26.6	100%	0.0
Lead alloys	11.5	50%	5.8
Sub total	*38.1*	*85%*	*5.8*
Total	**100.0**	**91%**	**9.4**

Recycling will be reduced from the current 26 % to only 6 %, because antimony applications as PET catalyst and in batteries will have been substituted. The remaining extraction of primary antimony is about 12 % of the current extraction rate (a reduction from the current 74 units in Figure 4-3 to 9 units). But we need to achieve a 96 % reduction of the current extraction. In the next paragraphs we will investigate how material efficiency and extra recycling can contribute to the additionally required extraction reduction of antimony.

Whether or not, to what extent and how fast the potential antimony substitutability will be realized will depend on a number of factors, whereof the most important are government regulation and the costs of substitutes versus their performance. Another practical factor will be the time that industry will need for switching from antimony to a substitute without too many capital costs in connection with the needed adaptation of production facilities.

4.5   IMPROVING MATERIAL EFFICIENCY AND INCREASING RECYCLING OF ANTIMONY-CONTAINING PRODUCTS

4.5.1   Material efficiency

Generally, material efficiency can be improved by:
- Lower losses in production processes and supply chains
- More economical application in products (lower concentration)
- More economical use of products (longer product life times, shared use of products, e.g. electric and electronic equipment)

In principle, all these material efficiency options are applicable for many of the current antimony applications. However, in section 4.4 we have seen that in a substantial part of its applications antimony is substitutable by other products. Therefore we will focus on the material efficiency potential of the antimony applications that remain after substitution. It concerns the remaining antimony use in:

- Flame retardants
- Glass
- Other non-metallic uses, such as additive to some lubricants, as passivating agent, as phosphoring agent, as vulcanization agent, for fireworks, as cross-linking agent and as reactant in organic chemical reactions.
- Metallic uses, such as antimony application in bearings, solders, ammunition, cable covering and various alloys for specific applications.

In a situation of a great variety of small uses it is difficult to provide a reliable estimation on the possible material efficiency. Henckens et al., 2015 have made plausible that a prudent (default) material efficiency of 10 % for the remaining antimony applications can be assumed. The result is presented in Table 4-7. The conclusion is that material efficiency might supposedly further reduce the antimony end-use from 9.4 % of the current use to 8.5 % of the current end-use and the extraction of primary antimony from about 12 % of the current extraction to 11 %.

Table 4-7 the reduction effect of material efficiency measures on the remaining antimony use after substitution

	Remaining antimony end-use after substitution	Reduction through material efficiency	Remaining antimony end-use after substitution and material efficiency measures
	Units	%	Units
Non-metallurgical applications			
Flame retardants	2.6	10%	2,3
Plastic catalyst			
Heat stabilizer			
Glass	0.2	10%	0,2
Ceramics			
Other	0.9	10%	0,8
Sub total	*3.2*		
Metallurgical applications			
Lead-acid batteries			
Lead alloys	5.8	10%	5,2
Sub total	*5.8*		
Total	**9.4**	**10%**	**8,5**

The conclusion is that, after material efficiency measures, still an extra effort is needed to achieve the final goal of 96 % reduction of primary antimony use.

4.5.2 Improved recycling

Currently, antimony recycling mainly includes antimony in PET (8 % recycling), in lead batteries (90% recycling) and other metallic uses (10% recycling). Further improvement of PET recycling and antimony recycling from batteries is theoretically possible, although not simple as far as it is PET applications in textiles concerned. But considering increased antimony recycling in PET and in lead-acid batteries is not necessary anymore, because we have assumed that antimony in both applications will be 100 % substituted by other products. As far as antimony in lead-acid batteries is not substituted it is easily recyclable. Recycling of antimony from ceramics and from products wherein it is used as heat stabilizer is difficult, because of the low concentration and the complex mix of materials in the end-of-life products. But also for these two applications we have supposed that antimony is 100 % substitutable.

For further increasing antimony recycling, we therefore concentrate on:
- Flame retardants
- Glass
- Other non-metallic uses (as chemical)
- Non –battery metallic uses (mainly in alloys)

The EU WEEE Directive (2012) facilitates the opportunity to concentrate antimony from WEEE. In principle various recycling routes are possible. Plastics that contain brominated flame retardants may be separated per type of material and (partially) be reused in the original products. Another possible route is incineration, whereby antimony will mainly be concentrated in the incineration fly ashes. A substantial recycling of antimony is possible in this way, if one would succeed in collecting and incinerating all products with antimony-containing flame retardants.

For achieving an overall 96 % reduction of primary antimony use it will be necessary to take for instance the following measures: (1) recycle 70 % of the antimony from the remaining non-substituted antimony-containing flame retardants instead of 0% at this moment, (2) increase recycling of antimony from other metallic uses from 10% currently to 75 % in the future. These necessary extra recycling ambitions for achieving an overall 96 % reduction of antimony extraction lead to the overview of Table 4-8 and the flow chart of Figure 4-4.

The conclusion is that the required goal of 96 % reduction of primary antimony use is achievable with a mix of 91 % substitution of antimony in the current applications, 10 % material efficiency with regard to antimony in the remaining applications and 65 % reduction of the remaining antimony use by recycling of WEEE waste and improved recycling of antimony in lead alloys. The resulting end-use of antimony in products will be 8.5 % of the current end-use.
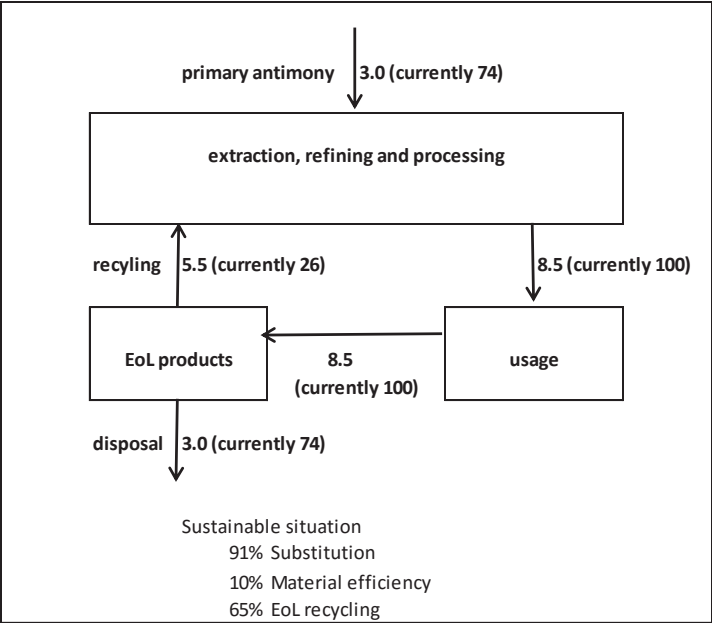
Figure 4-4 Antimony flow chart with 96 % reduction of primary antimony compared to the current situation. The current end-usage is normalized at 100 units.

Table 4-8 the reduction effect of improved recycling of remaining antimony use after substitution and material efficiency measures

	Remaining antimony end-use after substitution and material efficiency measures. See table 4-7	Reduction through improved recycling	Remaining primary antimony use after substitution, material efficiency and improved recycling
	Units	%	Units
Non-metallurgical applications			
Flame retardants	2.3	70%	0.7
PET catalyst			
Heat stabilizer			
Glass	0.2	0%	0.2
Ceramics			
Other	0.8	0%	0.8
Sub total			
Metallurgical applications			
Lead-acid batteries			
Lead alloys	5.2	75%	1.3
Sub total			
Total	**8.5**	**65%**	**3.0**

4.6 CONCLUSION AND DISCUSSION

The technical possibilities of a 96 % reduction of the extraction of primary antimony have been investigated.

Attaining this high ambition with respect to reduction of primary antimony extraction seems hard, but could be feasible by a combination of:

- An overall substitution of antimony in its end-uses of about 90 %. This requires 100 % substitution of antimony in lead-acid batteries, in its use as catalyst in the PET production, as heat stabilizer (mainly in PVC) and in its use in ceramics, 95 % substitution of antimony in antimony-containing flame retardants, 80 % substitution of antimony in its glass applications and 50 % in its application in lead alloys.
- Material efficiency measures to reduce 10 % of the antimony use that remains after 90% substitution of antimony in its applications
- A 65% antimony recycling rate from the end-of-life antimony-containing products that remain after 90 % substitution and 10% material efficiency. This requires 70 % recycling of antimony from its remaining applications in flame retardants and 75 % recycling of antimony from antimony-containing lead alloys.

The results of the various reduction steps are presented in the flow diagram of Figure 4-5.

Because the necessary measures to reduce the use of primary antimony to a sustainable level are major, we recommend further research into the following subjects:

- The assumed substitutability of antimony, especially in flame retardants, glass and lead alloys.
- The assumed material efficiency improvement of 10 %
- The feasibility of 70 % recycling of antimony from flame retardants
- The feasibility of 75 % recycling of antimony from antimony-containing lead alloys
- The economically optimal mix of measures to reduce the use of primary antimony with 96 %. Maybe recycling of antimony from flame retardants and car batteries is economically more attractive than substitution of antimony in these applications.
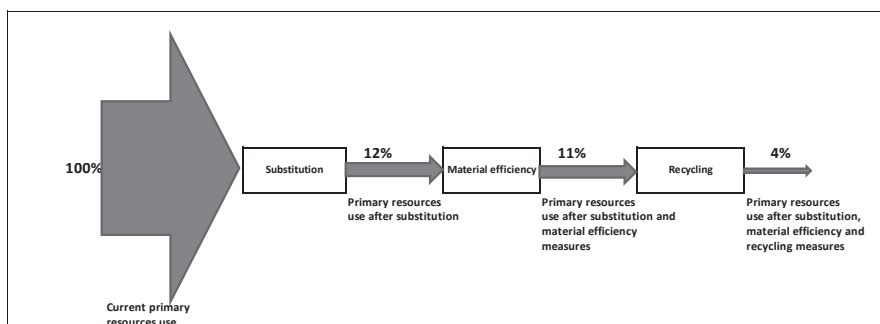
Figure 4-5 Steps for a sustainable use of primary antimony

ACKNOWLEDGMENTS

REFERENCES

Babinsky, R., 2006, PVC additives: a global review. Plast. Addit.Compd. January/February

Biron, I., Chopinet, M.H., 2013, Coloring, decolouring and opacifying of glass, Modern methods for analyzing archaeological and historical glass, vol.1, p 49-65

Booser, E.R., 1992, Bearing Materials, in: Kirk-Othmer encyclopedia of chemical technology, vol. 4, 4th ed. John Wiley&Sons, New York, p 1-21

Brown, R.D., 2001, Bismuth, in Metals and Minerals: US Geological Survey Minerals Yearbook 1999, vol.1, p 12.1-12.5

Butterman, W.C., Carlin, J.F., 2004, Mineral commodity profiles, Antimony, US Geological Survey

Carlin, J.F., 2006, Antimony recycling in the United States in 2000, USGS, 1196-Q

Cusack, P., 2007, EU flame retardant consumption 2006. In: Proceedings of the 5th International Conference on Design and Manufacturing for Sustainable Development, Loughborough University, July, p 10-11

Erickson, R.I., 1973, Crustal occurrence of elements, mineral reserves and resources, In: USGS, Professional Paper vol. 820, p21-25

European Union, Annex II of the Directive 2011/65/EU on the Restriction of the use of certain hazardous substances in electrical and electronic equipment (8-6-2011).

European Union, Directive 2012/19/EU of the European Parliament and the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE)

European Union, Directive 2008/98/EC of the European Parliament and the Council of 19 November 2008 on waste

European Union, Regulation no 305/2011 of the European parliament and of the Council of 9 March 2011 laying down harmonized conditions for the marketing of construction products and repealing Council Directive 89/106/EEC

Furlong, K., Titanium – a real alternative to antimony catalysts in PET bottles, http://www.jmcatalysts.com/pct/news2.asp?newsid=76 , 6-1-2014

Gross, R.A., Ganesh, M., Lu, W., 2010, Enzyme-catalysis breathes new life into polyester condensation polymerisations, Trends Biotechnol. 28,435-443

Henckens, M.L.C.M., Driessen, P., Worrell, E., 2014, Metal scarcity and sustainability, Analyzing the necessity to reduce the extraction of scarce metals. Resour. Conserv. Recycl. 93,1-8

Henckens, M.L.C.M., Driessen, P., Worrell, E., 2015, Towards a sustainable use of primary boron, Approach to a sustainable use of primary resources. Resour. Conserv. Recycl. 103,9-18

Keyser, C., 2009, Fire retardant global industry overview, December 14, 2009, Personal email communication with Mike Kiser, placed on internet.

Lassen, C., Lokke, S., Andersen, L.I., 1999, Brominated flame retardants – Substance flow analysis and assessment of alternatives, Danish Environmental Protection Agency, Environmental project no 494

Markarian, J., 2007, PVC additives, What lies ahead? Plast. Addit. Compd. (November/December)

May, G.J., 1992, Gelled-electrolyte lead/acid batteries for stationary and traction applications. J. Power sources, 40, 187-193

McLaren, W., 2008, Eco-tip: antimony free clothing, Living/Culture, April 9

Misra, S.S., 2007, Advances in VRLA battery technology for telecommunications. J. Power Sources, 168, 40-48

Noone, A., 2008, Collected PET bottles. In: Proceedings of the 13th International Polyester Recycling Forum

Prengaman, R.D., 1995, Lead alloys, In: Kirk Othmer Encyclopedia of Chemical Technology. 4th ed. John Wiley and Sons, New York, vol.15, pp.113-132, 2001

Rabin, A., 2001, Solders and brazing filler metals, Kirk-Othmer Encyclopedia of Chemical Technology, 4th ed., John Wiley and Sons, New York, , vol.22, pp. 482-497

Rankin, W.J., 2011, Minerals, metals and sustainability, CSIRO

Rögels T, Scheuten Glas, Venlo, The Netherlands, personal communication on 27-1-2014.

Roskill Consulting Group Limited, 2011, Study of the antimony market (October)

Roskill Information Services Ltd, 1997, The economics of antimony, 8th ed. Roskill Information Services Ltd., London, United Kingdom, 184 p., 2 appendices

Shigemoto, I., Kawakami, T., Okumura, M., 2013, A quantum chemical study on polymerization catalysts for polyesters: Catalytic performance of chelated complexes of titanium, Polymer 54, 3297-3305

Shotyk, W., Krachter, M., Chen, B., 2006, Contamination of Canadian and European bottled waters with antimony from PET containers. J.Environ.Monit. 8, 288-292

Skinner, B.J., 1976, Second iron age ahead? Am. Sci. 64,158-169

Thiele, U.K., 2009, 13th International Polyester Recycling Forum, p22-23

Thiele, U.K., 2006, Polyester catalysts: a critical analysis of current technology and available alternatives. In: The European PET conference, Barcelona, 11-12 October

Thiele, U.K., 2004, Quo vadis polyester catalyst? Chem. Fibers Int. 54 (June) 162-163

Thiele, U.K., 2001, The current status of catalysis and catalyst development for the industrial process of PET polycondensation. Int. J. Polym. Mater. 50,387-394

Toniazzo, V., 2006, The key to success: gelled-electrolyte and optimized separators for stationary lead-acid batteries, J. Power Sources 158, 1124-1132

Townsend Solutions, 2013, Plastic additives Global Market Study, 2012, cited by Flame-Retardants-on-line.com

Tri-star resources, http://www.tri-staresources.com, Antimony uses, production and prices, 2-11-2015

UNEP International Working Panel on Sustainable Resource Management, Working group on geological stocks of metals, working paper: April, 2011

US Geological Survey, 2015a, Mineral Commodity Summaries, Antimony

US Geological Survey, 2015b, Antimony Statistics

US Geological Survey, 2015c, Antimony, 2013 Minerals Yearbook, September

Yang, Y.K., Bae, S.B., Hwang, Y.T., 2013, Novel catalysts based on zirconium (IV) for the synthesis of poly(ethylene terephthalate-co-isophthalate)polyesters, Tetrahedron Lett. 54,1239-1242

Yang, Y.K., Yoon, S.W., Hwang, Y.T., Song, B.G., 2012, New titanium-based catalysts for the synthesis of polyethylene terephthalate, Bull.Korean Chem.Soc. 33(10)3445-3447

Chapter 5

Toward a sustainable rate of zinc extraction. An investigation of measures to reduce primary zinc use to a sustainable level

ABSTRACT

A comparison of the current rate of zinc extraction with the globally available resources of zinc reveals that zinc is geologically scarce. In the long term, the global rate of zinc extraction is only sustainable if it is reduced by approximately 80%, to 20% of the current rate. We investigated whether and how this would be feasible via substitution, improved material efficiency, dissipation reduction and increased recycling without losing any of the services zinc currently provides. The conclusion is that this can be achieved by a 50–70% substitution, combined with a further increase of the end-of-life recycling rate from the current 33% to 50–80% in the future.

5.1   INTRODUCTION

Zinc is important for modern economies. Its main application is the protection of steel against corrosion. Future scarcity of zinc might therefore have a substantial impact on society. The extractable global resources of zinc will be exhausted before 2100 if their extraction rates continue to increase at the current pace (Henckens et al., 2014). See Table 5-1.

Table 5-1 Geological scarcity of metals and metalloids (Henckens et al. 2014)[a]

Element	Remaining time span until depletion (years, from 2050)	Element	Remaining time span until depletion (years, from 2050)
Antimony	-9	Tin	230
Gold	6	Silver	240
Zinc	47	Lead	250
Molybdenum	52	Nickel	320
Rhenium	80	Iron	330
Copper	120	Tungsten	330
Chromium	150	Arsenic	440
Bismuth	160	Cadmium	540
Boron	200	48 other metals and metalloids [b]	>1000 years

[a] The table is based on the following assumptions:
-   The extractable global resources are 0.01% of the total amount of a metal in the top 1 km of the continental part of the earth's crust (Skinner, 1976; Rankin, 2011; Erickson, 1973; UNEP International Resources Panel, 2011a)
-   Global extraction increases by 3% annually until 2050, after which it stabilizes
[b] Includes aluminum, barium, beryllium, cobalt, gallium, germanium, mercury, lithium, magnesium, manganese, niobium, platinum group metals, rare earth metals, selenium, strontium, tantalum, titanium, thallium, uranium, vanadium, zirconium

According to our definition of the sustainable extraction of mineral resources (Henckens et al. 2014), in order to be sustainable, the extraction rate of zinc should be reduced by 82%. Technical ways to do so are substitution, material efficiency, dissipation reduction, and recycling. The purpose of this chapter is to investigate whether and—if so, how—the use of primary zinc can be reduced to about 20% of the current use, without losing any of the current services provided by zinc. After an inventory of the current applications and flows, we will investigate:

(1) The substitutability by other elements or alternative types of services
(2) The material efficiency potential
(3) The dissipation reduction potential
(4) The recycling potential

We will investigate via which combinations of the above types of technical measures an 82% reduction in zinc extraction can be achieved.

5.2   OCCURRENCE AND APPLICATIONS

Zinc ores are extracted in more than 50 countries. In 2014, total production was 13,300,000 metric tons. China (37%), Australia (12%) and Peru (10%) were the three largest zinc mining countries in that year. Data are derived from USGS (2016). The development of the world zinc production over time is presented in Figure 5-1.
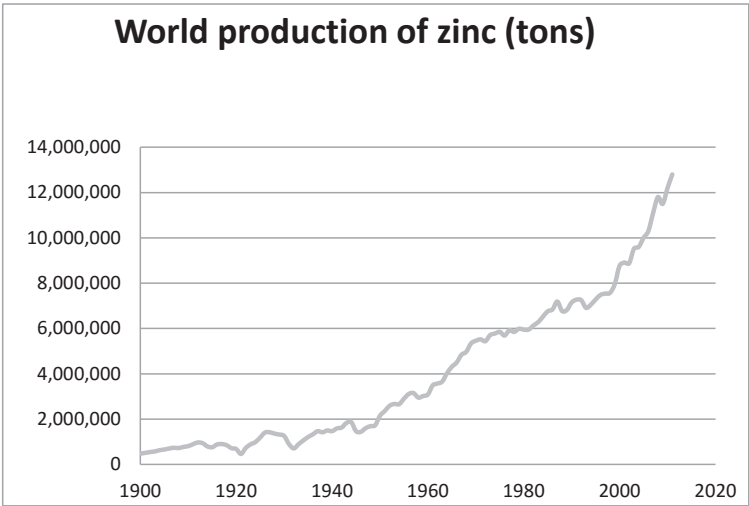
Figure 5-1 Development of zinc production (derived from USGS, 2012 b)

The major applications of zinc are presented in Figure 5-2.
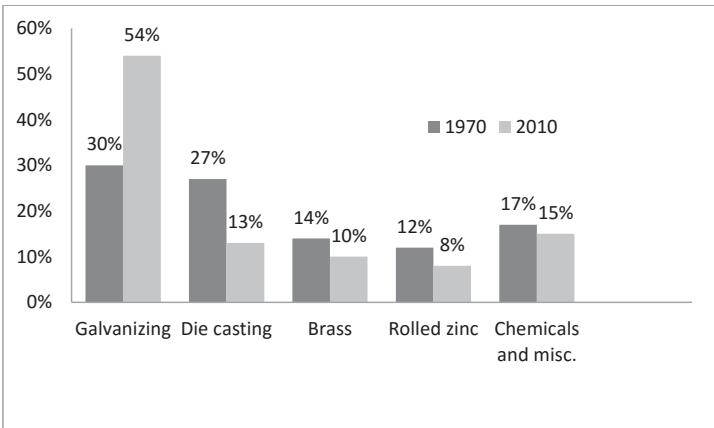
Figure 5-2 Main end uses of zinc (derived from International Zinc Association, 2014a)

Galvanizing is by far the most important application of zinc. Galvanizing provides a zinc coating on another metal, mostly steel, to protect the metal against corrosion. Zinc is more reactive than iron and will be oxidized (corroded) first until it completely corrodes away. Actually it is not zinc itself but the resulting surface layer of zinc oxide and zinc carbonate that is responsible for the protection. Application of zinc is relatively easy on many different surfaces and zinc is still a relatively cheap material. Galvanized steel can easily be coated with paint. Well known zinc applications include on highway crash barriers, on lamp posts, and on automobile bodies. The protection layer of zinc oxide is a physical barrier in itself. But if this layer is damaged, the zinc will serve as sacrificial anode and will—before steel— combine with oxygen or other reactive chemicals in the air (or water). In this way, zinc is an important element for so-called cathodic protection: for instance to protect underground pipelines and also the steel rudders, keels and propellers of ships, especially in (relatively) corrosive sea water.
The information in the above paragraph is from International Zinc Association, 2013a.

Die casting entails forcing molten metal under high pressure into a mold. Most die castings are made from non-ferrous metals, i.e. zinc-, copper-, aluminum-, magnesium-, lead-, pewter-, and tin-based alloys . Zinc die casts are used for e.g. bathroom fixtures, door and window hardware, tools, electronic components, automotive components.
The information in the above paragraph is from International Zinc Association, 2013a.

Brass and bronze are both alloys with copper as the main component and mixtures of other metals. When zinc is the main other metal, the alloy is called *brass*. Brass is a copper-zinc alloy containing 3% to 45% zinc, depending on the type of brass. Brass is more ductile and stronger than copper and has a better corrosion resistance. Therefore, uses of brass include in communication equipment, musical instruments, and water valves. Bronze is a copper-tin alloy to which zinc may be added.
The information in the above paragraph is from International Zinc Association, 2013a.

Rolled zinc has an important application as roofing, gutters, and downpipes. (International Zinc Association, 2013a).

Chemicals. Zinc is applied in chemicals as pigment (zinc oxide, zinc sulfate, and zinc sulfide), fire retardant (zinc chloride), and biocides (zinc dithiocarbamate, zinc naphthenate, zinc pyrithione). Another application of zinc oxide is as vulcanizing accelerator in rubber tires. Furthermore, zinc compounds are used as additive to livestock (swine) feed and as additive to lubricants.
The information in the above paragraph is from International Zinc Association, 2013a.

Miscellaneous. Zinc may be included in various materials such as solder and casting aid. Zinc is also used as anode material in batteries, for example in lithium batteries, in alkaline batteries and in zinc–air batteries. Zinc products are used in blasting grit.
The information in the above paragraph is from International Zinc Association, 2013a.

5.3   CURRENT ZINC FLOWS

Much work on analyzing the anthropogenic zinc cycle has been done in the framework of the Stocks and Flows project at Yale University. This project aimed at quantifying global, regional, and national amounts of metals mined, refined, fabricated, and manufactured. (Graedel et al., 2005 and Graedel and Cao, 2010).

5.3.1   *Zinc losses during mining, melting, fabrication, and manufacturing of zinc*

The purpose of the first processing steps of metal ores is enrichment. These steps typically consist of milling, grinding, and flotation. If the ore consists of metal sulfides, as is the case with zinc, the next step is roasting, in which the metal sulfide is oxidized to metal oxide. In the literature, the data on losses of zinc during primary zinc production and processing vary. According to James et al. (2000), referred to by Gordon et al. 2003), the average zinc losses in the enrichment steps (tailings) are 5% and during the roasting process another 7% (slag), so in total are 12% (Gordon et al., 2003). According to Guo (2010), zinc losses in tailings and smelting slag in China in 2006 totaled about 15%. According to Plachy (2000), the processing losses of zinc during domestic zinc production in the USA in 1998 were about 10%. Meylan and Reck (2016) provide a more comprehensive global picture: compared to the quantity of primary zinc extracted from the earth's crust, the quantities lost during the various steps from mining until manufacturing total 19% (tailings: 13%, slag: 5%, losses during fabrication and manufacturing: 1%). We use the figures of Meylan and Reck (2016) in our calculations.

5.3.2   *Dissipation*

Compared to other metals, a relatively large part of zinc use is dissipative because of the nature of the use. This is especially the case for zinc in chemicals (i.e. pigments, animal feed, rubber) and zinc used for the protection of steel against corrosion. The zinc runoff from die casts and from brass and bronze objects is very small. Die casts are usually not exposed to wet situations. Zinc in brass and bronze objects is not concentrated on the metal surface but is distributed throughout the metal object.

The zinc emission from rolled zinc (i.e. used on roofs and in gutters), expressed in grams per square meter, is comparable to the zinc emission from exposed galvanized products. But the zinc in rolled zinc is much thicker (10-50 x) than the zinc on galvanized products. Therefore, zinc dissipation from rolled zinc is negligible compared to the dissipation from galvanized products. We will therefore focus on dissipation from zinc-containing chemicals and from galvanized products.

Zinc dissipation from products with zinc-containing chemicals
The most important applications of zinc-containing chemicals are presented in Table 5-2. The total amount of zinc in these applications was about 15% of total zinc use in 2010 (International Zinc Association, 2014a). This proportion differs per country, as well as per sub-application. Zinc in swine feed will be completely dissipated in the environment via swine manure. Rubber

Table 5-2 Applications of zinc-containing chemicals and the most important routes of zinc at the end-of-life stage. The estimates are the author's, unless indicated otherwise.

	Percentage of zinc in zinc-containing chemicals (%) (derived from Annema and Ros (1994)	Dissipation through usage	Disposal of EoL products (landfill or incineration)	Recycling
Pigment		0%	100%	
Fire retardant		0%	100%	
Biocide, fungicide for potatoes		100%		
Oil additive in lubricating oil	10%	100%		
Blasting grit		Little		Most
Vulcanizing accelerator for rubber tires	6%	8%	92%	
Additive in swine feed	14%	100%		
Zinc anodes		Little		Most
Other applications (solder, casting aid, batteries)		Little		Most
Total zinc in zinc-containing chemicals	100%			

tires contain an average of 1.6 weight% of zinc. This will be partly lost to the environment by tire wear. Based on data from Vos and Janssen (2008) it can be calculated that the average Zn emission from rubber tires due to wear is about 8% of the total zinc content in tires.

Based on these data, we estimate the total dissipation of zinc from zinc-containing chemicals during usage is in the order of 25% (i.e. the applications in biocides, in lubricating oil, in tires, and in swine feed).

Zinc dissipation from galvanized products

Estimates of the zinc runoff rate from exposed zinc surfaces vary. Japanese researchers estimate the yearly runoff rate at about 2% on the basis of the total weight of the zinc layer (Tabayashi et al. 2009). On the basis of a study by Wallinder et al. (1998), the Netherlands Centre for Water Management (2008) in its report on the atmospheric corrosion of galvanized steel and sheet zinc provides the following formula for zinc runoff from horizontal surfaces that are exposed to rain, assuming the average SO_2 concentration in the air: zinc runoff rate (g/m^2/year) = 1.36 + 0.164 x $[SO_2](\mu g/m^3)$. This Zn runoff rate still needs to be corrected for spatial orientation of the objects. Measurements by Mourik et al. (2003) show that the runoff rate from horizontal zinc surfaces is almost four times higher than that from vertical surfaces. The average correction factor in the Netherlands is 0.84. Assuming the current average SO_2 concentration of 2 $\mu g/m^3$ (National Institute for Public Health and Environment (2012), this leads to an average zinc runoff rate of 1.7 g/m^2/year. Assuming the average amount of zinc on galvanized products is 200 g/m2 (based on data from the International Zinc Association (2014b)), this leads to the conclusion that the zinc dissipation from exposed galvanized products is about 1 weight% per year, which is half the estimate of Tabayashi et al. (2009). This discrepancy may be due to differ-

ent assumptions about the extent of exposure to rain, to a different amount of zinc per m^2 or to different conditions (acidity and salt content of rain). Note that not all galvanized products are exposed, and those that might be are not exposed continuously.

Dissipation summarized

According to Meylan and Reck (2016), zinc dissipation in 2010 was about 8 weight% of the total amount of zinc entering the usage phase in 2010. Assuming a dissipation of 25% of zinc in chemicals and other miscellaneous use and 0% zinc dissipation from die casts, brass, bronze, and rolled zinc, this leads to the conclusion that the zinc dissipation from galvanized products must be about 8 weight%. This is a plausible result in view of the above considerations on zinc dissipation from galvanized steel. If we assume the average lifetime of galvanized products is 20 years, 25% of the galvanized products are exposed and annual dissipation is 1.5 weight%, then the total annual loss from galvanized products is 7.5 weight percent. The results are presented in Table 5-3.

Table 5-3 Zinc dissipation from various zinc applications. The usage proportions are from the International Zinc Association (2014a). Total end-use in 2010 is 12.9 million tons (International Zinc Association, 2013b) and normalized at 100 units.

	2010 usage of Zn total = 100	zinc dissipation through usage	remaining zinc after dissipation
	(units)	(%)	(units)
Galvanizing	54	8%	50
Die casts	13	0%	13
Brass and bronze	10	0%	10
Rolled zinc	8	0%	8
Chemicals + misc.	15	25%	11
Total	100	8%	92

5.3.3   Zinc to the anthropogenic stock

In Japan, the average lifetime of zinc-containing products is about 30 years in construction and in buildings, and about 10 years in machinery (Yokota et al., 2003). In emerging economies like China and India, the economy is growing so fast that the input of zinc to the anthropogenic stock is still much larger than the output in end-of-life products. In industrialized countries like Japan, the build-up anthropogenic stock has nearly stabilized (Tabayashi et al. 2009). At a global scale, however, the anthropogenic stock of zinc is still growing. For 2010 it was estimated at almost 40% of the quantity of zinc entering the use phase (Meylan and Reck, 2016). In the further future, it can be expected that global anthropogenic stocks will gradually stabilize and that there will be equilibrium between the zinc flow into the usage phase and the flow out of the usage phase (by dissipation and in end-of-life products).

5.3.4 Zinc recycling

Until recently, zinc recycling concentrated on die casts and rolled zinc, which are almost completely recycled. We shall assume a 90% end-of-life zinc recycling rate from die casts and rolled zinc (International Zinc Association, 2013b, Van Beers et al. 2007). Until relatively recently, zinc was hardly recycled from galvanized products. However, this is now changing, due to improved de-zincing technologies for steel scrap and hydro-metallurgical leaching of zinc from Electric Arc Furnace dust. Zinc recycling from galvanized steel will depend on the collection rate of end-of-life galvanized steel products and the zinc recovery from these products

Brass and bronze are almost completely recycled due to their valuable copper content. If not remelted to brass or bronze, zinc moves to the dust phase. However, dusts from the copper industry are not (directly) suitable for application in the primary zinc industry, because of their halogen content. Currently, zinc in brass and bronze remains in the copper cycle. (Antrekowitsch et al., 2014, Tabayashi, 2009). Recycling of zinc from zinc-containing chemicals is difficult, because of the low concentrations (pigment) or because of the inherent dissipative use (in swine feed, fungicide). Theoretically, zinc could be recovered from applications in anodes, tires, batteries and solder. However, we assume that zinc recycling from chemicals is 0%.

Zinc recycling data vary. According to recent data on the website of the International Zinc Association (2013 b) the overall/global end-of-life recycling rate of zinc is 60%. Graedel et al. (2005) quantified recycled zinc flows from end-of-life products in 1994 at 41%. In a later article by Graedel et al. (2011), the end-of-life recycling rate of Zn is estimated to be >50%. This is similar to the figure provided by UNEP, 2011. However, Meylan and Reck (2016) estimate a global EoL recycling rate of only 33% in 2010. The recycling rates vary regionally: Asia 24%, Europe 46%, Latin America 35%, North America 42%, and China 21% (Meylan and Reck, 2016). Spatari et al. (2003) also provide an end-of-life recycling rate of 34%. For the actual situation, we use the data from Meylan and Reck (2016), assuming a global end-of-life zinc recycling rate of 33%.

Assuming an overall zinc recycling rate of 33%, 90% zinc recycling rate from die casts and from rolled zinc and 0% recycling of zinc from chemicals, the estimated current zinc recycling from galvanized products is currently about 30%. For this calculation it was assumed that the distribution of the zinc in the anthropogenic stock is equal to the distribution of zinc in its original applications, excluding dissipative zinc applications in chemicals and miscellaneous (see Table 5-4).

5.3.5 Current zinc flows summarized

The figures provided in this section result in the zinc flow diagram presented in Figure 5-3.

The question now is how to achieve the sustainability goal of an 82% reduction of the primary zinc inflow. In Figure 5-3 this means that the inflow of primary zinc should be reduced from the current 103 units, representing primary zinc, to less than 0.18*103 = 19 units in a situation of sustainable zinc extraction.

The extent to which substitution, material efficiency, dissipation reduction, and improved recycling can contribute to reduce the use of primary zinc is discussed below.

Table 5-4 Current zinc recycling rates of end-of-life zinc products and the resulting quantity of secondary zinc

	Zinc in end-of-life products (units after dissipation, see Table 5-3)	Zinc to anthropogenic stock (40%, see section 5.3.3)	Remaining zinc in end-of-life products	Current zinc recycling rate from end-of-life products	Secondary zinc from end-of-life products
	Units	units	units	%	units
Galvanized products	50	23	26	30%[a]	8
Die casts	13	6	7	90%	6
Brass and bronze	10	5	5	0%	0
Rolled zinc	8	4	4	90%	4
Chemicals + misc.	11	0	11	0%	0
Total	92	38	54	33%	18

[a] Percentage calculated by the author
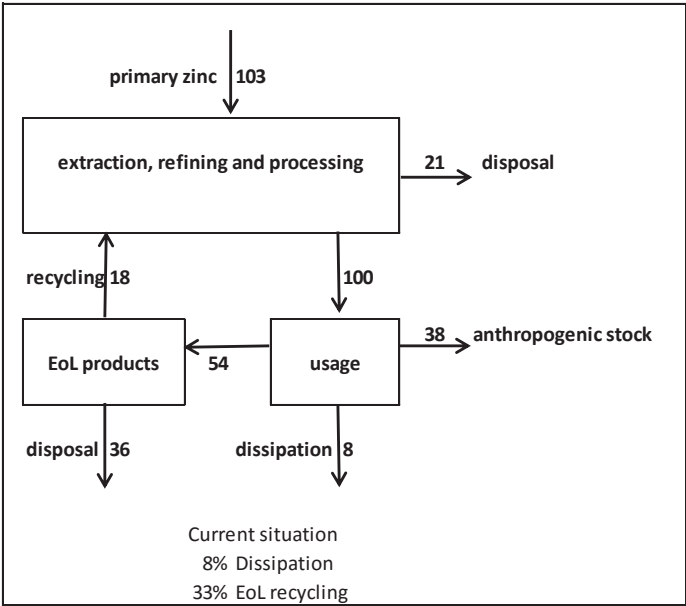
Figure 5-3 Diagram of zinc flows in 2010. Current zinc use has been normalized at 100 units. Total primary zinc production in 2010 was about 14 million tons (USGS, 2012b)

5.4   SUBSTITUTABILITY OF ZINC

General

There is an abundance of literature on zinc recycling and its potential, but systematic and quantitative research of the substitutability of zinc in its various applications is limited. Substitutability is used as one of the indicators for measuring the vulnerability of society to scarcity of a mineral. In the study by Oakdene Hollins and Fraunhofer (2014) in a report in the framework of the EU Raw Materials Initiative, the substitutability of various mineral resources in different applications was scored by experts on a scale from 0 to 1. The possible values for substitutability were:

0.0 Easily and completely substitutable
0.3 Substitutable at low cost
0.7 Substitutable at high costs and/or loss of performance
1.0 Not substitutable

The substitutability score of zinc in the report is as follows:
Galvanizing: 0.7
Brass and bronze: 0.5
Zinc-based alloys: 0.7
Zinc in chemicals: 1.0

Substitution of zinc in galvanizing

According to the US Geological Survey (2013a), galvanized steel can be substituted by aluminum, stainless steel, and plastics. Plastic coatings, paint, and aluminum alloy coatings are zinc substitutes for corrosion protection. In 1994, Annema and Ros estimated that 20% of galvanized steel can be adequately replaced by products with an equal performance. A literature search revealed no further quantitative data on the substitutability of zinc as a steel protector.

Substitution of zinc in die casts

According to the US Geological Survey (2013a) aluminum, plastics, and magnesium are competitors for die casting materials based on zinc. For a number of applications, substitutability may be 100%, e.g. in bathroom appliances, door and window hardware, and tools. The substitutability of zinc in other zinc-based die cast products (e.g. in certain electronic components) may be more difficult. Searching the scientific literature yielded no figures on the substitutability of die cast products based on zinc.

Substitution of zinc in brass and bronze

Although according to US Geological Survey (2013a) aluminum alloys can be used in place of brass, no quantitative data could be found on the substitutability of brass and bronze.

Substitution of zinc in its application as rolled zinc
According to Annema and Ros (1994) rolled zinc can be 100% replaced by other materials such as aluminum and plastics.

Substitution of zinc in chemicals and miscellaneous substances
Substitutability varies per application. In lubricants and as fungicide 100% substitution is possible(Annema and Ros,1994). According to USGS (2013a) "many elements are substitutes for zinc in chemical, electronic, and pigment uses". Zinc anodes are 100% substitutable by aluminum anodes and/or magnesium anodes (derived from data from Roovaart and van Duijnhoven, 2007). On the other hand, the application of zinc in batteries is increasing rapidly and there is no substitute for zinc as a feed additive.

The substitutability of zinc is not static: it will depend partly on the costs of primary and secondary zinc compared to the costs of the substitutes, partly on technological developments, and partly on society's environmental protection requirements.

5.5   MATERIAL EFFICIENCY

Zinc losses during the primary production and processing are about 20%. These losses could be reduced (e.g. by improving the flotation process, and by chemical recovery of zinc from tailings and slag). However, the material efficiency gains of such measures need to be economically balanced with their costs. This is not a static situation. The higher the price of primary zinc, and the lower the costs of material efficiency measures, the more attractive it will be to further reduce zinc losses during primary production and processing. The potential improvement of the primary enrichment steps, together with the exploitation of lower grade zinc ores will need to be determined on a case-by-case basis, taking into consideration both technological developments and economic considerations. Furthermore, in general, the following methods contribute most to material efficiency (Allwood, 2013):
-    Minimizing the amount of material in products, and lightweight design
-    Extending product lifetimes
-    Shared use of products
Given the types of zinc applications, lightweight design probably does not have much material efficiency potential in the case of zinc. The other methods mentioned would be applicable for zinc. We have, prudently, assumed an overall material efficiency potential of 10% on top of the dissipation reduction and recycling measures that will be further elaborated in sections 5.6 and 5.7 (Henckens et al., 2015).

5.6   REDUCTION OF ZINC DISSIPATION DURING USAGE

Zinc dissipation from galvanized products can be reduced by covering the galvanized products with an organic coating, or, depending on the requirements and circumstances, by replacing zinc by another coating. According to Sullivan and Worsley (2002), organic coatings are very effective in reducing zinc dissipation from galvanized steel (>90% reduction to < 0.25 g/m2 over 16 months). Research by Gouman (2004) also results in the conclusion that a > 90% reduction in zinc dissipation could be achieved by covering galvanized surfaces with an impermeable plastic coating. Hence, adequately protecting galvanized products by a plastic coating can reduce total zinc runoff from galvanized products from 8% to < 1%. The zinc runoff from rolled zinc, die casts, brass, and bronze is negligible.

As for zinc-containing chemicals, we assume that zinc dissipation cannot be further reduced, except by substituting for zinc.

5.7   IMPROVED RECYCLING OF ZINC-CONTAINING PRODUCTS

Since the current recycling rate of die casts and rolled zinc is already high, the focus will be on recycling of zinc from galvanized steel and from brass and bronze. We will assume that the zinc recycling rates from the other types of zinc applications stay at the current level indicated in Table 5-4. A small contribution to zinc recycling could be provided by recycling zinc from the ash from incinerated rubber tires (Martin et al. 2001). However, we do not take this into account in the calculations below, because the amounts that could be potentially recovered in this way are relatively small, though not negligible (less than 1% of total zinc use)

The current recycling rate of zinc from galvanized steel is estimated at 30%. See section 5.3.4. Galvanized steel scrap is usually recycled to Electrical Arc Furnaces (EAF), in which new steel is produced. The zinc that is contained in steel scrap is mainly "gassed off" and concentrated in the so-called EAF dust. A relatively small part of zinc is contained in slag from steel production. EAF dust contains an average of about 20% of zinc according to USGS (1998), Jha et al. (2001), Nakajima et al. (2003), Antrekowitsch et al. (2014), Spatari et al. (2003), and Ma et al. (2011). Dust from the copper and brass industry may contain more than 40% zinc (Antrekowitsch, 2014). Both the zinc in EAF dust and the zinc from recycling brass and bronze can be completely recycled. EAF dust can be recycled in the so-called Waeltz process, resulting in Waeltz oxide containing more than 40% zinc, which can be used for zinc oxide production or to produce zinc metal or zinc alloys (Spatari 2003). Zinc from recycled brass and bronze contains halogens. Because primary zinc production (electrowinning) is very sensitive to the presence of halogens, to become suitable for application in the zinc production, the zinc in flue dust from the copper industry needs separate hydrometallurgical or pyro metallurgical treatment (Antrekowitsch et al., 2014). Hence, actually, zinc in recycled brass and bronze remains in the copper cycle and is not recycled to the zinc cycle. An alternative to zinc recovery from

EAF dust is to de-zinc steel scrap into two fractions before steel refining: clean steel and zinc-containing caustic liquid (USGS 1998).

Summarizing, technically, zinc in galvanized steel and brass and bronze is completely recyclable. For economic reasons (low landfill costs, and low costs of primary zinc), zinc recycling from galvanized steel at a global scale is still limited. Though recycling of zinc from waste incineration residues is technically possible, it is not economically viable (Fellner et al., 2015, Shen and Forssberg, 2003). By using specific hydrometallurgical and pyro metallurgical processes, zinc can practically always be recovered from any industrial waste or end-of-life products (Rabah and El-Sayed, 1995, Jha et al., 2001, Basir and Rabah, 1999). However, so far, the economic viability has been questionable, although in future, zinc recycling may increase if and to the extent that zinc prices increase e.g. due to increasing scarcity of zinc.

We shall consider three recycling scenarios for zinc in galvanized steel: (1) the current recycling rate (with 30% zinc recycling from galvanized steel and 0% recycling of zinc in brass and bronze back to the zinc cycle), (2) a medium recycling scenario (50% zinc recycling from galvanized steel and 50% zinc recycling from brass and bronze back to the zinc cycle) and (3) a high recycling scenario (80% zinc recycling from galvanized steel and 80% zinc recycling from brass and bronze back to the zinc cycle). Zinc recycling from die casts and rolled zinc remains 90% in all three scenarios.

5.8   ALTERNATIVE SCENARIOS

The goal is for the extraction of primary zinc to be reduced by 82% to achieve sustainable zinc extraction. Figure 5-3 shows that this means it is necessary to reduce the current 103 units of primary zinc use to less than 19 units of primary zinc use in the future. In this section we shall examine the potential zinc extraction reduction rates by combining three substitution scenarios with three recycling scenarios.

The three substitution scenarios considered are: (1) a low zinc substitution scenario (20% substitution), (2) a medium zinc substitution scenario (50% substitution) and (3) a high zinc substitution scenario (70% substitution). Table 5-5 shows how these three different substitution outcomes could possibly be reached. In line with the data provided by Oakdene Hollins and Fraunhofer (2014), we have assumed that substitution for brass and bronze is easier than substitution for galvanizing and die casts. Following Annema and Ros (1994) we have assumed that rolled zinc can easily be substituted. Research will be needed to determine the technical and financial modalities of the three scenarios.

We combine the three substitution scenarios with three recycling scenarios. We will assume that dissipation reduction and recycling of the distinct zinc applications can be kept at the same level in all substitution scenarios. We have calculated the outcome of the various sce-

Table 5-5 Three zinc substitution scenarios

	Zinc applications in 2010	Substitution scenario		
		Low	Medium	High
Galvanized products	54	15%	50%	70%
Die casts	13	15%	50%	70%
Brass and bronze	10	30%	60%	90%
Rolled zinc	8	90%	90%	90%
Chemicals and miscellaneous	15	0%	25%	45%
Total/average	100	20%	50%	70%

narios with and without material efficiency measures (10% reduction in use), and with and without reducing dissipation of zinc from galvanized products (Table 5-6).

The calculations concern the future. The benchmark situation is a steady state without further accumulation of zinc in the anthropogenic stock . In the industrialized part of the world, this is probably already pretty close to reality, zinc consumption having more or less stabilized and in the process of becoming decoupled from a further growing GDP. See Halada et al. (2008) and Meylan and Reck (2016).

Table 5-6 Extraction reduction scenarios for primary zinc, assuming a steady-state situation (no further accumulation of zinc in the anthropogenic stock, the same zinc applications in the same proportion as currently). The numbers represent the reduction of primary zinc use compared to the 2010 primary zinc use represented in Figure 5-3. For details, see the Supplementary information (m.e. = material efficiency; d.r.= dissipation reduction)

	Current zinc recycling rates (30% zinc recycling from galvanized steel, 0% zinc recycling from brass and bronze)	Medium recycling scenario (50% Zn recycling from galvanized steel, brass, and bronze)	High recycling scenario (80% Zn recycling from galvanized steel, brass, and bronze)
No substitution, no m.e., no d.r. measures	19%	37%	59%
20% substitution, no m.e., no d.r. measures	31%	46%	64%
20% substitution + 10% m.e. + d.r.	39%	53%	70%
50% substitution, no m.e., no d.r. measures	57%	65%	76%
50% substitution + 10% m.e. + d.r.	62%	70%	80%
70% substitution, no m.e., no d.r. measures	74%	78%	84%
70% substitution + 10% m.e. + d.r.	77%	81%	87%

With regard to the outcome of the various combinations in Table 5-6, the following observations can be made:
- Stabilization of the anthropogenic stock as such results in a relative extraction reduction of 19% compared to 2010, without any further measures being taken.
- The required 82% reduction requirement is achievable only in the high recycling scenario in combination with 70% zinc substitution with or without improved material efficiency or measures to reduce dissipation from galvanized steel.

Figure 5-4 represents the resulting zinc flows of the 50% substitution–high recycling scenario including 10% material efficiency measures and 6% dissipation reduction. In this scenario, the total reduction in zinc extraction is 80% compared to the level of zinc extraction in 2010.
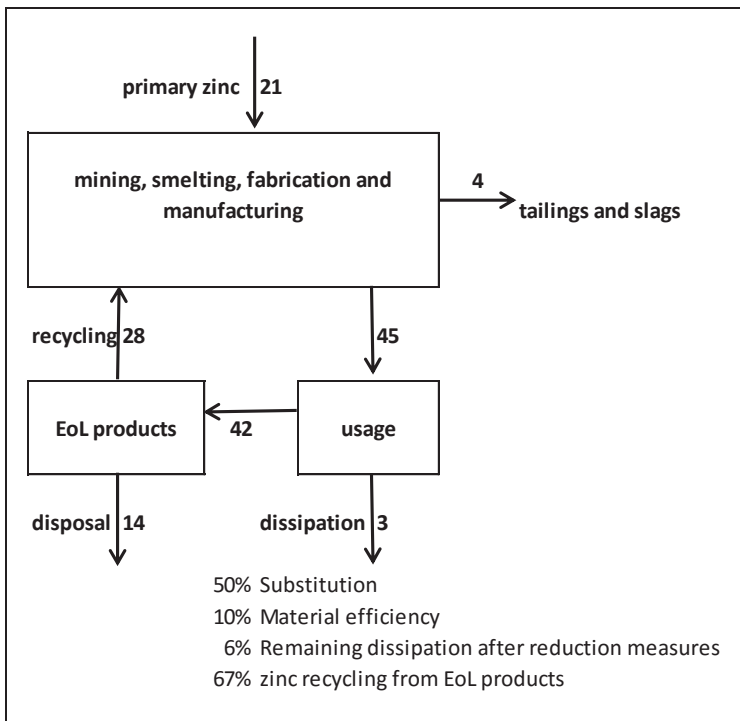
Figure 5-4 Future zinc flows in a medium substitution–high recycling rate scenario with a total reduction of primary zinc use of 84% compared to the 2010 use of primary zinc. There is no further build-up of the anthropogenic stock of zinc.

5.9   CONCLUSIONS, DISCUSSION, AND RECOMMENDATIONS

Technically, various reduction scenarios are imaginable to reduce the use of primary zinc and to achieve a sustainable production. The optimum scenario will depend on economic and

environmental factors. The various reduction steps of the zinc reduction scenario with 50% substitution and 67% zinc recycling from EoL products are represented in Figure 5-5.

No further build up of anthropogenic stock | Substitition | Material efficiency measures (10 %) | Dissipation reduction 8 % --> 4 % | Recycling 33 % --> 67 %

100%   80%   43%   38%   37%   20%
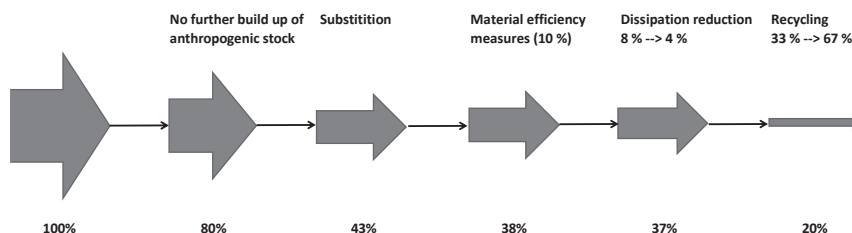
Figure 5-5 Steps to reduce zinc use, in order to achieve sustainable extraction. Point of departure is the 2010 use of primary zinc. For details, see the Supplementary Information.

Zinc is part of metal scrap and needs to be recycled to a high extent. This means that in future, attention will need to be paid to further optimizing scrap processing to retrieve geologically scarce metals, such as zinc. Whether this is realized will mainly depend on the profitability of the measures required. This will depend on the price of secondary zinc compared to the price of primary zinc. If the market hampers replacement of primary metal by secondary metal, the question arises of whether regulatory measures need to be implemented in order to promote the use of secondary zinc and to keep this metal sufficiently available for future generations.

Recommendations derived from this chapter are:
- To undertake further research into the substitutability of zinc.
- To investigate how scrap recycling technology can be further improved in view of recycling zinc.
- To investigate which policy measures could be taken to increase the price of primary zinc artificially.

REFERENCES

Allwood, J.M., 2013, Transitions to material efficiency in the UK steel economy. Phil.Trans.R.Soc.A 371,20110577, 28-1-2013

Annema, J.A., Ros, J., 1994, Management of the zinc chain. Resour. Conserv. Recycl. 13, 209-219

Antrekowitsch, J., Steinlechner, S., Unger, A., Rösler, G., Pichler, C., Rumpold, R., 2014, Zinc and residue recycling. In: Cht 9 of Handbook of Recycling, edited by Ernst Worrell and Markus A.Reuter

Basir, S.M.A, Rabah, M.A., 1999, Hydrometallurgical recovery of metal values from brass melting slag. Hydrometallurgy 53, 31-44

Erickson, R.L., 1973, Crustal occurrence of elements, mineral reserves and resources. USGS, Professional Paper 820, p21-25

Fellner, J., Ledere, J., Purgar, A., Winterstetter, A., Rechberger, H., Winter, F., Laner, D., 2015, Evaluation of resource recovery from waste incineration residues – The case of zinc. Waste Manage. 37, 95-103

Gordon, R.B., Graedel, T.E., Bertram, M., Fuse, K., Lifset, R., Rechberger, H., Spatari, S., 2003, The character-ization of technological zinc cycles. Resour. Conserv. Recycl. 39, 107-135

Gouman, E., 2004, Reduction of zinc emissions from buildings; the policy of Amsterdam. Environmental Services Department of the City of Amsterdam. Water Sci. Technol. 49 (3) 189–196

Graedel, T.E., Allwood, J., Birat, J-P, Buchert, M., Hagelüken, C., Reck, B.K., Sibley, S.F., Sonnemann, G., 2011, What do we know about metal recycling? J. Ind. Ecol.,0(0)1-12

Graedel, T.E., van Beers, D., Bertram, M., Fuse, K., Gordon, R.B., Gritsinen, A., Harper, E.M., Kapur, A., Klee, R.J., Lifset, R., Memon, L., Spatari, S., 2005, The multilevel cycle of anthropogenic zinc. J. Ind. Ecol. 9 (3) 67-90

Graedel, T.E., Cao, J., 2010, Metal spectra as indicators of development. Proc. Natl. Acad..Sci. USA 107, 20905-10

Guo, X., Zhong, J., Tian, Q., 2010, Substance flow analysis of zinc in China. Resour. Conserv. Recycl. 54 171-177

Halada, K., Shimada, M., Ijima, K., 2008, Decoupling status of metal consumption from economic growth. Mater. Transact., 49 (3) 411-418

Henckens, M., Driessen, P., Worrell, E., 2015, Towards a sustainable use of primary boron, Approach to a sustainable use of primary resources. Resour. Conserv. Recycl. 103, 9-18

Henckens, M.L.C.M., Driessen, P.P.J., Worrell, E, 2014, Metal scarcity and sustainability, analyzing the necessity to reduce the extraction of scarce metals. Resour. Conserv. Recycl. 93, 1-8

International Zinc Association (http://www.zinc.org/basics/zinc_statistics , 9-02-2014a

International Zinc Association, Zinc coatings protecting steel, www.zinc.world, 25-2-2014b

International Zinc Association, Zinc recycling, closing the loop, (www.zinc.org 4-6-2013 b

International Zinc Association, www.zinc.org 30-5-2013 a

James, S.E. 2000, Zinc production – A survey of existing smelters and refineries. In Dutrizac et al. editors. Lead zinc 2000. Warrendale:TMS, pp. 205-225

Jha, M.K., Kumar, V., Singh, R.J., 2001, Review of hydrometallurgical recovery of zinc from industrial wastes. Resour. Conserv. Recycl. 33, 1-22

Ma, H., Matsubae, K., Nakajima, K., Tsai, M., Sha, K., Chen, P., Lee, C., Nagasaka, T., 2011, Substance flow analysis of zinc cycle and current status of electric arc furnace dust management for zinc recovery in Taiwan. Resour. Conserv. Recycl. 56, 134-140

Martin, D., Garcia, M.A., Diaz, G., 2001, Zinc recovery from tire ashes, Recycling and reuse of used tires. In: Proceedings of the International Symposium, University of Dundee, 19-20 March

Meylan, G., Reck, B.K., 2016, The anthropogenic cycle of zinc: status quo and perspectives. Resour. Conserv. Recycl. http://dx.doi.org/10.1016/j.resconrec.2016.01.006

Nakajima, K., Matsubae-Yokoyama, K., Nakamura, S., Itoh, S., Nagasaka, T., 2003, Substance flow analysis of zinc associated with iron and steel cycle in Japan, and Environmental Impact Assessment of EAF dust Recycling Process. Resour. Conserv. Recycl. 39,137-160

National Institute for Public Health and the Environment, 2012, Large-scale concentration and deposition maps for The Netherlands (Rijksinstituut voor Volksgezondheid en Milieu, Grootschalige concentra-tie- en depositiekaarten Nederland, Rapportage 2012)

Netherlands Centre for Water Management, 2008, Atmospheric corrosion of galvanized steel and sheet zinc, June

Oakdene Hollins, Fraunhofer, 2013, Study on critical raw materials at EU level, a report for DG Enterprise and Industry of the European Commission, 16 December

Plachy, J., 2001, Zinc Recycling in the United States in 1998. US Geological Survey Circular 1196-D

Rabah, M.A., El-Sayed, A.S., 1995, Recovery of zinc and some of its valuable salts from secondary resources and wastes, Hydrometallurgy 37, 23-32

Rankin, W.J., 2011, Minerals, metals and sustainability, CSIRO

Roovaart, J.C., van Duijnhoven, N., 2007, Zinkanodes binnenscheepvaart, Emissieschattingen diffuse bronnen, Werkdocument nr. 201.088X, 7, RIZA,

Shen, H., Forssberg, E., 2003, An overview of recovery of metals from slags, Waste Management 23, 933-949

Skinner, B.J., 1976, A second iron age ahead? American Scientist 64, 158-169

Spatari, S., Bertram, M., Fuse, K., Graedel, T.E., Shelov, E., 2003, The contemporary European zinc cycle: 1-year stocks and flows. Resour. Conserv. Recycl. 39, 137-160

Sullivan, J.H., Worsley, D.A., 2002, Zinc runoff from galvanized steel materials exposed in industrial/ marine environment, British Corrosion Journal 37 (4) 282-288

Tabayashi, H., Daigo, I., Matsuno, Y., Adach, Y., 2009, Development of a dynamic substance flow model of zinc in Japan, ISIJ International 49 (8) 1265-1271

UNEP International Panel on Sustainable Resource Management, Working Group on Geological Stocks of Metals, Working Paper, April 6, 2011a

UNEP International Resource Panel, Recycling rates of metals, a status report, 2011

USGS 2011 Mineral yearbook, Zinc, 2012 a

USGS 2012, Zinc statistics, modification October 25, 2012 b

USGS website http://minerals.usgs.gov/minerals/pubs/commodity/zinc/zinc_mcs05.pdf, 2013 a

USGS, Zinc recycling in the United Sates in 1998

Van Beers, D., Kapur, A., Graedel, T.E., 2007, Copper and zinc recycling in Australia: potential quantities and policy options, J. Cleaner Prod. 15, 862-877

Van Mourik, W., van der Mijle Meijer, H.J., van Tilborg, W.J.M., Teunissen, R.J.M., 2003, Emissions of building materials: determining leaching rates based on experimental measurements. National Institute of Water Management and Wastewater Treatment, RIZA report 2003, 027, ISBN 9036956412, November

Vos, J.H., Janssen, M.P.M., 2008, EU-wide control measures to reduce pollution from WFD relevant substances, Copper and zinc in the Netherlands, RIVM, Report 607633002

Wallinder, O., Verbiest, P., He, W., and Leygraf, C., 1998, The influence of patina and pollutant levels on the runoff rate of zinc from roofing materials, Corros. Sci. 40 (11) 1977-1982

Yokota, K., Matsuno, Y., Yamashita, M., Adachi, Y., 2003, Int. J.LCA 8, 129

Chapter 6

Toward a sustainable extraction rate of molybdenum

ABSTRACT

Comparing the current extraction rate of molybdenum with the globally extractable resources of molybdenum reveals that molybdenum is geologically scarce. Its global extraction rate becomes sustainable only if it is reduced to approximately 20% of the current rate. We investigated whether and how it would be feasible to achieve this goal through substitution, improved material efficiency, dissipation reduction, and increased recycling, without losing any of the services currently provided by molybdenum. The conclusion is that to attain the sustainability goal it will be necessary to increase the end-of-life recycling from the current rate of 20% to 87%. This is only possible if steel scrap recycling includes molybdenum recycling in its processing strategy.

6.1 INTRODUCTION

The extractable resources of molybdenum are relatively scarce. Molybdenum is essential for the production of stainless steel. Future scarcity of molybdenum might therefore have a substantial impact on society. The extractable global resources of molybdenum would be exhausted by 2100 if the molybdenum extraction rate continues to increase at the current pace (Henckens et al., 2014). See Table 6-1.

Table 6-1 Geological scarcity of metals and metalloids (Henckens et al. 2014)[a]

Element	Years until depletion, relative to 2050	Element	Years until depletion, relative to 2050
Antimony	-9	Tin	230
Gold	6	Silver	240
Zinc	47	Lead	250
Molybdenum	52	Nickel	320
Rhenium	80	Iron	330
Copper	120	Tungsten	330
Chromium	150	Arsenic	440
Bismuth	160	Cadmium	540
Boron	200	48 other metals and metalloids [b]	>1000 years

[a] The table is based on the following assumptions:
- The extractable global resources are 0.01% of the total amount of a mineral resource in the top 1 km of the continental part of the earth's crust (Skinner, 1976; Rankin, 2011; Erickson, 1973; UNEP International Resources Panel, 2011a)
- Global extraction increases by 3% annually until 2050, after which it stabilizes

[b] Includes aluminum, barium, beryllium, cobalt, gallium, germanium, mercury, lithium, magnesium, manganese, niobium, platinum group metals, rare earth metals, selenium, strontium, tantalum, titanium, thallium, uranium, vanadium, zirconium

We have defined the sustainable extraction of mineral resources as follows. *The extraction rate of a mineral resource is sustainable if a world population of 9 billion can be provided with that material for a period of at least 1000 years, assuming that the average per capita consumption of the mineral resource is equally divided over the world's countries.* For a sustainable extraction of molybdenum, its extraction should be reduced by 81% (Henckens et al. 2014).

Technical ways to reduce the use of a primary material, and thus its extraction, are substitution, material efficiency, dissipation reduction, and recycling.

The purpose of this chapter is to investigate whether and—if so, how— the use of primary molybdenum can be reduced to a (sustainable) level of 19% of the current use, without losing any of its current services. After an inventory of the current applications and flows of molybdenum, we will investigate:

(1) The substitutability of molybdenum by other elements or alternative types of services.

(2) The material efficiency potential of molybdenum.
(3) The dissipation reduction potential of molybdenum.
(4) The recycling potential of molybdenum.

6.2   OCCURRENCE AND APPLICATIONS

The most important molybdenum-containing ore is molybdenite (MoS_2). Molybdenite can occur separately in an ore body, but is often combined with the sulfide minerals of other metals, i.e. copper and tungsten. The molybdenum content of viable ore bodies ranges between 0.01% and 0.25% (International Molybdenum Association, 2015). According to Peiró et al. (2013), 60% of molybdenum is produced as by-product of copper production. According to USGS (2012c), in 2011 by-product molybdenum mines produced 54% of the molybdenum and primary mines 46%.

The development of the world molybdenum production is presented in Figure 6-1 and the main molybdenum-producing countries in Figure 6-2.

Molybdenum's applications worldwide are presented in Table 6-2.

Molybdenum in grade alloy steels and irons (59%)
Molybdenum is used in alloy steel and iron to improve a diversity of characteristics, such as the hardenability, resistance against high temperatures, sea water and chemicals. Industrial sectors where these steels are used include automotive, shipbuilding, aircraft, energy, chemical , offshore.
The molybdenum content is usually between 0.2% and 0.5% and exceeds 1% seldom.
The information is from the International Molybdenum Association (2015)

Molybdenum in stainless steels (22%)
Molybdenum improves the corrosion resistance of stainless steels, especially in chloride-containing liquids such as sea water. Stainless steels contain at least 10.5% chromium. (Information from International Molybdenum Association).
Stainless steels are categorized according to three types: ferritic, austenitic, and duplex steels. These three main categories of stainless steels contain some 150 different stainless steel grades (Battrum, 2008). Molybdenum is applied in about 10% of the stainless steels (Battrum, 2008). According to that author, only 44% of these stainless steel categories contain molybdenum. Most of the stainless steel market concerns non-molybdenum-containing grades. Only 10% of the stainless steels (so about 15 different stainless steel grades) are really relevant to molybdenum, according to Battrum (2008). Austenitic stainless steel is the main steel used for building and construction, household applications, and industrial applications (IMOA, 2015a). Of these austenitic steels, the so-called 316 stainless steel is the major molybdenum-bearing grade, with a molybdenum content of 2.1%. But the market share of
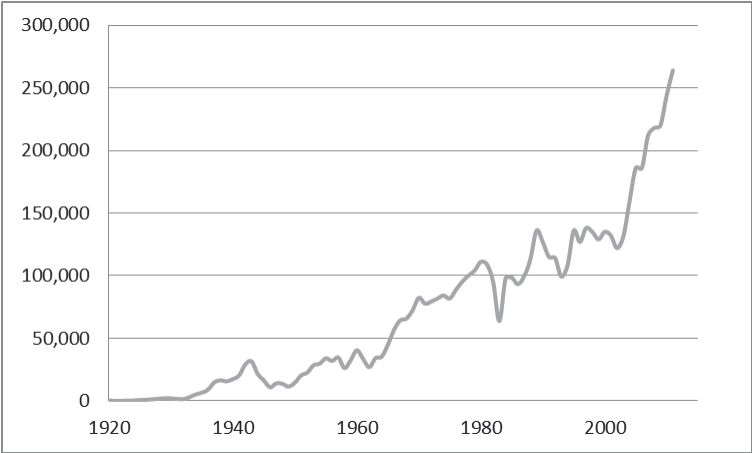
Figure 6-1 Development over time of the world molybdenum production (tons/year). Derived from USGS (2012d).
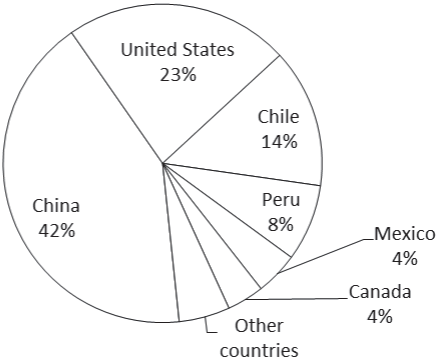
Figure 6-2 Molybdenum-producing countries in 2012. Total production is 250,000 tons (USGS, 2013b)

Table 6-2 Molybdenum's applications in 2012. Derived from the website of the International Molybdenum Association (2015)

Application	
Molybdenum grade alloy steels & irons	59%
Stainless steels	22%
Molybdenum metal	5%
Super alloys	3%
Chemicals	12%
Total	100%

this steel grade is only 7% (Battrum, 2008). According to these data and the data on the world use of 316 stainless steel (about 30 million tons per year), application of molybdenum in 316 stainless steel covers about 20% of global molybdenum use. "Lean duplex" stainless steels contain about 0.3% molybdenum. According to Battrum (2008) these grades are gradually replacing 304 stainless steel, which occupies half of the stainless steel market and does not contain molybdenum. High quality stainless steels used in corrosive environments may contain up to 3–6% of molybdenum. Examples are stainless steel grades such as 254 SMO (6% molybdenum) and SAF 2507 duplex stainless steel (3–5% molybdenum), both used in desalination plants and in oil and gas coolers in offshore oil and gas exploitation.

Molybdenum metal (5%)
Molybdenum metal is utilized in many applications, such as i.e. high temperature heating elements, rotating X-ray anodes used in clinical diagnostics and glass melting furnace electrodes.
For specialized applications, molybdenum metal is alloyed with other metals such as tungsten, copper and rhenium.
The information is from the International Molybdenum Association (2015)

Molybdenum super alloys (3%)
Molybdenum super alloys are low in iron content, but high in nickel and chromium content (respectively about 40–70% and 20–30%). These alloys fall into two basic classes: corrosion-resistant alloys (5.5–28.5% molybdenum) and high temperature alloys (2–15% molybdenum). The information is from the International Molybdenum Association (2015).

Molybdenum in chemicals (12%)
Main applications are in sulfurization catalysts, pigments, corrosion inhibitors, smoke suppressants, lubricants and in agriculture as micro-nutrient (International Molybdenum Association, 2015).

6.3   CURRENT MOLYBDENUM FLOWS

6.3.1   *Molybdenum losses during mining and processing of primary molybdenum*
Molybdenum losses during milling/grinding/flotation/roasting are assumed to be comparable to the losses of zinc during the same steps: about 20% (Meylan and Reck, 2016). We did not find any scientific literature specifically on molybdenum, but the extraction processes are largely similar for various metal ores based on sulfide.

6.3.2   *Molybdenum dissipation through usage*
About 12% of molybdenum is used in various chemicals. According to Nakajima et al. (2007), in 2004 in Japan, 36% of molybdenum in chemicals was used as catalyst and was recycled. It is assumed that the other molybdenum-containing chemicals are largely used in a dissipative

way. Thus, on the basis of the Japanese situation, dissipation of molybdenum from chemicals would concern 64% of 12%, being about 8% of the total molybdenum use. The additional dissipation of molybdenum from other applications will be relatively small, because of the type of application in metals and metal alloys. The wear of railroads can be mentioned, but the volume is small.

On the basis of these data, we shall assume that an approximate amount of about 10% of current molybdenum end-use is (unavoidably) dissipated and is not available for recycling.

6.3.3   Accumulation of molybdenum in the anthropogenic stock

We did not find figures on the build-up of anthropogenic stock of molybdenum. According to Chen and Graedel (2012), until 2012, a global-level cycle of molybdenum had not yet been derived. As more than 80% of molybdenum is applied in steel, we will assume that the build-up of anthropogenic stock of molybdenum is comparable to the build-up of anthropogenic stock of zinc. According to Blossom (2002), the lifetime of molybdenum-containing products is between 10 and 60 years, but with an average of 20 years. These lifetimes are of the same order of magnitude as the lifetimes of zinc (Yokota et al., 2003). Similar to zinc, we suppose that build-up of molybdenum in the anthropogenic stock will differ depending on the rate of industrialization of a country. In industrialized countries, further accumulation of molybdenum in the anthropogenic stock has already slowed down and is relatively low, whereas in industrializing countries the build-up of molybdenum in the anthropogenic stock is still relatively high. Hence, we assume that currently the global build-up of anthropogenic stock of molybdenum is in the order of 40% of the yearly inflow of molybdenum, which is similar to zinc. This means that at current rates, annually, only about 60% of the amount of molybdenum entering the usage phase becomes end-of-life product. To the extent that the GDP of developing countries increases, further accumulation of molybdenum in the anthropogenic stock will gradually decrease to zero.

6.3.4   Current molybdenum recycling from molybdenum-containing products

About 88% of molybdenum is used in various alloys or as molybdenum metal. See Table 6-2. According to Blossom (2002), in 1998, old scrap recycling efficiency (recycled old scrap divided by total old scrap produced) in the USA was 30%. This figure for old scrap molybdenum recycling efficiency is also used by UNEP (2011). Globally, however, recycling of molybdenum will be less than in the USA. Global figures are not available. Using zinc as comparison (46% zinc recycling from old scrap in the USA versus 33% globally: Meylan and Reck, 2016), we estimate that the global recycling of molybdenum from old scrap will be in the order of 33/46*30 = 20% (rounded). The main reason for this relatively low amount of secondary molybdenum is that molybdenum- containing old scrap is normally not purchased and recycled for the sake of molybdenum, but for other metals, mostly iron. Steel scrap is processed in electric arc furnaces (EAFs). Molybdenum and other elements such as nickel, cobalt, tungsten and copper remain unintentionally in the molten steel (Nakajima et al. 2011). In this way a substantial part of molybdenum is down-cycled and "lost" in diluted form in various lower quality types of steel.

According to USGS (2012c), recycling efficiency is not expected to increase significantly as long as cheaper alternatives are available in the form of relatively cheap primary molybdenum. In this context it is relevant that about half of the primary molybdenum produced in the world is a by-product of the production of another metal, mostly copper. This means that 50–60% of molybdenum's world production is a by-product of the copper production, regardless of the specific demand for molybdenum and its increase or decrease. On the other hand, regardless of the demand for molybdenum, the molybdenum price can increase as a result of a decrease of copper mining due to geological scarcity of copper,

6.3.5   Current molybdenum flows summarized

Figure 6-3 is a simplified molybdenum flow diagram, created under the following assumptions:
- a molybdenum recycling from old scrap of 20%
- a dissipation of molybdenum from its application in chemicals of 10% of the annual molybdenum consumption
- 20% losses during molybdenum mining, processing and manufacturing
- 40% build-up in the anthropogenic stock.

The question now is how primary molybdenum use can be reduced by 81% compared to the 2010 extraction. This means that primary molybdenum extraction in Figure 6-3 should decrease from 110 to 21. In the next sections we will discuss to which extent substitution, material efficiency, dissipation reduction, and improved recycling can contribute to reducing the use of primary molybdenum.
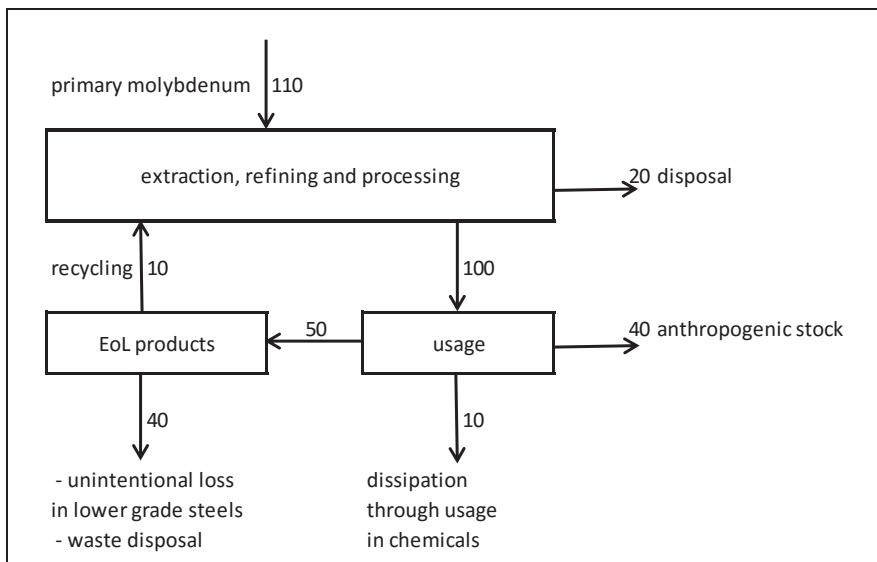
Figure 6-3 Current molybdenum flows. The annual usage of molybdenum has been normalized at 100 units.

6.4   SUBSTITUTION OF MOLYBDENUM-CONTAINING PRODUCTS

There is little scientific literature on the substitutability of molybdenum. According to USGS (2013c) potential substitutes for molybdenum in some of its applications include:
-    chromium, vanadium, niobium (columbium) and boron in alloy steels,
-    tungsten in tool steels,
-    graphite, tungsten, and tantalum for refractory materials in high-temperature electric furnaces,
-    chrome-orange, cadmium-red, and organic-orange pigments for molybdenum orange.

However, these applications concern a relative small amount of molybdenum. Moreover, most of the substitutes mentioned are geologically scarce themselves. In general, according to USGS (2013c), there is little substitutability for molybdenum in its major application as an alloying element in steels and cast irons.

Oakdene Hollins and Fraunhofer (2103) provide an estimation of the substitutability of molybdenum use in various applications and economic sectors (Table 6-3)

Based on the above considerations we shall assume that substitution of molybdenum cannot contribute to reducing primary molybdenum extraction.

Table 6-3 Substitutability of molybdenum according to Oakdene Hollins and Fraunhofer (2013)

Sector/application	Substitutability
Oil	1.0
Chemicals	1.0
Road-transport	1.0
Mechanical Equipment	1.0
Electrical equipment	1.0
Electronics	1.0
Aerospace and defence	1.0
Construction	0.3

0.0	Easily and completely substitutable at no additional cost
0.3	Substitutable at low cost
0.7	Substitutable at high cost and/or loss of performance
1.0	Not substitutable

6.5   MATERIAL EFFICIENCY MEASURES WITH RESPECT TO MOLYBDENUM-CONTAINING PRODUCTS

Similar to zinc, the most important factors for an efficient use of primary molybdenum are a high collection and recycling rate of new and old scrap, and a low dissipation rate from molybdenum-containing products. Both factors will be discussed separately in sections 6.6 and 6.7. The applicability of other material efficiency measures (e.g. efficiency increase during mining and processing of primary materials, minimization of the material amount in products and lightweight design, extending product lifetimes, shared use of products) needs to be

assessed on a case-by-case basis and is determined both by technological developments and economic considerations. Based on an earlier publication (Henckens et al. 2015), we shall, prudently, assume an overall material efficiency potential of 10% on top of the dissipation reduction and recycling measures.

6.6   REDUCTION OF MOLYBDENUM DISSIPATION

The dissipative use of molybdenum is linked to its use in chemicals used in catalysts, pigments, corrosion inhibitors, smoke suppressants, lubricants, and fertilizer. The dissipation is partly direct (use as fertilizer), and partly indirect via landfills and incinerators. The only possibility for reducing this type of molybdenum dissipation is to diminish the use of molybdenum in its various applications in chemicals. To some extent this might be possible for some of the applications, such as the more general use of molybdenum in pigments, as corrosion inhibitor and as smoke suppressant. This type of reduction is already included in the material efficiency category. Therefore, we shall prudently assume that the supposed current dissipation of molybdenum of 10% can hardly be reduced.

6.7   IMPROVED MOLYBDENUM RECYCLING

The big obstacle for separating molybdenum from its alloys is that molybdenum-containing scrap is mostly used for its iron content and not for its molybdenum content. In the melting process, molybdenum will—unintentionally—accumulate in the metal phase and occur as an impurity in the produced metal.

In order to achieve the required reduction to 19% of the current extraction rate, molybdenum recycling efficiency must be increased from the current 20% to 87% in the future, taking into account 10% material efficiency measures and 10% dissipative usage. See Figure 6-4. The question is whether it is possible to achieve an 87% molybdenum recycling rate from end-of-life products. A number of authors (Javaid and Essadaqi, 2003, Gaustad, 2009, Ohno, 2014, Gurell, 2012, Nakajima, 2007, Blossom 2002, Castro, 2004, Froelich, 2007) indicate that by taking adequate measures, it would be possible to substantially increase the recycling of molybdenum. These measures concentrate on:
- Selective dismantling
- Better scrap sorting
- Adapted product design

The main purpose of the measures described is to separate molybdenum-containing end-of-life products into distinctive streams according to their molybdenum content in such a way that these molybdenum-containing streams can directly replace virgin molybdenum with a minimum of unnecessary dilution in lower quality types of steel. In this context, the Institute of Scrap Iron and Steel has defined groups of ferrous scrap materials of similar composition

representing marketable commodities. Javaid and Essadaqi (2003) also provide categories of ferrous scrap.

Selective dismantling

The purpose of selective dismantling is to selectively remove parts with a relatively high content of the relevant material from a complex object, such as an end-of-life vehicle, before shredding it. In order to achieve an effective dismantling the following key measures are required:

- The recycler is instructed which parts need to be removed separately
- It is made financially attractive to do this. Sale at a minimum price, making selective dismantling profitable, should be guaranteed

See Gaustad (2009), Javaid and Essadiqi (2003), Ohno (2014)

Better scrap sorting

Thus far, scrap has not been used as a source of alloying elements by EAF steel-making companies, unless it is specially separated, such as austenitic stainless steels that have a high content of chromium and nickel. According to Ohno (2014), obstacles for better sorting end-of-life vehicle scrap are:

- Recycling companies lack information on the composition of the scrap.
- Scrap is classified and traded on the basis of its shape and not on its composition. The exception is austenitic stainless steels, because they are non-magnetic.
- The absence of affordable, efficient sorting technology.

According to Javaid and Essadaqi (2003), for aluminum alloys, several technologies are already commercially available:

- Magnetic separation
- Eddy current separation
- Heavy media separation
- Color sorting
- Sorting by using Laser Induced Breakdown Spectroscopy (LIBS)
- Sorting by using optical emission spectroscopy

Gurell (2012) et al. show the high success rate of LIBS when classifying scrap in 8 different certified reference materials, including molybdenum, iron, chromium, nickel, manganese, copper, and silicium in various proportions, molybdenum varying between 0 and 3.6%. According to Javaid and Essadiqi (2003) sorting can be improved by prior "cleaning" of scrap, for instance by:

- Incineration of plastics around the metal parts
- De-zincing
- De-tinning

According to Gaustad (2009), an optimal strategy for more efficient recycling of ferrous metals such as molybdenum includes:

- Making efficient blending plans
- Redesigning alloys to accommodate more scrap for recycling

- Widening fields of application of scrap
- Improving scrap quality

Nakajima et al. (2007) make clear that steel scrap needs to be standardized in order to promote molybdenum recycling. According to Blossom (2002), recycling of molybdenum-containing scrap will remain dependent on the market for the principal alloy metals such as iron, nickel, and chromium. As long as the value of molybdenum remains relatively low, scrap metal is not likely to be sought for its molybdenum content.

Adapted product design
According to Castro et al. (2004), it is fundamental to design products in such a way that losses and contamination during recycling are minimized by the use of material combinations that are compatible for recycling. During recycling, contaminants might accumulate irreversibly and high purity resources must be constantly added to dilute the contamination. According to Froelich et al. (2007) a new approach is required in order to integrate the limits of the shredding and dismantling process regarding metal scrap quality into design. They propose four key criteria for the design of parts made mainly of aluminum or steel: (1) choose materials with a low degree of contaminants, (2) choose materials with a large gap of material ductility, (3) choose part geometry in a way that enclosure of contaminants is avoided (4) choose a suitable contaminant particle size.

Conclusion
The conclusion is that there are several techniques to further improve the current global EoL molybdenum recycling efficiency of 20%. An EoL recycling efficiency of 87% is required for sustainable extraction and use of molybdenum in the future. It needs to be investigated whether such a high molybdenum EoL recycling efficiency is feasible by using the technologies discussed in this section. Anyhow, it will be necessary to recycle molybdenum-containing metals on the basis of their molybdenum content instead of on the basis of their iron, nickel or chromium content. The molybdenum flow scheme that represents 81% reduction of the use of primary molybdenum compared to the present use of primary molybdenum is presented in Figure 6-4.

6.8   CONCLUSIONS, DISCUSSION, AND RECOMMENDATIONS

There is little or no substitution potential for molybdenum in its major applications. A substantial reduction of molybdenum dissipation through its application in chemicals also seems hardly possible. This means that the required 81% reduction of molybdenum extraction has to take place through improved material efficiency and increased recycling of molybdenum.

Assuming a possible increase of material efficiency of 10%, recycling of molybdenum needs to increase from the current 20% to 87% in the future. More research is needed to find out whether the assumed 10% material efficiency potential is realistic or could even be higher
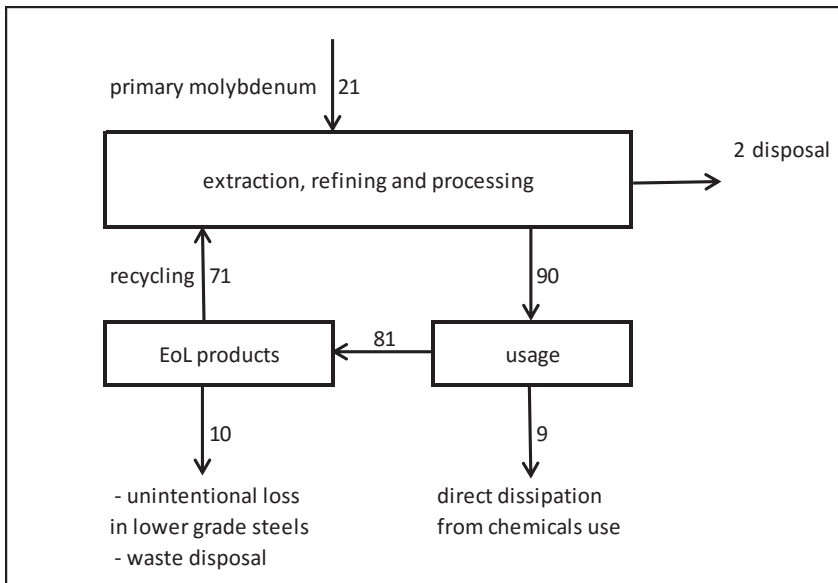
Figure 6-4 Molybdenum flows for obtaining 81% reduction of the primary molybdenum extraction compared to the current situation. Compared to Figure 6-3, it has been assumed that molybdenum usage has decreased by 10% because of an improved material efficiency. The EoL recycling rate is 87%. Substitution and dissipation reduction are both assumed to be 0%. Dissipation remains 10%. It is assumed that there is no further build-up of molybdenum in anthropogenic stock.

than 10%. Research issues in that framework could, for example, be: can material losses during the manufacturing of products from molybdenum alloys be reduced? can the molybdenum content in certain alloys possibly be reduced without losing the required product quality? is the required steel quality really necessary in all applications?

For sustainable molybdenum extraction, an EoL recycling rate of 87% is required. This is only possible, if the "leading" material in scrap recycling is no longer iron but materials that are relatively scarcer than iron, such as i.e. molybdenum. Whether this can be achieved will depend on the profitability of the required measures. A lower price of secondary molybdenum (encompassing the recycling costs) compared to the price of primary molybdenum will be essential. If technology and market hamper replacement of primary metal by secondary metal, the question arises whether regulatory measures need to be taken, in order to promote the use of secondary molybdenum and to keep this metal sufficiently available for future generations.

Another special point of attention is that, worldwide, about 50–60% of molybdenum is a by-product of the mining of other metals, mainly copper (Peiró et al. 2013, USGS 2012c, Blossom 2002). An important conclusion is that as a consequence of the necessity to reduce the use of primary molybdenum to only 19% of the current use (1) molybdenum mines would need

to be closed and (2) the molybdenum produced as a by-product of the copper mining would need to be partly stored for use by future generations. Relevant in this framework is that copper is also a geologically scarce mineral resource whose extraction needs to be reduced to become sustainable.

REFERENCES

Battrum, D., 2008, Stainless steel and molybdenum, In: http://www.thompsoncreekmetals.com/i/pdf/Molybdenum_Stainless_Steel.pdf, 27-3-2014

Blossom, J.W., 2002, Molybdenum recycling in the United States in 1998, USGS, Open file report 02-165

Castro, M.B.G., Remmerswaal, J.A.M., Reuter, M.A., Boin, U.J.M., 2004, A thermodynamic approach to the compatibility of materials combinations for recycling. Resour. Conserv. Recycl. 43,1-19

Chen, W., Graedel, T.E., 2012, Anthropogenic cycles of the elements: a critical review. Environ.Sci.Technol. 46, 8574-8586

Erickson, R.L., 1973, Crustal occurrence of elements, mineral reserves and resources, USGS, Professional Paper 820, p21-25

Froelich, D., Haoues, N., Leroy, Y., Renard, H., 2007, Development of a new methodology to integrate ELV treatment limits into requirements for metal automotive part design. Miner. Eng. 20, 891-901

Gaustad, G.G., 2009, Towards sustainable material usage: time-dependent evaluation of upgrading technologies for recycling. PhD in Material Science and Engineering, Massachusetts Institute of Technology

Gurell, J., Bengtson, A., Falkenström, M., Hansson, B.A.M., 2012, Laser induced breakdown spectroscopy for fast elemental analysis and sorting of metallic scrap pieces using certified reference materials. Spectrochimica Acta Part B 74-75, 46-50

Henckens, M., Driessen, P., Worrell, E., 2015, Towards a sustainable use of primary boron, Approach to a sustainable use of primary resources. Resour. Conserv. Recycl. 103, 9-18

Henckens, M.L.C.M., Driessen, P.P.J., Worrell, E, 2014, Metal scarcity and sustainability, analyzing the necessity to reduce the extraction of scarce metals. Resour. Conserv. Recycl., 93,1-8

International Molybdenum Association (IMOA) www.imoa.info 2015, Molybdenum uses, Molybdenum metal & alloys

Javaid, A., Essadiqi, E., 2003, Final report on scrap management, sorting and classification of steel. Report for the government of Canada, no 2003-23(CF), December

Meylan, G., Reck, B.K., 2016, The anthropogenic cycle of zinc: status quo and perspectives. Resour. Conserv. Recycl. http://dx.doi.org/10.1016/j.resconrec.2016.01.006

Nakajima, K., Yokoyama, K., Matsuno, Y., Nagasaka, T., 2007, Substance flow analysis of molybdenum associated with iron and steel flow in Japanese economy. ISIJ International, 47(3) 510-515

Nakajima, O., Takeda, O., Miki, T., Matsubae, K., and Nagasaka, T., 2011, Thermodynamic analysis for the controllability of elements in the recycling process of metals. Environ. Sci.Technol. 45, 4929-4936

Oakdene Hollins, Fraunhofer, 2013, Study on critical raw materials at EU level, a report for DG Enterprise and Industry of the European Commission,, 16 December

Ohno, H., Matsubae, K., Nakajima, K., Nakamura, S., Nagasaka, T., 2014, Unintentional flow of alloying elements in steel during recycling of End-of-Life vehicles. Journal of Industrial Ecology, 0(0)

Peiró, L.T., Méndez, G.V., Ayres R.U., 2013, Material flow analysis of scarce metals: sources, functions, end-uses and aspects for future supply. Environ.Sci.Technol. 47, 2939-47

Rankin, W.J., 2011, Minerals, metals and sustainability, CSIRO

Skinner, B.J., 1976, A second iron age ahead? American Scientist 64, 158-169

UNEP International Panel on Sustainable Resource Management, Working Group on Geological Stocks of Metals, Working Paper, April 6, 2011a

UNEP International Resource Panel, Recycling rates of metals, a status report, 2011

USGS, 2011 Minerals Yearbook, Molybdenum, 2012 c

USGS, Mineral Commodities Summaries 2012, Molybdenum, 2013 b

USGS, Molybdenum Statistics, 2012d

USGS, Molybdenum, Mineral Commodity Profiles, January 2013 c

Yokota, K., Matsuno, Y.,Yamashita, M., Adachi, Y., 2003, Int. J.LCA 8, 129

Chapter 7

Mineral resources: geological scarcity, market price trends, and future generations[11]

ABSTRACT

The extractable ores of the world's geologically scarcest mineral resources (e.g. antimony, molybdenum and zinc) may be exhausted within several decades to a century, if their extraction continues to increase. This paper explores the likelihood that these scarce mineral resources can be conserved in time for future generations without intervening but instead simply relying on the price mechanism of the free market system. First we discuss the role of geological scarcity in the long-term price development of mineral resources. Then, to see whether geological scarcity affects the price of minerals we compare the historical trends in the prices of geologically scarce mineral resources with those of geologically more abundant mineral resources. The results show that in the period 1900 to 2013 the price mechanism did not result in high prices that provide advance warning of exhaustion of minerals. We therefore argue that if conservation is left to market forces, it is not certain that geologically scarce minerals will be timely, automatically, and sufficiently conserved for future generations. We recommend preparing international policy measures targeted at a price increase of the scarcest mineral resources, in order to accelerate substitution and recycling of these materials and help save the geologically scarcest mineral resources for future generations.

KEYWORDS

Scarce minerals, sustainable extraction, price mechanism, free market system

7.1 INTRODUCTION

Achieving sustainable development is a central goal of the United Nations. It is the main issue in a number of agreements, conventions, and declarations, such as the Stockholm Convention (1972), the Rio Declaration (Agenda 21, 1992), the Rio+20 Declaration (The Future We Want, 2012), and the UN Report on the implementation of Agenda 21 (United Nations, 2014). In the latter document, the Sustainable Development Goal 12 is: *"Ensure sustainable consumption and production patterns"* and sub-goal 12.2 is: *"By 2030, achieve the sustainable management and efficient use of natural resources"*.

The leading definition of sustainability was formulated in 1987 by the Brundtland Commission in its report *Our Common Future: "Sustainable development is the kind of development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* (World Commission on Environment and Development, Our Common Future, 1987).

There is debate on the interpretation of the Brundtland definition of sustainable development in the context of use of resources. According to Johnston et al. (2007), in 2007 there were some 300 interpretations. Two main lines of interpretation can be distinguished: (a) the *"weak sustainability"* interpretation and (b) the *"strong sustainability"* interpretation. Adherents to the *"weak sustainability"* interpretation argue that future generations should not have fewer consumption opportunities than the current generation and that natural resources may be exhausted on condition that they are replaced adequately by equivalent substitutes and human-made capital. However, adherents to the *"strong sustainability"* concept argue that the current generation should not deprive future generations from using natural resources. The concepts of weak and strong sustainability are discussed further in Baumgärtner and Quaas (2010), Johnston et al. (2007), Goodland (1995), Hansson (2010), Ayres et al. (2001), van den Bergh (2010), and White (2013).

The argumentation behind the *"weak sustainability"* concept is that the current generation needs commodities today in order to construct a society that improves the living conditions for current and future generations. From this point of view, exhaustion of mineral resources is not necessarily bad for future generations and their welfare does not necessarily decline as a result of exhaustion, particularly if the resources are used for investment in human-made capital. Supporters of the *"strong sustainability"* concept tend to be more cautious about exhaustion of resources. They argue that from the point of view of inter-generational responsibility the current generation is morally obliged to use scarce resources as efficiently as possible, and thus the use of geologically scarce mineral resources should be made sustainable. In this paper we focus on the "strong sustainability" interpretation, because this interpretation is explicitly based on the principles of sustainable use of resources and inter-generational equity that are part of many international environmental agreements (Table 7- 1).

Our interpretation of these principles is that the current generation is morally obliged to use geologically scarce resources in a sustainable way. This means that these resources must

Table 7-1 The "sustainable use of resources" principle and the "inter-generational equity" principle in international conventions and agreements

Normative principle	Included in
Sustainable use of resources	- 1958 Convention on fishing and conservation of the living resources of the high seas - 1972 United Nations Conference on the human environment (Stockholm Conference) - 1992 Convention on biological diversity - 1995 Agreement for the implementation of the provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the conservation and management of straddling fish stocks and highly migratory fish stocks - 1992 United Nations Framework Convention on Climate Change - 2006 International Tropical Timber Agreement - 1985 ASEAN Convention - 1987 Zambezi Action Plan Agreement - 2000 Biosafety Protocol - 2010 Nagoya Protocol - 1992 OSPAR Convention - 1994 WTO General Agreement on Tariffs and Trade, Article 20)
Inter-generational equity	- 1992 Rio Declaration on environment and development - 1992 United Nations Framework Convention on Climate Change - 1972 World Heritage Convention - 1978 Kuwait Convention, Preamble - 1983 Cartagena de Indias Protocol, Preamble - 1982 Jeddah Convention Art.1(1) - 1976 South Pacific Nature Convention, Preamble - 1977 ENMOD Convention, Preamble

be kept available for future generations as well, to ensure that geologically scarce mineral resources do not become prohibitively expensive for future generations. A strict application of the strong sustainability concept would mean, however, that no generation (neither current, nor future) may extract any quantity of a mineral resource, because extraction always ultimately leads to exhaustion. This is neither practical nor necessary, because by sufficiently sparing on the geologically scarcest resources, humankind can buy time to work on problem solving in the future. Using this point of departure, Henckens et al. (2014) made the concept of sustainable extraction of mineral resources operational by formulating the following definition. *"The extraction rate of a mineral resource is sustainable if it can provide 9 billion people with that mineral for at least 1000 years, assuming that the per capita use is equally divided over the countries of the world".* This definition reconciles both views (on weak sustainability and strong sustainability), because it recognizes that ultimately, exhaustion is unavoidable, but exhaustion of the geologically scarcest mineral resources in question is delayed for an acceptably long period of time. Using this definition, the reduction of extraction required has been calculated for four minerals: antimony (96 % reduction required: Henckens et al. 2016b), boron (44% reduction required: Henckens et al. 2015), zinc (82 % reduction required: Henckens et al 2016a), and molybdenum (81 % reduction required: Henckens et al.2016a).

An interesting question is whether the sustainable use of geologically scarce mineral resources can be achieved automatically by the influence of the price mechanism of the free market system. Would the reaction of the price mechanism to increasing geological scarcity of mineral resources trigger a timely and sufficient reduction in the use of mineral resources? Although this question was asked by Dasgupta and Heal (1979, p. 2), it has not yet been unambiguously answered and remains relevant today.

According to Tilton (2001, chapter 3) the price of a mineral is only a limited indicator for geological scarcity. This is supported by Seyhan et al. (2012) in their theoretical investigation of the exhaustion of the essential resource phosphorus. They concluded that the market price cannot serve as a reliable indicator of scarcity, because when on an optimal path, the price can fall temporarily, despite ongoing exhaustion. Farley and Costanza (2002) found that markets are not efficient mechanisms for allocating scarce resources. In a vision on a sustainable and desirable USA in 2100, they indicate that *"most forms of natural capital will be recognized as inter-generational assets"* (Farley and Costanza, 2002, p. 251). Famous in this context is the wager between the economist Julian Simon and the environmentalist Paul Ehrlich made in 1980, on the price development of commodities (Worstall, 2013). Ehrlich expected prices to increase, because of growing demand. Simon argued that more people mean more brains and better methods of extraction, combined with a more efficient use of primary materials. Although Simon won the bet for the 10-year period in question (1980-1990), it is not certain that the outcome can be extrapolated to any period in the (far) future.

The key question of this paper is whether the price mechanism of the free market system will timely and automatically lead to sufficient conservation of geologically scarce mineral resources for future generations. To answer this question, we will first discuss the concept of geological scarcity. How scarce is scarce? We will distinguish very scarce, scarce, and moderately scarce mineral resources.

In Section 7.3 we explore how prices of minerals might react to increasing geological scarcity in general. Then we study actual trends in market prices of mineral resources for the period between 1900 and 2013 (Section 7.4). Finally, we analyze whether the price development in that period shows that price is related to geological scarcity (Section 7.5). Our conclusions are presented in Section 7.6.

7.2   GEOLOGICAL SCARCITY OF MINERAL RESOURCES

Geological scarcity of mineral resources must be distinguished from economic scarcity. Economic scarcity of mineral resources is the umbrella concept and can be caused not only by geological scarcity, but also by many other factors. Ultimately, the market price is determined by the balance between demand and supply. A higher demand for a commodity may be caused by new applications (e.g. rare earth elements in electronics), or the fast industrial development of large countries such as China and India. A lower demand may be caused by the discovery of cheaper and/or better substitutes for an application. A higher or lower sup-

ply can be artificially caused by a political decision of monopoly or oligopoly countries (e.g. oil-producing countries). Factors causing a reduction in supply include accidents, strikes, and geopolitical actions (e.g. boycotts). The main difference between the latter causes of scarcity and geological scarcity is that geological scarcity is a more structural phenomenon, whereas the other causes have a more cyclical character.

Globally, extraction of minerals is increasing rapidly. Simultaneously, the ore grades mined are declining. Many mines in the old industrial regions of the world (USA and Europe) have been closed due to low ore grades. Prior et al. (2012) show that ore grades in Australia, an important mineral-producing country, have declined by a factor of 2 to 5 since the beginning of mining in that country, and that environmental and social costs are increasing at the same pace. They argue that mineral production in Australia has become unsustainable because of the high external costs. In the USA, the grade of mined copper has declined from more than 2 % in the early part of the 20th century to 0.5 % at the beginning of the 21st century (Tilton, 2003). During the same period and also in the USA, the grade of iron ore declined from 60 % to 20 % (Tilton, 2003).

The growth of global production and consumption is determined by a combination of population growth and GDP per capita increase. The rising trend in raw materials use is partly offset by increasing material efficiency and recycling. The UN expects that population growth will level off by the end of the 21st century (United Nations, 2011). However, thereafter GDP per capita will probably continue to grow. There is a positive relationship between GDP and metal consumption: the wealthier a country, the higher its metal use per capita (Graedel and Cao, 2010). But from a certain GDP onward, materials consumption per capita does not necessarily continue to increase concomitantly with GDP, as shown by Halada et al. (2008) and UNEP (2011b). These studies indicate that consumption of materials may decouple from GDP growth. According to Halada et al. (2008) this decoupling will start from a per capita GDP of about USD 10,000 per capita (1980 dollars). UNEP (2011b) has developed a scenario showing that from 2050 stabilization of the use of raw materials would be possible, assuming consumption worldwide continues to grow by 3% per annum until 2050. A 3 % growth scenario is prudent, given the historical growth rates of the extraction of several important mineral resources (Table 7-2).

This scenario assumes net zero growth of raw materials use in the industrialized world and a higher (> 3%) growth of raw materials consumption in the developing part of the world. The "*freeze*" scenario for the industrialized part of the world is supported by Bringezu and Schütz (2001), Eurostat (2002), Weisz et al. (2006), NIES/MOE (2007), and Roglich et al. (2008). The *"catching up"* scenario for the rest of the world is supported by studies of Giljum (2002), Gonzalez-Martinez and Schandl (2008), Chen and Qiao (2001), Perez-Rincon (2006), Russi et al. (2008), and OECD (2008). In the *"freeze and catching up"* scenario, the developing part of the world will have caught up with the industrialized part of the world in 2050, and from that year on it would be possible to globally decouple primary materials consumption from

Table 7-2 Incremental extraction of seven mineral resources worldwide: average annual increase over 1900–2013, 1950–2013, and 2000–2013. All figures calculated by the authors based on United States Geological Survey Historical Statistics, 2015.

Average annual increase in extraction rate								
Period considered	Molybdenum	Chromium	Nickel	Copper	Zinc	Lead	Tin	Grand average
1900-2013	16.5%	7.6%	7.3%	3.9%	3.5%	2.8%	1.9%	6.2%
1950-2013	6.0%	4.9%	4.5%	3.5%	3.4%	2.3%	1.2%	3.7%
2000-2013	5.4%	5.3%	3.3%	2.6%	3.9%	4.4%	1.8%	3.8%

further GDP growth. The global primary materials consumption level per capita that will be attained in 2050 would then equal the level prevailing today in the industrial world. In this scenario it is assumed that from 2050 onwards total annual consumption of primary materials will stabilize at a level of about 3.3 times the level in 2010. This is a large amount, despite the optimistic assumption that the annual use of mineral resources would stop increasing after 2050. This therefore raises the question of whether at this high level of primary materials consumption (which equals extraction), exhaustion of the geologically scarcest materials might become a problem.

Not all mineral resources are equally scarce from a geological point of view. The extractability of a mineral from the earth's crust depends on its concentration in ores. Phillips (1977), Van Vuuren et al. (1999), Skinner (2001), and Tilton (2003) suppose that the distribution of grade and tonnage of major elements in the earth's crust (>0.1 weight % average content) has a unimodal bell shape. They suppose that the distribution of so-called *minor* elements (< 0.1 weight % average content) is bimodal. See Figure 7- 1.
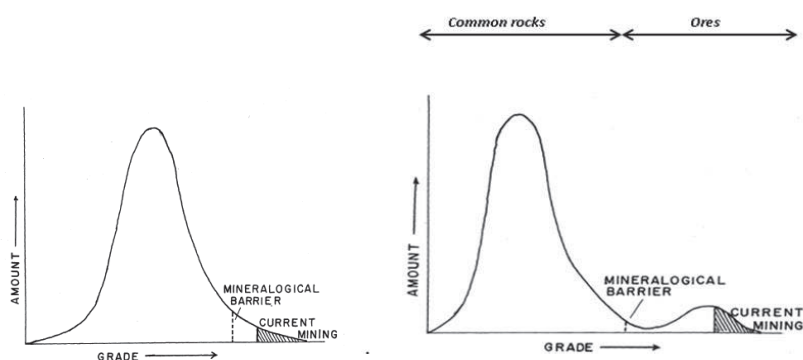
Figure 7-1 Grade and tonnage distribution of major elements (>0.1 weight %, such as aluminum, iron, titanium) in the earth's crust (left-hand graph) and minor elements (<0.1 weight %, such as copper zinc, nickel, tin, gold, lead) (right-hand graph). Assumption based on Skinner (2001)

Mining companies do not plan extraction further than about 30 years ahead, so therefore, the combined data from mining companies on reserves do not reflect the extractable global resources. The extractable global resources are represented by the right-hand tails of the two graphs in Figure 7- 1. The so-called "mineralogical barrier" is the threshold grade between extractability and non-extractability. However, this threshold grade is not immutable. The grade from which a mineral is considered extractable depends on the willingness-to-pay of the market. With technological development, extractability will extend to lower grades. The amount of mineral in common rocks, the left-hand parts of the graphs in Figure 7- 1, is huge compared to the amount that is considered extractable. Although, technically speaking, low grades are extractable as well, this may not happen due to the high energy costs of extracting a mineral from common rock. Skinner (1976) estimates that the extractable amount of copper (represented by the area under the curve to the right of the mineralogical barrier of the bimodal curve of Figure 7- 1) is between 0.01 and 0.001 % of the total amount of copper in the earth's crust. On the basis of the distribution of known deposits of minerals, Rankin (2011) points out that the total amount of enriched deposits is proportional to the crustal occurrence of the mineral. This means that the extractable amount of all mineral resources would be between 0.01 % and 0.001 %. Erickson (1973) and the UNEP International Resource Panel (2011a) come to the same conclusion. According to the UNEP International Resource Panel (2011a), a reasonable estimate of the upper limit of the extractable global resources is 0.01 % of the total amount of a mineral in the top 1 kilometer of the earth's continental crust. The UNEP International Resource Panel has compared the reserve base estimates of the United States Geological Survey with the 0.01 % estimate for the extractable global resources. Their conclusion is that the 0.01 % estimate results in an average amount of extractable global resources that is approximately 35 times higher than the estimates given by USGS in its latest reserve base data (2009). The 0.01 % estimate is rough and general, but we have been unable to find any other more precise estimate of the amount of extractable global resources in the literature.

Departing from the 0.01% estimate for the total amount of extractable global resources, Henckens et al. (2014) subdivided 60 metals and metalloids into four scarcity classes (Table 7- 3). To calculate the exhaustion periods shown in Table 7- 3, they divided the extractable global resources of each element by the extracted quantity of that element as calculated for 2050.

The assumptions underlying the figures in Table 7- 3 are that after 2050 the extraction rate remains stable, the current recycling rates are maintained, and there is no substitution and neither are measures introduced to improve efficiency of raw materials consumption. In practice, recycling will improve, certain applications will be substituted, and efficiency of raw materials use will increase. However, new applications may be developed, increasing the demand for the mineral. Also, the growth of mineral consumption may not level off in 2050, or it may be higher than 3 % per year. Table 7- 3 is intended to clarify the distinction between very scarce, scarce, moderately scarce, and non-scarce, and to provide an order of magnitude of

exhaustion periods, if cumulative extraction were to be extrapolated into the future assuming that no further change will take place (such as extra substitution and improved recycling). An exhaustion period of 1000 years for making the distinction between scarce and not scarce is a rather arbitrary choice. We have followed the working definition proposed by Henckens et al. (2014) for sustainable extraction that was mentioned in the introductory section. The argument of Henckens et al. (2014) is that while any allowable exhaustion period would be arbitrary as point of departure for a working definition for sustainable extraction, a period of 100 years is perceived to be too short, as it would allow exhaustion to occur at relatively short notice, whereas a period of 10,000 years would be unnecessarily long. A period of 1,000 years

Table 7-3 Exhaustion periods of 60 elements (years after 2050) under the assumption that the extraction of all elements mentioned increases annually by 3 % until 2050, after which it levels off. Metals and metalloids classified according to geological scarcity. EGR = extractable global resources as defined by UNEP (2011a) (Source: Henckens et al., 2014). Rounded figures.

Very scarce (EGR exhausted before 2050)		Scarce (EGR exhaustion time <100 years after 2050)		Moderately scarce (EGR exhaustion time between 100 and 1000 years after 2050)		Not scarce (EGR exhaustion time >1000 years after 2050)	
Antimony	-10	Gold	10	Arsenic	400	Aluminum	20,000
		Molybdenum Rhenium	50	Bismuth	200	Barium	1,000
		Zinc	80	Boron	200	Beryllium	200,000
			50	Cadmium	500	Cobalt	2,000
				Chromium	200	Gallium	1,000,000
				Copper	100	Germanium	200,000
				Iron	300	Indium	10,000
				Lead	300	Lithium	9,000
				Nickel	300	Magnesium	30,000
				Silver	200	Manganese	2,000
				Tin	200	Mercury	400,000
				Tungsten	300	Niobium	2,000
						Platinum Group Metals	1,000
						Rare Earth Metals	20,000
						Selenium	300,000
						Strontium	10,000
						Tantalum	20,000
						Thallium	1,000,000
						Titanium	10,000
						Uranium	2,000
						Vanadium	20,000
						Zirconium	2,000

would entail delaying exhaustion for a considerable period of time, long enough to be able to organize a circular economy and to minimize extraction of new mineral resources to the amount that is dispersed in the environment by unavoidable dissipation.

The conclusion of Henckens et al. (2014) is that the 17 elements in the three left-hand columns of Table 7-1 need special attention. From a relatively near point in the future onward, these seventeen geologically scarce minerals will no longer be available for future generations to the extent and at the price that they are available for the current generation, unless their extraction is substantially reduced.

Exhaustion of a resource does not mean there will be complete absence of the commodity from that moment on. The earth's crust will still contain much, even most, of the resource. But these low-grade occurrences can only be extracted at (much) higher costs. The rising cost may be (partly) offset by new technologies and lower energy costs, if the latter were a realistic assumption. Moreover, unlike fossil fuels, elements such as copper or zinc will not disappear through being used. They will be dissipated in the environment or be contained in end-of-life products, from which, technically, they can be rescued and recycled. Therefore, one might wonder whether geological scarcity will really become a problem for future generations. After all, minerals that are extracted by the current generation will be part of the infrastructure and commodities remaining for future generations. Moreover, past and current generations have invented recycling technologies, and such technological development will continue. Future generations might not need to extract any more primary raw materials, instead using and applying what they have inherited from previous generations. However, mining results in a mineral being isolated and concentrated, after which it is applied in many different products. In these applications, or by use, the mineral is diluted again. Inevitably, some of it will be dissipated by disposal in landfills, waste incineration, or directly by usage, such as by use in fertilizers, washing products, or paint. The main application of zinc is to protect steel against corrosion. A substantial part of this zinc dissolves in rainwater and is washed away in surface water, groundwater, and seawater. Some of the boron used is in fertilizer and ends up directly or indirectly in groundwater or in sewer systems. The main application of molybdenum is in stainless steel. From end-of-life products, an important part of molybdenum is down-cycled into lower quality steel products, where it no longer has a function.

7.3   TRENDS IN MARKET PRICE FOR MINERAL RESOURCES

In this paper we investigate the long-term price trends of mineral resources in order to examine how these are affected by geological scarcity. This will result in a general long-term price development hypothesis for mineral resources. On the basis of this hypothesis we will be able to compare the actual market price development of mineral resources with the price development that can be expected on the basis of the hypothesis.

It should be noticed that historical prices for mineral commodities do not reflect the costs of extraction and processing only. World production of some minerals is largely concentrated in only one or a few countries, so these producers can dictate the price for a shorter or longer time. Other factors that may influence the market price are geopolitical circumstances, such as boycotts of an important producer, wars, accidents, or strikes. Also, a strong increase of demand can cause the supply of commodities to the market to lag behind the demand, so that prices will increase. Another important circumstance in which the market price does not reflect the production costs is when a relatively large proportion of the resource is obtained as a by-product of the production of other mineral resources, as is the case, for instance, for rhenium, molybdenum, and cobalt. The largest part of the volume of these minerals extracted worldwide is a by-product of copper extraction (rhenium: 90 %, cobalt: 70 %, molybdenum: 60 %) (Copper Alliance, 2015). The market prices of by-product minerals will mainly be determined by the trade-off between the volume of by-product generated and the market demand for this by-product.

Although growing geological scarcity is mitigated by the current state of technology, the increasing dependence of humankind on ever lower ore grades and remoter and deeper mines is irreversible. This means that in the longer term, the bottom price for a mineral is determined by the marginal extraction costs of that mineral. Cyclical variations of the market price are superposed on the extraction costs. Nevertheless, the market price will not decrease structurally below the level of the marginal costs for extraction and exploration, because mine owners will not want to work at a loss. At that point, mines will be closed, as has happened to many mines in Europe and the United States.

7.3.1   The relationship between extraction costs and geological scarcity

The cumulative supply curve (or cumulative availability curve) is a theoretical concept that reflects how the total of cumulative supply of a mineral could vary over *all time* with the extraction costs (Tilton and Skinner, 1987). For mineral commodities, cumulative supply at a certain price is fixed by the amount of the mineral that can be produced profitably at that price. A rising price permits the extraction of a lower grade mineral and higher external costs,
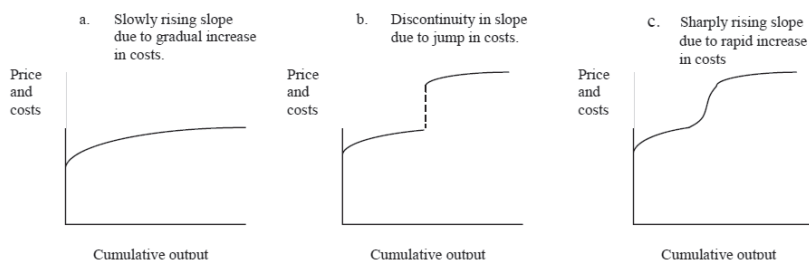
Figure 7-2 Illustrative cumulative supply curves (after Tilton and Skinner, 1987)

if these are included in the price. The higher the price that consumers are willing to pay for a mineral, the greater its possible cumulative extraction.

The type of distribution of the resource in the earth's crust (unimodally or bimodally) determines the slope of the cumulative curve. Tilton and Skinner (1987) present three model cumulative supply curves (See Figure 7- 2).

In Figure 7- 2a a small price increase allows a large increase in cumulative supply and, inversely, a growing demand will only trigger a relatively small increase in price. This type of curve belongs typically to a mineral with the bell-shape unimodal distribution of abundant minerals in the earth's crust, such as aluminum. If a mineral is bimodally distributed in the earth's crust, the cumulative supply curve will have the form shown in Figure 7- 2b or 2c. The steep part of the curves in Figure 7- 2b and 2c represents the so-called mineralogical barrier between the occurrence of a mineral in enriched ores and its occurrence in common rock. Costs may rise by a factor of 10 to 1,000 in a relatively short period of time (Steen and Borg, 2002).

Yaksic and Tilton (2009) have determined the cumulative availability curve for lithium (see Figure 7-3). According to them, the 2009 price of lithium carbonate is USD 6 per kg. The right-hand – flat – part of the curve represents the situation when lithium is extracted from seawater (an almost inexhaustible source of lithium). The costs would then increase until USD 16–22 per kg (USD 7–10 per pound). Such costs do not seem to be insurmountable for application of lithium in lithium batteries. It should be noted that only lithium, sodium, potassium, calcium, and chlorine are elements that can be extracted economically from seawater because of their relatively high abundance in seawater, as demonstrated by Bardi (2009).
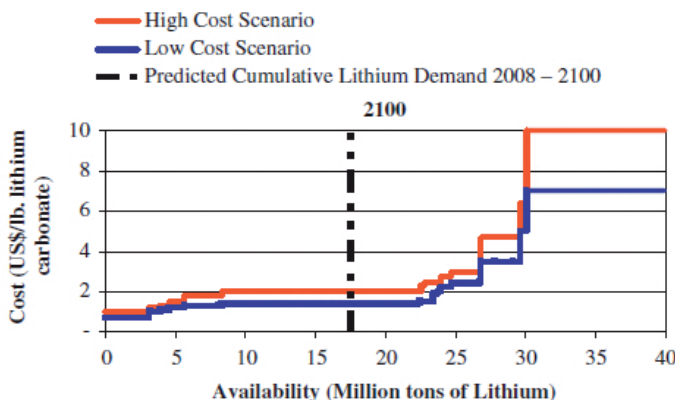
Figure 7-3 Cumulative availability curve for lithium. Derived from Yaksic and Tilton (2009). On the vertical axis the costs are expressed in USD per lb. of lithium. 1 lb. is 0.45359237 kg.

In the future, technological development may also include mining of ocean floor *deposits* of minerals. According to Rankin (2011), the oceanic *crust* is too young for geological processes to have formed ores (Skinner 1976). But large areas of ocean floor contain deposits of minerals formed from erosion processes on the continents (Rankin, 2011). These may be explored and exploited in the future, although their proper extraction will be an environmental and technological challenge. Because large areas of the ocean floor have not yet been explored it is difficult to estimate the total amount of enriched deposits of mineral resources. The oceans cover about 70 % of the earth's crust. It can therefore be prudently concluded that the extractable quantity of mineral deposits on the ocean floors may be substantial in an absolute sense, but will probably not be more important than the amounts available in the continental earth's crust. This means that the geological availability of various minerals on the sea bed will not be so high that the discussion on future geological scarcity of mineral resources will become irrelevant.

The maximum extraction cost of a mineral resource is determined by the cost of extraction from common rock or from seawater. Once this is the case, scarcity no longer plays a role. The quantities available in common rock and seawater are almost inexhaustible. Technically it is possible to extract minerals from common rock, but it is very expensive. According to Skinner (1976), the energy consumption for extracting copper from common rock is ten times higher than that for extracting copper from copper ore. This is supported by Harmsen et al. (2013), Bardi (2013), and Norgate and Jahanshahi (2010). Steen and Borg (2002) have calculated the costs of extraction of minerals from common rock for a number of metals (See Table 7-4).

Table 7-4 Cost increase for the production of ore-like metal concentrates from common rock in a sustainable way, including the external costs, compared to current price level (Steen and Borg, 2002)

	Cost increase compared to current price level		Cost increase compared to current price level
Cd	4,000-100,000	Ni	40
Co	30	Pb	700
Cr	20	Sn	200
Cu	90	W	20,000-200,000
Mn	10	Zn	50

The above implies that ultimately the extraction costs of a mineral will asymptotically reach the costs of extraction of the mineral from common rock and/or seawater. This means that the graph describing the development of resource extraction costs over time, assuming that mineral extraction continues after ore exhaustion, is duck-shaped. See Figure 7-4.

The duck shape is applicable for both major and minor elements. In the case of major elements, the slope of the curve (during time period B) will be gentle and stretched out, whereas
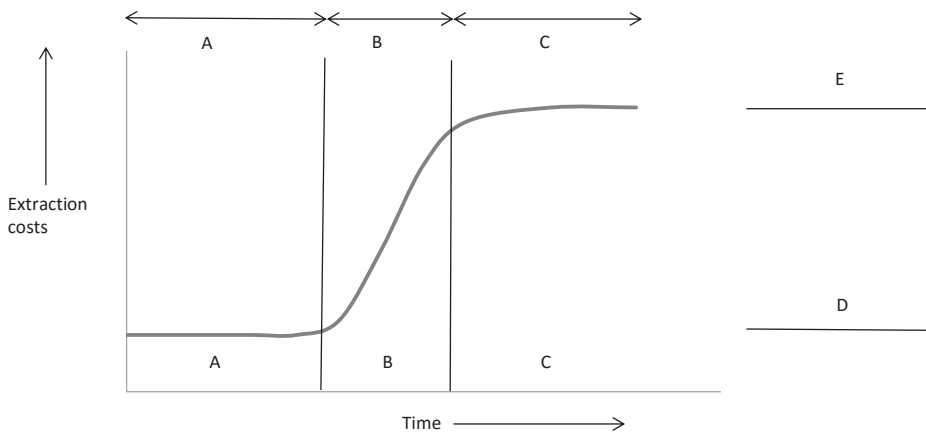
Figure 7-4 Expected trend in extraction cost of mineral commodities
A: Period of relatively low extraction costs. We suppose that this period corresponds with the exhaustion periods indicated in Table 7- 3.
B: Period of increasing extraction costs. This is the transition period between the extraction of minerals from ores and extraction of minerals from common rock and seawater.
C: Period of stable high extraction costs. Ores are exhausted. Minerals are extracted from common rock and seawater.
D: Current extraction costs of commodities.
E: Ultimate cost level for extraction of commodity from common rock or from seawater.

in the case of minor elements with a bimodal distribution in the earth's crust the slope of the curve will be much steeper.

In practice the high price level connected to the high level extraction costs at the right-hand side of Figure 7- 4 will probably not be attained for most minerals in most applications. Depending on the application, from a certain price level on, a substitute will replace the mineral and the so-called choke price will be attained. The choke price is the price level at which the demand for a commodity for a given application will fall to zero because a substitute is available. Extraction will stop as soon as the choke price of a mineral for its last application is reached. Prediction of the specific form of Figure 7- 4 for a given element would be possible in principle but will be complex, e.g. because data are lacking on the distribution of minerals in the earth's crust or because of a lack of data on the availability of future substitutes which will delay exhaustion of ores.

An important question is how much time will elapse between leaving the low price level and reaching the high price level (the duration of the B period in Figure 7- 4). Will the market timely anticipate future scarcity and will prices start to rise appreciably a long time before scarcity of ore reserves is in sight, well before the A period in Figure 7- 4 has ended? This seems unlikely. The price will probably follow the extraction costs, which means that prices will start to increase only in period B. That would be too late, if humankind aims to conserve sufficient ores for future generations.

If scarcity increases rapidly and adequate substitutes are absent or few in number, the market price will probably rise relatively rapidly to a level sufficient to cover the higher costs of extraction or of developing suitable substitutes. However, even a quick price increase of a raw material may not have an immediate effect on demand. This depends on the share of the costs of the raw material in the total costs of its main product applications. A threefold price increase of a raw material may make an average end product no more than about 10% more expensive. This is based on the assumption that raw material prices nowadays usually make up only a small percentage of the cost of an end product (De Bruyn et al., 2009). Only if prices of raw materials were to increase by a factor 10-100 would this result in products that are in the order of 50% to five times more expensive. This means that the eventual price increase of a raw material due to exhaustion of the ores in which it is contained does not necessarily lead to a proportional decrease in the demand for the raw material. The conclusion is that extraction of ores may continue at the same pace even when that they are practically exhausted. This will certainly be the case if a proper substitute is available. In that case mine owners may try to make their capital as profitable as possible and try to sell as much as possible of the remaining ore before it becomes "worthless". More information on the possible impact of substitutability, material efficiency improvement, and recycling on the long-term development of mineral resource prices is included in the supplementary data.

We expect that ultimately the price of mineral resources is determined by geological scarcity and is duck-shaped, as indicated in Figure 7- 4. The scarcer a mineral resource, the earlier the market price will start to increase.

7.4   ACTUAL TRENDS IN MINERAL RESOURCE MARKET PRICES

To investigate whether geological scarcity is visible in the price development of a mineral resource we selected 38 minerals, including two groups of minerals: REE (Rare Earth Elements) and PGM (Platinum Group Metals). They have various geological degrees of scarcity. Table 7- 5 shows the differences between the exhaustion rates of the four scarcity groups. In this context, exhaustion rate is defined as the total amount of the mineral extracted in the 10-year period 2004–2013 as a proportion of the extractable global resources (as derived from UNEP, 2011a).

We have carried out a trend analysis of the market price development of each of the mineral resources of Table 7- 5. Figure 7- 5 presents the trend analysis for antimony. The individual results for the other minerals are included in the supplementary data.

The rate of increase or decrease of the real price of minerals over time is represented by the coefficients of the linear functions. If the coefficient is positive, the long-term trend is a price increase. If the coefficient is negative, the long-term trend is a price decrease. The higher (or lower) the coefficient, the faster the price increase (or decrease).

Table 7-5 Ten-year exhaustion rate in relation to geological scarcity

		Total world extraction between 2004 and 2013 (USGS, 2014)(tons)	Extractable Global Resources (derived from approach of UNEP, 2011a)(tons)	Total extraction in decade between 2004 and 2013 as proportion of the extractable global resources
Very scarce minerals	Antimony	1,722,000	8,000,000	22%
Scarce minerals	Molybdenum	2,211,000	60,000,000	4%
	Gold			
	Rhenium			
	Zinc	116,000,000	2,800,000,000	4%
Moderately scarce minerals	Tin	2,724,000	220,000,000	1%
	Chromium	69,500,000	3,300,000,000	2%
	Copper*	160,000,000	7,500,000,000	2%
	Lead*	40,860,000	3,750,000,000	1%
	Silver	224,000	20,000,000	1%
	Arsenic	465,300	60,000,000	1%
	Bismuth	69,500	5,200,000	1%
	Cadmium	208,400	39,000,000	1%
	Iron ore (gross weight)	22,830,000,000	5,700,000,000,000	0.4%
	Nickel	16,510,000	1,800,000,000	1%
	Tungsten	659,200	80,000,000	1%
	Tin	2,724,000	220,000,000	1%
	Chromium	69,500,000	3,300,000,000	2%
	Boron (as B2O3)	41,330,000	1,900,000,000	2%

	Total world extraction between 2004 and 2013 (USGS, 2014)(tons)	Extractable Global Resources (derived from approach of UNEP, 2011a)(tons)	Total extraction in decade between 2004 and 2013 as proportion of the extractable global resources
Non-scarce minerals			
Aluminum	389,500,000	3,200,000,000,000	0.01%
Magnesium	52,050,000	530,000,000,000	0.01%
Beryllium	1,910	120,000,000	0.002%
Barium	42,802,525	22,000,000,000	0.2%
Cobalt	655,600	680,000,000	0.1%
Gallium	1,692	680,000,000	0.0002%
Germanium	1,168	64,000,000	0.002%
Mercury	16,930	2,700,000,000	0.001%
Indium	6,585	20,000,000	0.03%
Lithium	4,587,000	800,000,000	0.6%
Manganese	132,000,000	24,000,000,000	0.6%
Niobium	579,400	480,000,000	0.1%
Rare Earth Elements (as RE oxide equivalent)	1,211,000	6,700,000,000	0.02%
Platinum Group Metals	4,755	1,900,000	0.3%
Selenium	20,810	2,000,000,000	0.001%
Tantalum	9,908	4,300,000,000	0.0002%
Strontium	4,126,000	14,000,000,000	0.03%
Titanium	100,370	170,000,000,000	0.0001%
Vanadium	642,400	4,300,000,000	0.01%

*The extractable global resources of copper and lead calculated on the basis of 0.01 % of their amounts in the top 1 km of the earth's crust appear to be lower than the USGS Reserve Base figures. Therefore, for these two elements, the supposed extractable global resources have been increased to 2.5 times the USGS Reserve Base figures. This is in line with Rankin (2011, p. 303), who compared the results of an assessment of undiscovered deposits of gold, silver, copper, lead, and zinc in the USA with the ratio of the (UNEP) extractable global resources to the (USGS) reserve base.
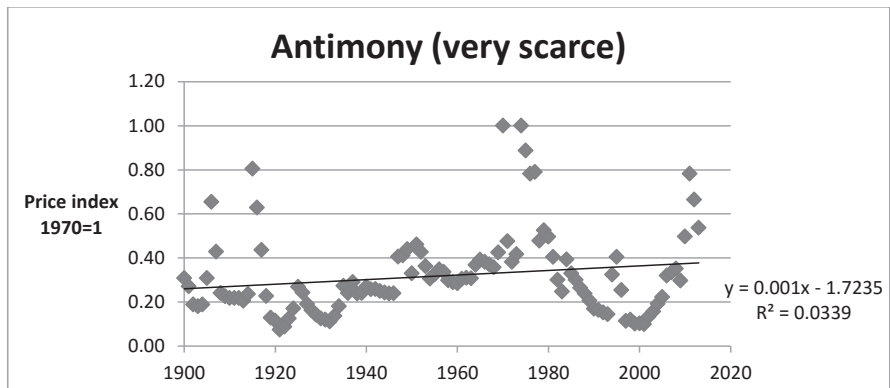
Figure 7-5 Actual price trend for antimony

The line that represents the trend in the price of a specific mineral over time is calculated by the least squares linear regression method. The quality of the fit is presented by R^2. The so-called P-value of the coefficient represents the probability that the value of the coefficient is determined by chance. If the P-value is smaller than or equal to 0.05, the slope of the linear function (the coefficient) is considered to represent the price trend of the mineral in question over time in a significant way. Table 7- 6 presents the coefficients and the related P-values for all the minerals that we have investigated. We compared these coefficients with the geological scarcity of the mineral. To obtain a simple number for the degree of scarcity, we expressed the geological scarcity as the natural logarithm of 1,000,000 divided by the exhaustion time after 2020. This results in a scale from 0 to 11:

- 11: very scarce
- between 9 and 10: scarce
- between 7 and 9: moderately scarce
- <7: not scarce

The significance indicates whether there is a significant correlation between the coefficient of the calculated linear function describing the price development, and the observed price trend.

Table 7- 6 is graphically presented in Figure 7- 6. In this Figure we have only taken into consideration the 25 mineral resources with significant results (coefficients with a P-value ≤ 0.05). A regression analysis of the data shows that there is no significant correlation between geological scarcity and price trend. The P-value is 0.98. See the supplementary data. A second observation is that the price trend coefficients are all near to zero, regardless of geological scarcity.

Table 7-6 Price-trend-over-time coefficient and geological scarcity

Mineral	Period considered	Price-trend-over-time coefficient	P-value of price-trend-over-time coefficient	Significance	Scarcity [a]	Scarcity class
Antimony	1900-2013	0.0010	0.050	*	10.8	Very scarce
Gold	1900-2013	0.0202	5.3E-08	***	10.2	Scarce
Zinc	1900-2013	-0.0036	0.0025	**	9.5	
Molybdenum	1912-2013	0.0022	0.45	Ns	9.4	
Rhenium	1980-2013	0.0062	0.11	Ns	9.1	
Copper	1920-2013	0.0020	0.010	**	8.8	Moderately
Chromium	1900-2013	0.015	1.9E-13	***	8.6	scarce
Boron	1900-2013	-0.0066	0.0047	**	8.4	
Tin	1900-2013	0.0024	0.027	*	8.3	
Silver	1900-2013	0.0037	0.068	Ns	8.2	
Lead	1900-2013	-0.0030	0.00038	**	8.2	
Bismuth	1900-2013	-0.010	1.1E-22	***	8.6	
Nickel	1920-2013	0.0047	0.00002	***	8.0	
Iron	1900-2013	0.0043	9.7E-07	***	7.9	
Tungsten	1900-2013	-0.000092	0.95	Ns	7.9	
Arsenic	1925-2013	-0.0059	0.0007	***	7.7	
Cadmium	1900-2013	-0.0070	7.2E-17	***	7.5	
Barium	1900-2013	-0.0054	2.6E-06	***	6.6	Not scarce
PGM	1940-2013	0.0071	3.2E-05	***	6.6	
Manganese	1900-2013	0.012	5.3E-08	***	6.5	
Cobalt	1900-2013	-0.013	5.3E-05	***	6.1	
Niobium	1964-2000	-0.015	0.10	Ns	6.1	
Lithium	1960-2013	-0.015	1.2E-11	***	4.7	
Indium	1946-2013	-0.0057	0.11	Ns	4.6	
Strontium	1935-2013	0.022	9.0E-05	***	4.5	
REE	1960-2013	0.11	0.0014	**	4.2	
Tantalum	1964-2013	-0.0033	0.82	Ns	4.0	
Vanadium	1910-2013	-0.011	6.4E-09	***	3.8	
Aluminum	1940-2013	-0.0097	2.1E-16	***	3.7	
Magnesium	1950-2013	-0.0021	0.0012	**	3.6	
Germanium	1960-2013	-0.0047	0.093	Ns	1.8	
Beryllium	1940-2013	-0.019	1.4E-12	***	1.7	
Selenium	1920-2013	-0.0012	0.383	Ns	1.2	
Mercury	1900-2013	-0.0028	0.0029	**	1.0	
Gallium	1980-2013	-0.0044	1.5E-07	***	-0.1	

[a] Scarcity is expressed as Ln (1,000,000 / exhaustion time after 2020)
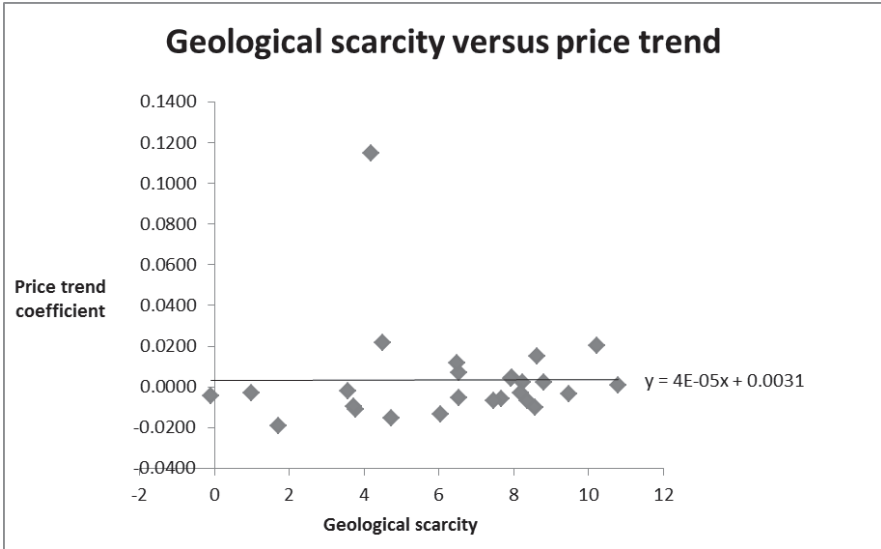
Figure 7-6 Geological scarcity versus price trend. Geological scarcity is expressed as Ln (1,000,000 / exhaustion time after 2020)

7.5 THE RELATION BETWEEN GEOLOGICAL SCARCITY OF MINERALS AND THEIR PRICE TREND

Although prices fluctuate in the course of time, it is striking that the real price of the investigated minerals remains remarkably stable over a long period.

The hypothesis, as explained in Section 7.3, is that after an initial price decrease at the start-up of extraction of a mineral, the market price of that mineral resource will remain stable for a long time. Then, exhaustion of ores will lead to a relatively fast price increase. The greater the geological scarcity of the mineral, the earlier the price increase will start.

The price trend analysis of 38 minerals for the period 1900 to 2013 demonstrates that none of the minerals considered shows a fast price increase. For a long time, price changes (whether an increase or decrease) are very small. Regression analysis demonstrates that there has been no significant difference in price trends between geologically scarce minerals and geologically abundant minerals thus far. The data and the detailed results of the regression analysis are included in the supplementary data.

Our conclusion is that, thus far, viewed over the long term, the prices of all minerals considered have stayed quite stable (shown by the very low slope values in Table 7- 6 and Figure 7- 6), regardless of their scarcity. The observation of stable prices is in line with the conclusions of Krautkraemer (1998).

We used the inflation correction figures provided by the United States Geological Survey (2015). USGS uses the official Consumer Price Index provided by the Bureau of Labor Statistics. However, according to Svedberg and Tilton (2003), the deflator used by USGS overestimates the inflation. They contend that the real price of copper, nickel and silver would fall over the long term (130 years), whereas the real prices of lead and zinc would be more or less constant on the long run. Cuddington (2010) and Fernandez (2012) also support the conclusion that the real prices of mineral resources have not changed much over a long period of time.

We hypothesized that the prices of geologically scarcer minerals will start rising earlier than the prices of less scarce minerals, but thus far the market has not differentiated on the basis of future geological scarcity. Hence, geological scarcity is not yet so critical that the market reacts. The market price does not (yet) reflect the large differences in geological scarcity of the minerals considered. This phenomenon might be explained as follows. The time horizon at which the effects of geological scarcity will be felt is at least several decades to centuries away. The time horizon of market prices seems to be some years to about a decade maximum, taking into consideration that the maximum forward time for futures on the London Metal Exchange is 123 months.

Table 7-7 Unit values of commodities in the USA in 2010, expressed in 1998 USD per kilogram. Derived from USGS (2014)

	2010 unit value in the USA per kg, expressed in 1998 USD, rounded
Scarce minerals	
-Antimony	7
-Molybdenum	26
-Zinc	2
Moderately scarce minerals	
-Tin	20
-Chromium	2
-Copper	6
-Lead	2
-Boron (as B_2O_3)	0.5
Non-scarce minerals	
-Aluminum	2
-Magnesium (as MgO)	0.4
-Beryllium	375
-Titanium (as TiO_2)	2
-Vanadium	19

Table 7- 7 shows that the absolute prices of minerals is not related to geological scarcity either. The most expensive mineral (beryllium) is part of the group of non-scarce minerals, and one of the cheaper minerals is zinc, which belongs to the group of scarce minerals.

On the basis of the analysis of the historical price trends we conclude that geological scarcity is not yet a factor with a discernable influence on the pricing of mineral resources. It remains unclear how near to exhaustion the market will react with price increases linked to geological scarcity. It also remains unclear whether – at the moment the market starts to reflect geological scarcity – a sufficient amount of the mineral resource will remain for extraction by future generations.

7.6 CONCLUSIONS AND DISCUSSION

The question addressed in this paper is whether the price mechanism of the free market system can be expected to slow down the extraction of geologically scarce minerals automatically and timely, in order to keep sufficient resources available for future generations. By comparing the real price development of commodities of varying geological scarcity over a long period of time, we investigated whether the price trends of mineral resources are related to geological scarcity. A limitation of the straightforward regression analysis of time series data applied in this study is that it is based on a large number of assumptions about the behavior of the variables, such as implied by stationarity of the system. We are aware that the relationships may become affected if non-stationary processes are involved.

We conclude that despite fluctuations in mineral resource prices, there is no significant correlation between the geological scarcity of a mineral resource and its price trend for the period that we have considered. The price trend of an abundant resource with sufficient geological reserves for thousands of years does not differ significantly from the price trend of a geologically scarce mineral resource whose ores may be exhausted within decades or a century. We therefore argue that we cannot be certain that the price mechanism of the free market system will lead to timely, automatic, and sufficient conservation of geologically scarce non-renewable mineral resources for future generations. When the point is reached that the ores of a geologically scarce mineral are nearly exhausted, the resource price is expected to increase rapidly. We raise the question of whether this is sufficiently timely for adequate conservation of geologically scarce mineral resources for future generations. We also question whether increased recycling of the stocks of minerals that have accumulated in society will eventually be sufficient to solve scarcity for future generations. Inevitably, some of the minerals will dissipate into the environment. Because of these concerns we suggest international policy measures be created and implemented to increase the price of the scarcest mineral resources, thus promoting accelerated substitution and recycling and safeguarding a sufficient supply of the geologically scarcest mineral resources for future generations.

ACKNOWLEDGMENTS

REFERENCES

Ayres, R.U., van den Bergh, J.C.J.M., Gowdy, J.M., 2001, Strong versus weak sustainability: economics, natural sciences, and "consilience". Environ. Ethics 23(2)155-168

Bardi, U., 2009, Mining the oceans: can we extract minerals from seawater? The oil drum: Europe

Bardi, U., 2013, Plundering the Planet, 33rd report for the Club of Rome

Baumgärtner, S., Quaas, M., 2010, Sustainable economics – General versus specific, and conceptual versus practical. Ecol. Econ. 69,2056-2059

Bringezu, S., Schutz, H., 2001, Material use indicators for the European Union, 1980-1997, Economy-wide material flow accountants and balances and derived indicators of resource use. Eurostat

Chen, X., Qiao, L., 2001, A preliminary material output analysis of China. Popul. Environ., 23(1)117-126

Copper Alliance, 2015, http://sustainablecopper.org/about-copper/33-more-than-copper.html://, 7-12-2015

Cuddington, J.T., 2010, Long term trends in the *Real* real process of primary commodities: Inflation bias and the Prebisch-Singer hypothesis. Resour. Policy 35, 72-76

Dasgupta, P., Heal, G., 1979, Economic Theory and Exhaustible resources. University Press, Cambridge.

De Bruyn, S., Markowska, A., De Jong, F., Blom, M., 2009, Resource productivity, competitiveness and environmental policies. CE Delft, December 2009, Publication number 09.7951, available from www.ce.nl

Erickson, R.L., 1973, Crustal occurrence of elements, mineral reserves and resources. In USGS: Professional Paper 820, p21-25

Eurostat, 2002, Materials use in the European Union, 1980-2000. Indicators and analysis. Office for official publications of the European Communities

Farley, J., Costanza, R., 2002, Envisioning shared goals for humanity: a detailed, shared vision of a sustainable and desirable USA in 2100. Ecol.l Econ. 43, 245-259

Fernandez, V., 2012, Trends in real commodity prices: How real is real? Resour. Policy. 37, 30-47

Giljum, S., 2002, Trade, material flows and economic development in the South: the example of Chile. Paper presented at the 7th biennial Conference of the International Society for Ecological Economics, Sousse Tunisia

Goodland, R., 1995, The concept of sustainability. Annu. Rev. Ecol. Syst. 26, 1-24

Graedel, T.E., Cao, J., 2010, Metal spectra as indicators of development. Proc. Natl. Acad.Sc. 107(49)20905-20910

Gonzalez-Martinez, A.C., Schandl, H., 2008, The biophysical perspective of a middle income economy: material flows in Mexico. Ecol. Econ. 68(1-2), 317-327

Halada, K., Shimada, M. Ijima, K., 2008, Decoupling status of metal consumption from economic growth, Mater. Transact. 49 (3) 411-418

Hansson, S.O., 2010, Technology and the notion of sustainability. Technol. Soc. 32, 274-279

Harmsen, J.H.M., Roes, A.L., Patel, M.K., 2013, The impact of copper scarcity on the efficiency of 2050 global renewable energy scenarios. Energy 50, 62-73

Henckens, M.L.C.M., Driessen, P.P.J., Worrell, E.,2014, Metal scarcity and sustainability, Analyzing the necessity to reduce the extraction of scarce metals. Resour., Conserv. Recycl., 93,1-8

Henckens, M.L.C.M., Driessen, P.P.J, Worrell, E., 2016a, The sustainable extraction of primary zinc and molybdenum. An investigation of measures to reduce primary zinc and molybdenum use to a sustainable level. Unpublished results

Henckens, M.L.C.M., Driessen, P.P.J, Worrell, E., 2015, Towards a sustainable use of boron. Approach to a sustainable use of primary resources. Resour. Conserv. Recycl. 103, 9-18

Henckens, M.L.C.M., Driessen, P.P.J, Worrell, E., 2016b, How can we adapt to geological scarcity of antimony? Investigation of antimony's substitutability and other measures to achieve a sustainable use, Resour. Conserv. Recycl. 108, 54-62

Johnston, P., Everard, M., Santillo, D., Robert, K.H., 2007, Reclaiming the definition of sustainability. Env. Sci.Pollut.Res. 14(1)60-66

Krautkraemer, J.A., 1998, Nonrenewable Resources Scarcity. J. Econ. Lit. 36(4) 2065-2107

NIES/MOE, 2007, Material flow account for Japan. National Institute of Environmental Studies on behalf of the Ministry of the Environment

Norgate, T., Jahanshahi, S., 2010, Smelt, leach or concentrate? Miner. Eng. 23, 65-73

OECD, 2008, Measuring material flows and resource productivity. Synthesis Report, OECD, Paris

Perez-Rincon, M.A., 2006, Colombian international trade from a physical perspective: towards an ecological "Prebisch thesis", Ecol. Econ. 59(4)519-529

Phillips, W.G.B., 1977, Statistical estimation of global mineral resources, Resour. Policy, 3(4), 268-280

Prior, T, Giurco, D, Mudd, G, Mason, L., Behrisch, J., 2012, Resource depletion, peak minerals and the implications for sustainable resource management. Glob. Environ. Change 22,577-587

Rankin, W.J., 2011, Minerals, metals and sustainability, Meeting future material needs, CRC Press

Roglich, D., Cassara, A., Wernick, I., Miranda, M., 2008, Material flows in the United States: a physical accounting of the US industrial economy, WRI report

Russi, D., Gonzalez-Martinez, A.C., Silva-Macher, J.C., Giljum, S., Martinez-Alier, J., Vallejo, M.C., 2008, Material flows in Latin America : a comparative analysis of Chile, Ecuador, Mexico and Peru (1980-2000). J. Ind. Ecol. 12(5-6): 704-720

Seyhan, D., Weikard H-P., van Ierland E., 2012, An economic model of long-term phosphorus extraction and recycling. Resour. Conserv. Recycl. 61,103-108

Skinner, B.J., 2001, Long run availability of minerals, keynote talk at a workshop "Exploring the resource base", Resources for the Future, Washington DC, April 22-23, 2001,

Skinner, B.J., 1976, A second iron age ahead? Am. Sci. 64, 158-169

Steen, B., Borg, G., 2002, An estimation of the cost of sustainable production of metal concentrates from the earth's crust, Ecol. Econ. 42,401-413

Svedberg, P., Tilton, J.E., 2003, The *real* real price of nonrenewable resources: copper 1870-2000, Seminar Paper no 723, Institute for International Economic Studies, Stockholm University

Tilton, J.E., 2001, Depletion and the long-run availability of mineral commodities, Workshop on the Long-Run Availability of Mineral Commodities sponsored by the Mining, Minerals and Sustainable Development Project and Resources for the Future in Washington D.C., April 22-23

Tilton, J.E., Skinner, J.B., (1987) The meaning of resources, Resources and World Development, In: D.J. McLaren and B.J. Skinner, John Wiley &Sons 13-27

Tilton, J.E., 2003, On borrowed time? Assessing the threat of mineral depletion, Minerals &Energy-Raw Materials Report, 18(1), 33-42

UNEP International Panel on Sustainable Resource Management, 2011a, Working group on geological stocks of metals, working paper

UNEP International Resource Panel, 2011b, Decoupling Natural Resource Use and Environmental Impacts from Economic Growth, UNEP

United Nations General Assembly, 2014, Report of the Open Working Group of the General Assembly on Sustainable Development Goals, 12 August

United Nations, 2011, World Population Prospects, The 2010 Revision, Population Division, Department of Economic and Social Affairs, United Nations

USGS, United States Geological Survey, 2015, Historical statistics for Mineral and Material Commodities in the United States

Van den Bergh, J.C.J.M., 2010, Externality or sustainable economics, Ecol. Econ. 69, 2047-2052

Van Vuuren, D., Strengers, B, de Vries, H., 1999, Long term perspectives on world metal use- a system-dynamics model. Resour. Policy, 25(4)239-255

Weisz, H., Krausmann, F., Amann, C., Eisenmenger, N., Erb, K.-H, Hubacek, K., Fischer-Kowalski, M.,2006, The physical economy of the European Union: cross-country comparison and determinants of material consumption. Ecol. Econ. 58(4) 676-698

White, M.A., 2013, Sustainability: I know it when I see it, Ecol. Econ. 86,213-217

World Commission on Environment and Development, 1987, Our Common Future

Worstall, T., 2013, But why did Julian Simon win the Paul Ehrlich bet? http://www.forbes.com/sites/timworstall/2013/01/13/but-why-did-julian-simon-win-the-paul-ehrlich-bet/

Yaksic, A., Tilton, J.E., 2009, Using the cumulative availability curve to assess the threat of mineral depletion, Resour. Policy 34,185-194

Chapter 8

Normative principles for the conservation and sustainable use of geologically scarce mineral resources[12]

12   Resubmitted for publication as: Henckens, M.L.C.M., Ryngaert, C.M.J., Driessen, P.P.J., Worrell,E., Normative principles for the conservation and sustainable use of geologically scarce mineral resources

ABSTRACT

The use of geologically scarce mineral resources needs to be reduced substantially in order to prevent that future generations are going to be deprived of these resources. We have analyzed whether normative principles in existing international environmental agreements are also applicable to the conservation and sustainable use of geologically scarce mineral resources. In the analysis we have focused on the following normative principles:
- The principle of conservation and sustainable use of resources
- The principle of protection of wild flora and fauna, environment and nature
- The precautionary principle
- The inter-generational equity principle
- The sustainable development principle

The result of our analysis is that two of these principles are also applicable to the problem of geologically scarce mineral resources: the principle on conservation and sustainable use of resources and the inter-generational equity principle. Our conclusion is that an international agreement on the conservation and sustainable use of geologically scarce mineral resources is legally and politically justified from the perspective of normative principles in existing international environmental agreements.

KEYWORDS

8.1   INTRODUCTION AND METHODOLOGY

8.1.1   Research question and background

In a previous publication (Henckens et al. 2014), we have made clear that it is necessary to reduce the extraction rate of geologically scarce minerals to a lower, sustainable level. It is not certain that the price mechanism will automatically and timely lead to a sustainable extraction rate (Henckens et al. 2016b). We have suggested that an international agreement be created and implemented with the purpose to artificially limit the extraction of the scarcest mineral resources (Henckens et al. 2016b).

The goal of achieving a sustainable use of mineral resources is a complex matter to regulate, because there is an area of tension between the sovereignty of states to exploit the natural resources on their territory on the one hand and the sustainable use of these resources on the other hand. The sustainable use of mineral resources exceeds the interest of a single state and even of a single generation.

Existing international environmental agreements are based on normative principles such as the principle of sovereignty over the national resources, the inter-generational equity principle and the intra-generational equity principle.

The question in this paper is whether, and if so, which normative principles from existing international environmental governance would also be applicable to justify an international agreement on the conservation and sustainable use of geologically scarce mineral resources.

The global use of a number of mineral resources, such as molybdenum, zinc, copper, chromium, tin and lead is so high that their ores will be depleted relatively soon. The use of these minerals needs to be reduced substantially to prevent that future generations are deprived from these resources (Henckens et al. 2014). Technically, humankind would be able to sufficiently economize on the use of these resources by a combination of substitution, material efficiency and recycling (Henckens 2015, 2016a, 2016c).

For *the short term*, in view of (uncertain) future crisis situations, some governments have decided to strategically stockpile certain raw materials. In EU Directive 2009/119/EC, EU member States are obliged to maintain minimum stocks of crude oil and/or petroleum products (EU, 2009). After the end of World War I the government of the USA decided to maintain strategic stocks of a number of materials (Global Security, 2015). Many governments (including the European Union, Germany, France, Finland, The Netherlands, USA, Canada, Japan, Korea and Taiwan) prepared strategies based on so-called criticality studies on the short term availability of materials that are critical for the economy (Department for Environment, Food and Rural Affairs, 2012). The background of these strategies is geopolitical in the first place: the fear that monopolist producers might deliberately stop or reduce the production and delivery of certain materials for political or financial reasons.

However - for *the long term* - despite the certainty of depletion of geologically scarce mineral resources, governments have not taken action thus far. Some international declarations and

charters directly address depletion of mineral resources (the declaration of the United Nations Conference on the Human Environment (Stockholm, 1972), the UN World Charter for Nature (1982) and the Earth Charter (UNESCO, 2000)). Additionally, there are some international agreements that address the exploitation of mineral resources :

- the United Nations Convention on the Law of the Sea (UNCLOS 1982),
- the Protocol on Environmental protection to the Antarctic Treaty (1991),
- the Agreement governing the Activities of States on the Moon and other Celestial Bodies (1979)).

But these agreements are limited to areas outside national jurisdiction and to the way of exploitation of mineral resources (for the benefit of mankind as a whole, application of the precautionary approach, use of best environmental practices, or prohibition of exploitation of mineral resources). They do not address scarcity and depletion.

Thus far, no internationally binding agreement that limits the extraction of geologically scarce mineral resources has materialized. Neither the international community nor individual countries have taken concrete measures or steps to prepare for future depletion of geologically scarce mineral resources. Resource efficiency and the sustainable use of resources are advocated in general terms, but thus far there is not a single specific international arrangement for any mineral resource, in contrast to the international agreements on the conservation and protection agreements on specific renewable resources such as biodiversity, endangered fish species, wild flora and fauna and tropical timber.

8.1.2 Geological scarcity of mineral resources and sustainable extraction

Since about 1800, concerns are expressed on depletion of resources (i.e. Malthus (1798), Ricardo (1817), the USA Conservation Movement between 1890 and 1920 (Tilton, 2001), Meadows et al. (1972 and 1992), Kesler (1994), Youngquist (1997), Diederen (2009) and Bardi (2013)). However, opposite opinions have been expressed as well by the so-called resource optimists (i.e. Barnett and Morse (1963), Simon (1980 and 1981), Maurice and Smithson (1984), Adelman (1990), Hodges (1995), Beckerman (1995), Lomborg (2001), Gunn (2011) and Diamandis and Kotler (2012). These authors do not deny the exhaustion of mineral resources, but they stress the potential of technology to solve the problems due to increasing scarcity. In the opinion of the resource optimists and also economists such as Dasgupta and Heal (1974 and 1979), Solow (1974), Goodland (1995) and Perman et al. (2003), a future exhaustion of mineral resources would not be problematic *per se* as long as an increasing amount of human capital such as knowledge, infrastructure and adequate substitutes can adequately replace the natural capital of mineral resources. The conclusion is that the possibility of depletion of certain mineral resources is recognized generally, but the seriousness of the phenomenon and the ethical aspects are valuated differently.

How serious is the depletion of mineral resources? Henckens et al (2014) have estimated for 65 minerals (mainly metals and metalloids) how many years remain (after 2050) until depletion of the global extractable resources of these minerals and how much the extraction rate

of these minerals must be reduced for being sustainable. The points of departure of their calculations were as follows:

- Extractable global resources can be estimated at 0.01 % of the total amount of the resource in the upper 1 kilometer of the continental earth's crust. This estimation is derived from a number of authors (UNEP 2011a, Skinner 1976, Rankin 2011, Erickson 1973)

- An annual increase of the use of mineral resources of 3 % until 2050. Thereafter: use stabilization. This assumption is in line with the decoupling scenario of UNEP (2011b)

With the above points of departure, the conclusion was that of the investigated 65 minerals, 15 will be depleted within about 350 years, if no special action is taken. Table 8-1 shows these 15 elements in order of geological scarcity. The mineral resources are subdivided in four groups according to geological scarcity:

(1) Very scarce: extractable global resources depleted before 2050

(2) Scarce: extractable global resources depleted within 100 years after 2050

(3) Moderately scarce: extractable global resources depleted between 100 and 1000 years after 2050

(4) Not scarce: depletion time of extractable global resources> 1000 years after 2050.

Table 8-1 shows that for some of the 15 minerals, depletion is just one or a few generations ahead.

Table 8-1 Remaining years until depletion of 15 elements and the necessary extraction reduction to attain sustainable extraction (Henckens et al. 2014). For the definition of sustainable extraction it is referred to in section 2.5. Table 8-1 is not exhaustive with respect to geologically scarce elements.

Element	Remaining years after 2050 until depletion	Grouping according to geological scarcity	Necessary extraction reduction compared to 2010 for sustainability
Antimony	-9	Very scarce	-96%
Gold	6	Scarce	-92%
Zinc	50	Scarce	-82%
Molybdenum	50	Scarce	-81%
Rhenium	80	Scarce	-74%
Copper	120	Moderately scarce	-63%
Chromium	150	Moderately scarce	-57%
Bismuth	160	Moderately scarce	-55%
Boron	200	Moderately scarce	-44%
Tin	230	Moderately scarce	-35%
Silver	240	Moderately scarce	-33%
Lead	250	Moderately scarce	-30%
Nickel	320	Moderately scarce	-12%
Iron	330	Moderately scarce	-11%
Tungsten	330	Moderately scarce	-10%

Depletion of a mineral resource does not mean that the mineral has fully disappeared. Ores contain only about 0.01 % of the total amount of the mineral so that 99.99 % of the mineral remains in the Earth's crust. However extraction of this low-grade part will be much more expensive because the concentration is 100s to 1000s of times less than the concentration of the mineral in the ore (Rankin, 2011, Steen and Borg, 2002).

According to Henckens et al. (2014), an extraction rate can be considered sustainable "*if a world population of 9 billion people can be provided with the resource for a period of at least 1000 years assuming that the average per capita consumption of the mineral is equally divided over the world's countries*".

Henckens et al. (2016b) have investigated the likelihood that geologically scarce mineral resources can be conserved for future generations without intervention but instead simply relying on the price mechanism of the free market system. Their conclusion is that, if conservation is left to market forces, it is not certain that geologically scarce minerals will be timely, automatically and sufficiently conserved for future generations. They recommend preparing international policy measures

8.1.3   Methodology

We analyze which normative principles act as the foundation of existing international environmental agreements, basing on literature research and analysis of the content of international environmental agreements. The resulting inventory will enable us to analyze whether these principles are also applicable to justify an international agreement to address the problem of geologically scarce mineral resources.

Normative principles act as foundations of principled environmental governance. We are particularly interested in such principles insofar as they have been legally codified in international environmental agreements. The legal character of normative principles adds a level of seriousness to proposed international policies (objectives which the international community seeks to achieve). International agreements indeed translate non-binding policies into binding legal principles and legal rules. Legal principles, for one, are binding but have a generic character. They do not specify particular actions. Examples are the precautionary principle, the principle of sustainable development, the inter-generational equity principle and the sustainable use of natural resources (Birnie et al. 2009). Legal rules specify particular goals or actions. Note, however, that the distinction between (legal) rules, (legal) principles and policies, as proposed by Dworkin (1977), cannot always be made unambiguously (Beyerlin, 2006).

For the selection of relevant existing international environmental agreements we have primarily used the International Environmental Agreements database of the University of Oregon (Mitchell, 2016). This database comprises over 1100 multilateral and 1500 bilateral agreements. We want to focus on agreements with a broad international support. Normative

principles, which are repeatedly used in broadly supported agreements, might be considered as principles with a broad international support as well. Hence, we have selected 29 multilateral agreements signed from 1960 onwards with a (semi-)global scope and which have been signed and ratified by a substantial number of relevant countries. For the selected agreements, the number of signatories and the number of countries which have ratified the respective agreements reference is made to the supplementary information.

The most important element in this framework is the gravity of the depletion problem as compared to the gravity of environmental problems that have been internationally addressed in various agreements. Our final goal is to find an answer to the question whether the creation of an international agreement on the conservation and sustainable use of geologically scarce mineral resources is justified from the perspective of normative principles that are the foundation of existing international environmental agreements. Our search is policy-oriented in the first place as we seek to identify general principles on which the future governance of mineral resources use could, and should be based.

8.2 NORMATIVE PRINCIPLES IN EXISTING INTERNATIONAL ENVIRONMENTAL AGREEMENTS,

Before focusing on normative principles in international environmental agreements we would like to mention three non-binding but relevant declarations and charters which address depletion of mineral resources:

- The Declaration of the United Nations Conference on the Human Environment in Stockholm (1972)
  Principle 5: "*The non-renewable resources of the earth must be employed in such a way as to guard against the danger of their future exhaustion and to ensure that benefits from such employment are shared by all mankind*"
- The World Charter for Nature (UN, 1982)
  Principle II(d) : "*Non-renewable resources which are consumed as they are used shall be exploited with restraint, taking into account their abundance, the rational possibilities of converting them for consumption, and the compatibility of their exploitation with the functioning of natural systems*".
- The Earth Charter (UNESCO,2000)
  Principle II.5.f: "*Manage the extraction and use of non-renewable resources such as minerals and fossil fuels in ways that minimize depletion and cause no serious environmental damage*"

Although, thus far, the mentioned two charters and the declaration have not paved the way for the adoption of binding international agreements on the depletion of geologically scarce mineral resources, the quoted principles remain relevant in the context of this paper because they might inform (future) customary and treaty law specifically aimed at regulating mineral resources depletion.

Even in the absence of currently applicable specific international norms on mineral resources depletion, we argue that *general* normative principles of environmental law, as they are laid down in international agreements as well as customary international law, could justify an international agreement regarding the depletion of mineral resources.

We have made an inventory of normative principles, which are included in the pre-ambules of the 29 selected international environmental agreements as mentioned in Section 8.1. From these principles we have selected the five principles, which are most directly applicable to achieving the goal of a sustainable extraction rate of mineral resources and could possibly justify an international agreement on this matter. Table 8-2 presents these five principles. As already said in Section 8.1, the selected agreements are all binding multilateral agreements that were signed and ratified by a substantial number of countries. It is referred to the supplementary information for more details.

Table 8-2 Five selected normative principles in 29 broadly supported binding international environmental agreements, which are applicable for achieving the goal of a sustainable extraction rate of mineral resources

Normative principles	Number of international environmental agreements with the respective normative principle
-Principle of Conservation and/or sustainable use of resources	8 out 29
-Principle of Protection of wild flora and fauna , environment and nature	18 out 29
-Precautionary principle	10 out of 29
-Inter-generational equity principle	6 out of 29
-Sustainable development principle	5 out of 29

International environmental agreements also contain other normative principles for instance principles that pertain to fairness, burden sharing and responsibility assignment. These principles include the sovereignty over natural resources principle, *the* intra-generational equity principle, the principle of priority for the special situation and needs of developing countries, the principle of Common but Differentiated Responsibilities in Accordance with Capabilities, the principle of Equitable Contribution to achieving the goal of a convention, the principle that activities may not cause damage to the environment of other states and the Polluter Pays Principle (Kiss and Shelton, 2004). Furthermore, agreements contain *operational principles* (such as the principles of international cooperation, non-discrimination, cost-effectiveness, subsidiarity, proportionality, consistency, resilience and feasibility). These normative principles relating to fairness, burden sharing, responsibility assignment and practicability are relevant as boundary conditions in an agreement on the conservation and sustainable use of mineral resources and determine the architecture of such an agreement. For more background information on these normative principles it is referred to Chapter 9 and the Annex of Chapter 9.

Analyzing the five normative principles of Table 8-2, the first question is whether these principles are all *relevant in* the framework of an international agreement on geologically scarce mineral resources. Application of the principle of protection of wild flora and fauna, environment and nature on scarce mineral resources as a value on their own, without further utility, seems less relevant, certainly compared to the protection of wild flora and fauna, endangered species, beautiful landscapes, etc. As far as we know, mineral ores in the earth do not have a specifically important role as habitat. The stock of minerals, outside ores, is very large, so absolute depletion of a mineral is not at stake. Mineral ores do not have a specific beauty, such as landscapes. Environment and nature protection are intended to protect environment and nature against damage and deterioration due to activities of man such as the extraction, manufacturing and use of mineral resources. Although this is an important issue, it is not the subject of this publication on depletion of resources. Hence, in our view, the principle of protection of wild flora and fauna, environment and nature is not a relevant principle to justify an international agreement on the conservation and sustainable use of geologically scarce mineral resources. The other four selected principles are all relevant for the problem of depletion of geologically scarce mineral resources.

The second question is whether the problem of geologically scarce mineral resources is *grave* enough in the light of the considered principle to justify an international agreement. In the next sections we will elaborate this, focusing on the four remaining selected normative principles (the conservation/ sustainable use principle, the precautionary principle, the intergenerational equity principle and the sustainable development principle).

8.3 THE PRINCIPLE OF CONSERVATION AND/OR SUSTAINABLE USE OF RESOURCES AS A NORMATIVE PRINCIPLE FOR APPLICATION ON THE PROBLEM OF GEOLOGICALLY SCARCE MINERAL RESOURCES

In this section we investigate whether the principle of Conservation and/or Sustainable Use would justify the creation of an international agreement on the conservation and sustainable use of geologically scarce mineral resources. The applicability of this is closely related to the gravity of the problem. For assessing the gravity of a resource problem we have analyzed the pre-ambles of the 29 international environmental agreements mentioned under Table 8-2 on the presence of one or more of the following elements: the size, the seriousness and the urgency of a problem. For each of these gravity elements, we have distinguished sub-elements (see Table 8-3). For details it is referred to the Supplementary Information. As for the sub-elements we assume that certain thresholds (or a combination of thresholds) must be exceeded to justify an international agreement. However, such thresholds cannot be found in the literature. It will remain difficult to design a generally accepted quantitative measuring stick composed from the elements in Table 8-3 along which problems can be put and that would enable to decide mathematically whether or not an international agreement is justified. The political perspectives and the economic interests of countries and individuals

Table 8-3 Elements for assessing the gravity of a resource scarcity problem in view of the potential justification of a global agreement.

Elements of gravity of a resource scarcity problem	Sub-elements
Potential size of the problem	- The number of countries affected (spatial dimension) - The proportion of the resource that is endangered (volume dimension) - The extent that future generations are affected (temporal dimension)
Potential seriousness of the problem	The potential extent of - (Ir)reversibility - The impact on human life, directly or indirectly - The impact on health, safety and survival of the living environment (animals, plants, natural cycles and equilibria, eco-systems, natural tipping points, food chains, biodiversity, habitats) - The impact on the uniqueness of the endangered resource - The impact on economy and welfare
Potential urgency of the problem	- Available time span to redress the developments in order to prevent the problem from becoming too grave to be adequately solved

are too different. The various elements and sub-elements in Table 8-3 have different weights for different actors. Each case will need consideration on its own basis.

Thus far, the principle of conservation and sustainable use in existing international environmental agreements is related to specific (types of) *renewable* resources: for instance the conservation and sustainable use of fish, biodiversity, and tropical timber. These resources are only renewable on the condition that their use is in balance with their natural recovery. The irreversible, global and short-term disappearance was feared if no urgent action was taken at an international level because their consumption rate was exceeding their recovery speed. As stated above, the conservation and sustainable use of *non-renewable* resources (such as mineral resources) is thus far not specifically addressed in binding agreements, only in non-binding instruments, namely the Declaration of the UN Conference in Stockholm on the Human Environment (1972), the UN World Charter for Nature (1982) and the Earth Charter (UNESCO, 2000).

Let us compare the gravity of extinction of endangered biotic resources and species with the gravity of depletion of geologically scarce mineral resources.
For at least four gravity elements, we assess the gravity of depletion of geologically scarce mineral resources to be comparable with the gravity of the problem of extinction of endangered biotic resources and species:
- The affected number of countries
- The extent that future generations are affected
- The irreversibility

- The impact on economy and welfare

The potential impact of depletion of mineral resources on economy and welfare is substantial, because after ore depletion, humankind must replace the resource by - probably more expensive - substitutes providing the same services. New applications of the mineral resource will be hampered because of its increased costs and the flexibility of future generations will be less than without depletion of the resource.

Our conclusion is that the relative gravity of the problem of depletion of geologically scarce mineral resources is such that there is sufficient reason to consider an international agreement from the perspective of the normative principle of conservation and sustainable use of resources.

8.4   THE PRECAUTIONARY PRINCIPLE AS NORMATIVE PRINCIPLE FOR THE PROTECTION OF GEOLOGICALLY SCARCE MINERAL RESOURCES

In this section, we investigate whether the precautionary principle would justify the creation of an international agreement on the conservation and sustainable use of geologically scarce mineral resources.

There are many *definitions* of the precautionary principle. Sandin (1999) provides an overview of 19 different definitions. One of the first internationally accepted definitions of the precautionary principle is included as Principle 15 of the Rio Declaration on Environment and Development (1992):

"In order to protect the environment, the precautionary approach shall be widely applied by States according to their capacities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as reason for postponing cost-effective measures to prevent environmental degradation".

The European Commission (2000) widened the definition of the precautionary principle to the health of humans, animals and plants:

"The precautionary principle covers those specific circumstances where scientific evidence is insufficient, inconclusive or uncertain and there are indications through preliminary objective scientific evaluation that there are reasonable grounds for concern that the potentially dangerous effects on the environment, human, animal or plant may be inconsistent with the chosen level of protection"

Douma (2003) and Trouwborst (2007) provide a concise overview of the application of the precautionary principle. There is no clear dividing line between prevention and precaution. It is a continuum. The difference is the degree of certainty. Preventive measures are taken when it is certain that something unwanted may happen (e.g. fire, disease). Precautionary action is needed when it is not yet completely certain whether a serious and unwanted event may occur and/or what dimensions it may have, but there is a reasonable foreseeability and the threat is realistic, plausible and not hypothetic (e.g. climate change). Some scholars and politicians, especially in the United States of America, consider the precautionary principle as incoherent, internally inconsistent and having a paralyzing effect on industrial and economic

development and therefore strongly oppose against application of the (stronger versions of the) precautionary principle (Sunstein 2005). However, there is also much scientific literature defending the precautionary principle (inter alia Sandin et al. 2002, Tickner et al. 2003, Tickner and Kriebel. 2006, Sachs 2011) or putting it into the perspective of risk assessment (Stirling 2007).

At present, the emphasis of the discussion is not on the fundamentals of the precautionary principle but on its implementation. The precautionary principle has been adopted as a corner stone in international and national declarations, agreements and regulations, both binding and non-binding. According to Sirinskiene (2009), there is sufficient state practice and *opinio iuris* to support the position that the precautionary principle has already crystallized into a general customary rule.

The question is whether the invoking criteria and the scope of the precautionary principle justify an international agreement for the conservation and sustainable use of geologically scarce mineral resources.

The *invoking criteria* of the precautionary principle are connected to the gravity of the problem. Criteria for invocation of the precautionary principle that are shared in most precautionary principle definitions are:

- Threat of serious or irreversible damage (Rio Declaration 1992) , potentially dangerous effects (EC 2000)
- Scientific evaluation of the risk cannot be determined with sufficient certainty (EC 2000), reasonable foreseeability of damage falling short of conclusive scientific proof (International Law Association 2014)

The irreversible damage of the depletion of mineral resources that we foresee is economic:

- Once ores have been depleted, minerals will become 10-1000 times more expensive (Steen and Borg 2002)
- Future generations will be deprived of resources that now are easily available

These damages can be considered serious because they regard humanity as a whole and because future generations will be deprived from certain mineral resources potentially encompassing substantial economic costs. The damages are irreversible because ores will be definitively depleted. In the light of our considerations in section 8.1.2 our conclusion is that there is a reasonable foreseeability of depletion of geologically scarce mineral resources, but there is a debate on the seriousness of the consequences.

The *scope* in the various definitions of the precautionary principle is generally limited to the protection of the environment and human, animal and plant health. Protection and conservation of biotic resources including biodiversity is included in the scope. We did not find any document from international organizations or institutions that includes the depletion of exhaustible mineral resources in the scope of the precautionary principle as applied thus far. The depletion of exhaustible mineral resources has serious risks for the economy in the first place, not for health, safety, or survival of mankind, animals and plants. Thus far a reasonable foreseeability of serious and irreversible damage to the *economy* is not within the *scope* of the precautionary principle as used in international agreements, except in some EU regulations.

However, we cannot think of a good argumentation to exclude future economic problems from taking precautionary measures. Precaution is an inherent part of economic decisions. Vice versa, economic theories are applied to the precautionary principle. See for instance the publications of Gollier and Treich (2003), Gollier et al. (2001), Gollier (2010a and 2010b) and Farrow and Hayakawa (2002). According to these authors, the loss of flexibility has a cost. This is due to irreversible developments (such as e.g. the depletion of mineral ores) and uncertainty and lack of knowledge on the consequences and size of future risks (such as e.g. the risks of climate change). According to Gollier (2010a and 2010b), uncertain future costs must be discounted to a net present value using lower discount rates to the extent that decisions regard a future further away and the uncertainty is bigger.

According to Trouwborst (2007, p. 190), *"the precautionary principle has, from the outset, been an environmental principle"*. On the other hand the European Commission stresses in its Communication (2000) that *"the precautionary principle goes beyond the problems associated with a short or medium term approach to risks. It also concerns the longer run and the well-being of future generations"*. Also, in the 2002 EU Regulation on state aid to the coal industry (EU, 2002, Preamble, par.7), the EU adopts a scope of the precautionary principle that is broader than the environment only: *"Strengthening the Union's energy security, which underpins the general precautionary principle, therefore justifies the maintenance of coal-producing capability supported by state-aid"*. The conclusion is that, at the time, the EU, in its regulations, has broadened the scope of the precautionary principle from human health and environment specifically to the well-being of future generations in general, including economic security.

Summarizing, one could say that there are different views on scope and invoking criteria of the precautionary principle and on the seriousness of the consequences of resources depletion. In Europe there appears to be a broad consensus on the application of the precautionary principle. However, beyond the EU there seems to be disagreement regarding the appropriateness of the precautionary principle. The conclusion is therefore that the applicability of the precautionary principle to the problem of depletion of geologically scarce mineral resources is not sufficiently unambiguous for justifying the creation of an international agreement on this issue.

8.5 THE INTER-GENERATIONAL EQUITY PRINCIPLE AS NORMATIVE PRINCIPLE FOR APPLICATION TO THE PROBLEM OF GEOLOGICALLY SCARCE MINERAL RESOURCES

In this section we investigate whether the inter-generational equity principle would justify the creation of an international agreement on the conservation and sustainable use of geologically scarce mineral resources. The principle of inter-generational equity is included in many international conventions and treaties, including the Rio Declaration on Environment and Development (1992) and the United Nations Framework Convention on Climate Change (1992). Inter-generational equity embodies care for future generations. It means that the current generation just "borrows" the earth from future generations. According to Brown

Weiss (1990a, 1990b, 1992a, 1992b), the inter-generational equity principle consists of three sub-principles:

1. The conservation of options. This concerns conserving the diversity of natural and cultural resource bases

2. The conservation of quality. This sub-principle requires that we leave the quality of the natural and cultural environments in no worse condition than we received it

3. The conservation of access. This means that each generation provides its members with equitable rights of access to the legacy of past generations and conserve this access for future generations.

Inter-generational equity means that future generations may have a legitimate expectation of equitable access to planetary resources (International Law Association 2014). According to Padilla (2002, p 81), "*we should recognize and protect the future generations' right to enjoy at least the same capacity of economic and ecological resources that present generations enjoy*". According to Shelton (2007, p 643), *"Those living have received a heritage from their forbearers in which they have beneficial rights of use that are limited by the interests and needs of future generations. This limitation requires each generation to maintain the corpus of trust and pass it on in no worse condition than it was received".* It is a matter of justice that an intergenerational community gives a voice to voiceless future generations. In this respect, as Agius et al. have pointed out (1998, p 11), "*future generations are similar to those that our society has declared legally incompetent*". It is undeniable that previous and current generations irretrievably and inevitably deplete(d) mineral resources. Therewith the options for future generations are gradually constrained and their flexibility is reduced. It will ultimately be a political decision, though mandated by the legal principle of inter-generational equity, how the current generation leaves the earth for the future generations.

Inter-generational equity needs to be distinguished from *intra-generational* equity. Intra-generational equity does not limit the *use* of resources as such, but it governs the *distribution* of resources and the distribution of the costs and benefits of conventions between people and peoples of the same generation.

There is surely a tension between intra-generational and inter-generational equity: the wish to distribute resources more equitably over the current generation could imply that there is pressure to use more resources than justified on the basis of intergenerational equity. One cannot impose austerity on the current poor for the sake of the future rich. Both now and in the future, intra-generational equity will be an important condition to be able to reach an international agreement on the conservation and sustainable use of geologically scarce mineral resources. It will be difficult to get a global arrangement on the conservation and sustainable use of geologically scarce mineral resources accepted without taking intra-generational equity into account. The availability of geologically scarce mineral resources will need to be limited for all countries and people, also for poor people and poor countries that have never had an abundant access to these resources. However, for mankind it is important to get the consent of poor countries for conservation and sustainable use as well. Without

intra-generational solidarity it will be difficult to ask poor countries for inter-generational solidarity. Intra- and inter-generational equity complement each other. Brown Weiss (1990a, 1990b, 1992a, 1992b) reconciles the inter-generational and intra-generational principle in her 3rd sub-principle of "conservation of access". So does the World Commission on Environment and Development (1987) in its definition of sustainable development. See section 8.6.

For *non-renewable* resources, an equilibrium in which the resource does not decrease in quantity and quality, would imply a zero use of the resource, which would deprive the current and the future generations of the resource. In this sense the sustainable extraction of mineral resources is an oxymoron. Anyhow, the current generation needs to deal as economically (or sustainably) as possible with mineral resources in general and especially with geologically scarce mineral resources, keeping the needs and rights of future generations in mind. The conclusion is that the inter-generational equity principle justifies the creation of an international agreement on the conservation and sustainable use of geologically scarce mineral resources.

8.6 SUSTAINABLE DEVELOPMENT AS NORMATIVE PRINCIPLE FOR THE PROBLEM OF GEOLOGICALLY SCARCE MINERAL RESOURCES

In this section we investigate whether the sustainable development principle would justify the creation of an international agreement on the conservation and sustainable use of geologically scarce mineral resources. It has been argued that the principle of sustainable development has risen to the level of a customary international legal norm (Sands, 2012, p 206 and 208). At the very least, it operates as a hermeneutical tool which helps in the interpretation of existing legal norms (Barral, 2012, p 398). Various international courts and tribunals have invoked the concept, although they have left its exact legal status somewhat unclear (e.g, Gabcíkovo-Nagymaros Project (Hungary v. Slovakia), Judgment, ICJ Reports (1997) 7, at para. 140; Award in the Arbitration regarding the Iron Rhine ('Ijzeren Rijn') Railway between the Kingdom of Belgium and the Kingdom of the Netherlands, 27 RIAA (2005) 35, at para. 59; Case Concerning Pulp Mills on the River Uruguay, ICJ, Judgment, 20 April 2010, para. 177).

The most influential substantive definition of sustainable development, and also the most followed one, is certainly the one formulated in 1987 by the so-called Brundtland Commission in their report "Our Common Future": *"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* (World Commission on Environment and Development 1987). Many natural resources are not sustainably managed. This has led to the introduction of the concept of sustainable use and sustainable development in many treaties and agreements. Also decisions of international courts support the concept of sustainable development (Birnie et al. 2009). However, the concept is interpreted in different ways. Governments, politicians, scientists and people from industry try to make the sustainable development concept operational in

their respective sectors. Johnston et al. (2007) estimate that in 2007 some 300 definitions of sustainability and sustainable development existed in the domain of environmental management and associated disciplines.

It is relevant in this framework to notice that there are diverging points of view on the concept of sustainable development that can be divided in two major classes: the weak sustainability concept and the strong sustainability concept (Hansson, 2010). According to the *weak sustainability* concept, elements of sustainable development are inter-changeable as long as (economic) development and welfare as a whole do not diminish. In this vision, maintaining sustainability is a matter of assuring that total capital (human plus natural) does not diminish. We may pass on less environmental resources to coming generations as long as we pass on more human-made capital instead. Or in Hansson's (2010, p 275) words: *"If we hand over to coming generations new technologies that reduce their needs of natural resources, then according to this view we can deplete more resources now and yet comply with the precepts of sustainability"*. According to Van Den Bergh (2010), adoption of the weak concept of sustainability for mineral resources is no problem as long as the environmental externalities are taken into full account.

The *strong sustainability* concept in its pure form sees human-made and natural capital as different categories that are not interchangeable and that must be preserved separately. In the most extreme version of the concept of strong sustainability, every species and resource must be preserved since it cannot be replaced. Further extraction of exhaustible resources would not be possible anymore. According to Hansson (2010), the strong concept is widely considered as not practicable, whereas the weak notion of sustainability has been criticized to be too lax because it enables depletion of resources provided that this is compensated for by increases in other resources, better health care for instance.

Ayres et al. (2001) suggest a compromise version; the strong concept of sustainability should focus on critical ecosystems and on environmental assets that cannot be replaced by anything else, while the weak sustainability concept should apply to mineral resources. The operational definition proposed by Henckens et al. (2014) for the sustainable extraction of and use of mineral resources, included in section 8.1, can also be considered as a compromise between the weak and strong sustainability concept. Hence, it is not surprising that the interpretation of the sustainable development principle and the connected obligations of states are evolving over time (Barral, 2012).

According to the Brundtland definition, the concept of sustainable development is an integrative principle; it includes previous principles described in this paper: sustainable use of resources and intra- and inter-generational equity. This is supported by Sands et al. (2012). However, the concept of sustainable development is also linked to the concept of the precautionary principle. The 1990 Bergen Ministerial Declaration on Sustainable Development in the United Nations Economic Commission for Europe Region provides that *"in order to*

achieve sustainable development, policies must be based on the precautionary principle". (Bergen, 16 May 1990, para 7; IPE (I/B16_05_90).

Due to the vagueness, the divergent interpretations and the evolving character of the sustainable development principle, it is in our view not unambiguously clear whether the principle of sustainable development would in itself justify the creation of an international agreement on the conservation and sustainable use of geologically scarce mineral resources.

8.7 CONCLUSIONS AND DISCUSSION

8.7.1 Conclusions

Two normative principles from existing international environmental agreements justify also an international agreement on the conservation and sustainable use of geologically scarce mineral resources: the principle of conservation and sustainable use of resources and the inter-generational equity principle. For two other normative principles no conclusion can be drawn whether or not they justify the creation of such an agreement: the precautionary principle and the sustainable development principle.

In our view, the normative principles of (1) Conservation and Sustainable Use of Resources and (2) Inter-generational equity justify an international agreement on geologically scarce mineral resources, because:

- the resources depletion problem is big (all countries will be affected, a large proportion of some resources is endangered, future generations will be affected permanently)
- the resources depletion problem is serious (depletion of resources is irreversible, the potential impact on the interest of future generations is substantial)
- the resources depletion problem is urgent (the available time span to address depletion of some resources has become short).

Because not all mineral resources are scarce and because scarce mineral resources are not all equally scarce, an international agreement on the conservation and sustainable use of geologically scarce mineral resources should at least address the following issues:

- priority ranking of geologically scarce mineral resources
- establishment of sustainable extraction rates for the priority minerals
- a phasing down scheme for the priority minerals.

8.7.2 Discussion

Actually, the problem of geologically scarce mineral resources is generally not perceived grave and urgent enough for an international agreement. This could be explained as follows:

- The consequences of exhaustion of mineral resources are economic. As far as we can see, there are no potentially major impacts on the environment and living species (humans, animals, plants, biodiversity, habitats, ecosystems, etc.)

- The potential consequences of exhaustion of mineral resources appear to be more pre-dictable than the consequences of e.g. the extinction of endangered biotic resources, the loss of biodiversity and climate change
- There is trust that humankind can solve the problems connected to exhaustion of mineral resources. (Hodges 1995, Gunn 2011, Simon 1980 and 1981, Adelman 1990, Beckerman 1995, Lomborg 2001, Perman et al. 2003, Dasgupta and Heal, 1974 and 1979, Heal 1998, Solow 1974)

However, in the opinion of the authors, this explanation does not lead to the conclusion that there would be insufficient reason to justify an international agreement on geologically scarce mineral resources.

Once the necessity and urgency of an international agreement on the conservation and sustainable use of geologically scarce mineral resources is accepted by the international community, the design of such an agreement becomes important. According to us, at least the following issues would need to be considered in a balanced way to reach agreement within the international community on the architecture of the agreement:

- The sovereignty of resource countries over their natural resources and a compensation mechanism for resource countries for their loss of income
- The intra-generational equity principle and the special position of poor user countries

Especially the issue of sovereignty of resource countries over their natural resources will be of eminent concern in an international agreement on the conservation and sustainable use of geologically scarce mineral resources. States have the right to exploit the resources on their territory. It will be difficult to expect that resource countries would voluntarily limit the production of mineral resources, losing the economic advantages. Compensation of the resource countries for their lost income is necessary. This is not new. One could compare it in this respect with the compensation of developing countries for not logging forests in the framework of the UN REDD compensation programme on Reducing Emissions from Defor-estation and Forest Degradation in Developing Countries (UN REDD, 2016). With respect to the principle of national sovereignty over natural resources on the own territory it is referred to the additional information in section A of the Annex with supplementary information to Chapter 9.

ACKNOWLEDGEMENTS

REFERENCES

Adelman MA. Mineral depletion, with special reference to petroleum, Review of Economics and Statistics, 1990; 72(1)1-10

Agius E. Busuttil S. Kim T-C. Yazaki K. Future Generations & International Law, In: Proceedings of the International Experts' meeting held by the Future Generations Programme at the Foundation for International Studies, University of Malta, in collaboration with the Foundation for International Environmental Law and Development (FIELD), University of London; the Future Generations Alliance Foundation, Japan; and the Ministry for the Environment, Malta, Earthscan Publications Ltd, London, 1998

Ayres RU. van den Bergh JCJM. Gowdy JM. Strong versus weak sustainability: economics, natural sciences, and "consilience". Environmental Ethics 2001; 23(2)155-68

Bardi U. Plundering the Planet, In: 33rd report for the Club of Rome, 2013

Barnett H. Morse C. Scarcity and Growth, the economics of natural resource availability, Baltimore, MD: Johns Hopkins University Press, for Resources for the Future, 1963

Barral V. Sustainable development in international law: nature and operation of an evolutive legal norm, European Journal of International Law, 2012;23 (2)377-400

Beckerman W. Small is stupid, London, Duckworth, 1995

Beyerlin U. Different types of norms in international environmental law, policies, principles and rules, The Oxford Handbook of International Environmental Law, edited by Bodansky D., Brunnée J., and Hey E., Oxford University Press, 2006

Birnie PW, Boyle A, Redqwell C, International Law and the Environment, 2009, Oxford University Press

Brown Weiss E. In fairness to future generations and sustainable development, American university International Law Review, 1992; 8 (1)19-26, 1992b

Brown Weiss E. In fairness to future generations, Environment, 1990; 32 (3) 7-11 and 30-31, 1990b

Brown Weiss E. Intergenerational equity: a legal framework for global environmental change, Chapter 12 in Environmental change and international law: New challenges and dimensions, Tokyo: United Nations University press, 1992a

Brown Weiss E. Our rights and obligations to future generations for the environment, The American Journal of International Law, 1990; 84 (1)198-207, 1990a

Dasgupta P. Heal G. Economic Theory and Exhaustible resources, University Press, Cambridge, 1979

Dasgupta P. Heal G. The optimal depletion of exhaustible resources, The Review of Economic Studies, Vol. 41, Symposium of the Economics of Exhaustible Resources 1974; 99, 3-28

Department for Environment, Food and Rural Affairs, UK, A Review of National Resource Strategies, www.defra.gov.uk, 2012

Diamandis PH. Kotler S. Abundance, The future is better than you think, Free Press, New York, 2012

Diederen A. Metal minerals scarcity: a call for managed austerity and the elements of hope, TNO, 2009

Douma WT. The precautionary principle, Its application in international, European and Dutch Law, PhD thesis, University of Groningen, The Netherlands, 2003

Dworkin R. Taking rights seriously, Harvard University Press, Cambridge, Massachusetts, USA, 1977

Erickson RL. Crustal occurrence of elements, mineral reserves and resources. In: USGS, Professional Paper 820, 1973, 21-25

European Commission, Communication from the Commission on the precautionary principle, COM, 2000

European Union, Council Directive 2009/119/EC, Imposing an obligation on Member States to maintain minimum stocks of crude oil and/or petroleum products, 14 September 2009

Farrow S. Hayakawa H. Investing in safety. An analytical precautionary principle, Journal of Safety Research, 33 (2002)165-174

Global Security, DLA Strategic Materials, http://www.globalsecurity.org/military/agency/dod/dnsc.html, 12-10-2015

Gollier C. Debating about the discount rate: the basic economic ingredients, Perspektiven der Wirtschaft-spolitik 2010; 11(s1):38-55, 2010b

Gollier C. Moldovanu B. Ellingsen T. Should we beware of the precautionary principle? Economic Policy, 2001; 16(33) 301-27

Gollier C. Treich N. Decision making under scientific uncertainty: the economics of the precautionary principle, The Journal of Risk and Uncertainty 2003; 27(1) 77-103

Golllier C. Ecological discounting, Journal of Economic Theory 2010; 145, 812-29, 2010a

Goodland R. The concept of sustainability, Annual Review of Ecology and Systematics,1995; 26, 1-24

Gunn G. Mineral scarcity – a non-issue? British Geological Survey, 2011

Hansson SO. Technology and the notion of sustainability, Technology in society 2010; 32 , 274-79

Heal G. Valuing the future, Economic theory and sustainability, Columbia University Press, 1998

Henckens MLCM, Driessen PPJ, Worrell E. Towards a sustainable use of primary boron, Approach to a sustainable use of primary resources, Resources, Conservation and Recycling, 2015; 103,9-18

Henckens MLCM. Driessen PPJ. Worrell E. How can we adapt to geological scarcity of antimony? Investigation of antimony's substitutability and of other measures to achieve a sustainable use, Resources, Conservation and Recycling, 2016; 108, 54-62, 2016c

Henckens MLCM. Driessen PPJ. Worrell E. The sustainable use of zinc and molybdenum. Investigation of measures to reduce primary zinc and molybdenum use to a sustainable level, unpublished results, 2016a

Henckens MLCM. Driessen PPJ. Worrell E., Metal scarcity and sustainability, analyzing the necessity to reduce the extraction of scarce metals, Resources, Conservation and Recycling, 2014; 93, 1-8

Henckens MLCM. Van Ierland EC. Driessen PPJ. Worrell E. Mineral resources: geological scarcity, market price trends, and future generations, Resources Policy, 2016; 49, 102-11, 2016b

Hodges CA. Mineral resources, Environmental issues and Land use, 1995, Science, New Series, 1995; 268 (5215) 1305-12

Johnston P. Everard M. Santillo D. Robert KH. Reclaiming the definition of sustainability, Env.Sci.Pollut. Res.2007; 14 (1)60-6

Kesler SE. Mineral resources, Economics and the Environment, New York, Macmillan, 1994

Kiss A., Shelton D., International Environmental Law, Transnational Publishers Inc., Ardsley, NY, USA, 2004

Lomborg B. The Skeptical Environmentalist, Cambridge University Press, 2001

Malthus T. An essay on the principles of population, 1798

Maurice C. Smithson CW. The doomsday myth, 10,000 years of economic crises, Hoover Institution Press, Stanford University, 1984

Meadows DH. and others, Beyond the limits, Post Mills, VT, Chelsea Green Publishing, 1992

Meadows, DH. and others, The limits to growth, New York, Universe Books, 1972

Mitchell RB. 2002-2016. *International Environmental Agreements Database Project (Version 2014.3).* Available at: http://iea.uoregon.edu/Date accessed: 2 May 2016

Padilla E. Intergenerational equity and sustainability, Ecological Economics 2002; 41, 69-83

Perman R. Ma Y. McGilvray J. Common M. Natural Resource and Environmental Economics, Pearson Education Limited, 2003

Rankin WJ. Minerals, Metals and Sustainability, CSIRO; 2011

Ricardo D. Principles of political economy and taxation, 1817

Rio Declaration, United Nations Conference on Environment and Development, Rio de Janeiro, 1992

Sachs NM. Rescuing the strong precautionary principle from its critics, University of Illinois Law Review, 2011; 1285-1338

Sachs NM. Rescuing the strong precautionary principle from its critics, University of Illinois Law Review, 2011; 1285-1338

Sandin P. Dimensions of the precautionary principle, Hum.Ecol.Risk Assess. 1999; 5 (5) 889-907

Sandin P. Peterson M. Hansson SO. Rudén C. Juthe A., Five charges against the precautionary principle, Journal of Risk Research 2002; 5(4), 287-99

Sands P. Peel J. Fabra A. MacKenzie R. Principles of International Environmental Law, Cambridge University Press, 2012

Shelton D. Equity, The Oxford Handbook of International Environmental Law, edited by Bodansky D., Brunnée J. and Hey Ellen, Oxford University Press 2007

Simon JL. Resources, population, environment: an oversupply of false bad news, Science 1980; 208, 1431-38

Simon JL. The ultimate resource, Princeton, NJ, Princeton University Press, 1981

Sirinskiene A. The status of the precautionary Principle: Moving towards a rule of customary law, Jurisprudence 2009, 4(118) p 349-64

Skinner BJ. A second iron age ahead? Am Sci 1976; 64; 158-69

Solow RM. Equity and exhaustible resources, The Review of economic studies, 41, Symposium on the economics of exhaustible resources, 1974; 29-45

Steen B. Borg G. An estimation of the cost of sustainable production of metal concentrates from the earth's crust, Ecological economics 2002; 42 , 401-13

Stirling A. Risk, precaution and science: towards a more constructive policy debate, EMBO Reports, 2007; 8 (4) 309-15

Stockholm Declaration, United Nations Conference on the Human Environment, Stockholm 1992

Sunstein CR. Laws of fear, Beyond the precautionary principle, Cambridge University Press, 2005

Tickner J. Kriebel D. The role of science and precaution in environmental and public health policy, In: Elisabeth Fisher, Judith Jones and René von Schomberg, Implementing the Precautionary Principle, Perspectives and Prospects, ELGAR, 2006 chapter 3, p 42-62

Tickner JA. Kriebel D. Wright S. A compass for health: rethinking precaution and its role in science and public health, International Journal of Epidemiology 2003, 32, 489-92

Tilton JE. Manuscript for the workshop on the long-run-availability of mineral commodities, sponsored by Mining, Minerals and Sustainable Development Project and Resources for the Future, Washington DC, April21-23, 2001

Trouwborst A. The Precautionary Principle in General International Law: Combating the Babylonian Confusion, Reciel, 2007;16(2) 185-95

UN REDD compensation programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries, www.un-redd.org, 10-6-2016

UNEP International Panel on Sustainable Resource Management. Working group on geological stocks of metals, working paper; April, 2011a

UNEP International Resource Panel, Decoupling natural resource use and environmental impacts from economic growth, UNEP 2011b

United Nations Framework Convention on Climate Change, Preamble, 1992

Van Den Bergh JCJM. Externality or sustainable economics, Ecological Economics 2010; 69, 2047-52

World Commission on Environment and Development (Brundtland Commission), Our common future, 1987

Youngquist, W., Geodestinies, Portland, OR, National Book,1997 Book, 1997

Chapter 9

The set-up of an international agreement on the conservation and sustainable use of geologically scarce mineral resources[13]

ABSTRACT

For more than a century, the use of mineral resources has increased exponentially with annual growth percentages of between 4 and 6%. While for most mineral resources, depletion is not an issue, for some mineral resources the current level of extraction is likely to pose a problem for future generations. Depletion of a mineral resource means that its enriched deposits will have been extracted, and consequently it will become much more expensive for future generations to continue to use these minerals. While technology may reduce some of the adverse effects of depletion, future generations may be deprived of potential innovations for which these specific materials would be essential. The question arises as to how the currently unsustainable extraction of mineral resources can be decreased to safeguard them for future generations. It is submitted that it is unlikely that market forces alone will sufficiently impact the prices of minerals to resolve the unsustainable use of certain minerals timely enough. In this article, it is posited that an international agreement on the conservation and sustainable use of geologically scarce minerals is necessary. The agreement will recognize that the geological scarcity of mineral resources differs between different minerals. It will therefore make a selection of priority minerals, determine how far the extraction rate of these substances must be reduced and decide on a fixed time period within which the extraction must decrease from the current rate to a sustainable rate. The design of such an agreement will be based on two basic principles contained in existing international environmental agreements: (1) the inter-generational equity principle and (2) the principle of conservation of natural resources. Furthermore, the obligatory reduction of the extraction of mineral resources will affect the sovereign rights of resource countries to exploit their own resources. Therefore, any international agreement should make arrangements to ensure resource countries are adequately compensated for their loss of income.

KEY WORDS

9.1 INTRODUCTION

For more than a century, the use of mineral resources has increased exponentially with annual growth percentages of between 4 and 6%. A mineral resource is a concentration of naturally occurring solid, liquid or gaseous material in or on the Earth's crust, in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible (Craig et al. 1988, p 20). Table 9-1 provides the annual increase of the extraction of a number of minerals. The growth is caused by a combination of population growth and economic growth per capita (see Figure 9-1).

Table 9-1 Historical growth rates of the extraction of several important mineral resources (United States Geological Survey, 2015)

	Molybdenum	Chromium	Nickel	Copper	Zinc	Lead	Tin	Grand average
average growth of the world extraction 1900-2013	16.5%	7.6%	7.3%	3.9%	3.5%	2.8%	1.9%	6.2%
average growth of the world extraction 1950-2013	6.0%	4.9%	4.5%	3.5%	3.4%	2.3%	1.2%	3.7%
average growth of the world extraction 2000-2013	5.4%	5.3%	3.3%	2.6%	3.9%	4.4%	1.8%	3.8%
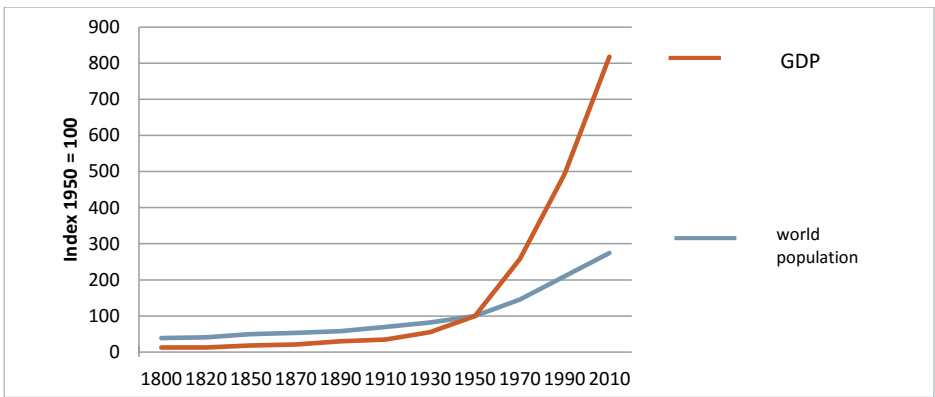
Figure 9-1 Development of world population and global GDP between 1800 and 2010
The population data until 1950 is from United Nations (1999), the population data since 1950 is from United Nations (2015), the GDP data until 1969 is from Maddison (2010) and the GDP data from 1970 is from the United Nations Statistics Division (2014). The GDP data is based on 2005 US$.

The question arises whether current levels of extraction of certain mineral resources will result in a problem for future generations and what measures, if any, humanity should take to reduce current levels of extraction of the scarcest mineral resources to safeguard them for future generations.

The goal of the present paper is to discuss the necessity of an international agreement on the conversation and sustainable use of geologically scarce mineral resources and the possible design of such an agreement.

Discussions on the geological scarcity of mineral resources and the consequences of unsustainable use are nothing new. Section 9.2 will provide a brief overview of the debate between the so-called resource pessimists and the resource optimists, and it will provide an operational starting point of what could be a *"sustainable extraction rate"* of mineral resources. Section 9.3 will examine the role that an international agreement on the conservation and sustainable use of geologically scarce mineral resources could serve, identifying key objectives. Section 9.4 outlines which policy instruments are adequate to implement these objectives. Section 9.5 will look at the set-up and principles in an international agreement. Section 9.6 will look at the financial mechanisms that can support the realization of objectives. Section 9.7 will provide an overview of the core elements of an international agreement on the conservation and sustainable use of geologically scarce mineral resources. Section 9.8 will provide recommendations on further research. Finally, the Supplementary Data include a draft framework agreement on the conservation and sustainable use of geologically scarce mineral resources.

9.2   GEOLOGICAL SCARCITY OF MINERAL RESOURCES AND SUSTAINABLE EXTRACTION

Malthus (1798) predicted that continuous population growth could outpace the production capacity of fertile land, which would then lead to massive starvation by hunger, epidemic diseases and wars for resources. The only solution, as he saw it, was to limit the number of children in poor families. Later, Malthus' pessimistic view on the limited resources for an increasing world population was followed by influential essays from Ricardo (1817) and Mill (1848). Ricardo includes minerals scarcity in his publication as a limiting factor for population growth. Mill, however, recognizes the possibilities of new technology for increasing the productivity of exploiting land and other resources and thus sustaining a growing world population.

By the end of the 19th century there was a broad concern about resource availability, especially in the USA. This was reflected by the so-called Conservation Movement that was active between 1890 and 1920 (Tilton, 2001). The origin of the concern about scarce resources was especially connected to the fast industrialization and the development of vast wild lands. This Conservation Movement, of which President Theodore Roosevelt was one of the prominent members and supporters, promoted the wise use of resources. This entailed using renewable resources instead of nonrenewable resources, more abundant nonrenewable resources instead of less abundant nonrenewable resources and recycled products instead of primary resources (Tilton, 2001).

After World War II, new concerns on the long-run availability of resources were raised in connection with the substantial resource use related to postwar reconstruction. In the USA, this led in 1952 to the creation of the President's Material Policy Commission (or Paley Commission, after its chairman). One of the consequences of the work of this Commission was the sponsoring of organizations and studies on growth and scarcity.

A very influential book within this framework was published by Barnett and Morse (1963). Their findings and views on the relationship between economic growth and depletion of nonrenewable resources stood in sharp contrast with those held previously. The opinion of Barnett and Morse is that technological developments have completely compensated for increasingly scarce, nonrenewable resources and can be expected to do so in future as well. The strong potential of technology development to solve scarcity problems was also emphasized in books by Maurice and Smithson (1984) and Diamandis and Kotler (2012). In 1979, a number of scientists reconsidered and nuanced Barnett and Morse's optimistic vision presenting a spectrum of different views on the subject of minerals' scarcity (Smith, 1979). In 1972, contradicting Barnett and Morse, Meadows et al. published *Limits to Growth* for the so-called Club of Rome, coming to the conclusion that per capita food and industrial output would collapse as a result of exhaustion of mineral resources and environmental degradation (Meadows et al, 1972).In 1992, Meadows and his co-authors updated their advice to the Club of Rome (Meadows et al., 1992), basically confirming their original point of view. The above described differences of view on scarcity reflect the discussion between the so-called resource optimists and resource pessimists. The resource pessimists support the so-called fixed stock paradigm. The Earth is finite, and so the amount of mineral resources is finite as well. However, demand will not stop growing so it is only a matter of time before supply cannot meet demand anymore. Resource pessimists include Meadows et al. (1972 and 1992), Kesler (1994), Diederen (2009) and Bardi (2013), amongst others.

On the other hand, the resource optimists support the so-called opportunity-cost paradigm. The optimists do not deny that mineral resources will deplete gradually, but they have a strong belief that humanity will be able to cope with the effects of depletion. When demand outpaces supply, the costs will rise and – simultaneously – the pressure to find substitutes or alternatives for the depleted mineral. According to the resource optimists, the market will automatically solve the problem. Moreover, mostly – and unlike oil, natural gas and coal – mineral resources are not destroyed by using them. Recycling and reuse are possible. Finally, the total geological stock is enormous. It will always be possible to extract minerals, although the costs will be considerable. Resource optimists are for instance Hodges (1995), Gunn (2011), Simon (1980 and 1981), Adelman (1990) and Beckerman (1995), Maurice and Smithson (1984). Diamandis and Kotler (2012) and Lomborg (2001).

The point of view of the resource optimists is shared by economists such as e.g., Goodland (1995), Perman et al. (2003), Dasgupta and Heal (1974 and 1979), Heal (1998) and Solow (1974). They find that future exhaustion of mineral resources is not problematic *per se,* as long as the decreasing natural capital of depleting mineral resources is sufficiently replaced by increasing human capital, such as knowledge, infrastructure and adequate substitutes. Gaudet (2007) and Hotelling (1931) have the opinion that non-renewable resources must be

"optimally" depleted. On the other hand, the view of the resource pessimists is supported by the International Law Association (2014) stating that future generations may have a legitimate expectation of equitable access to planetary resources.

Both resource pessimists and resource optimists acknowledge that mineral resources are exhaustible. The difference between them is that the optimists trust that humankind will find a timely solution by replacing scarce resources with substitutes. The pessimists, on the other hand, are of the opinion that humanity should not deliberately deprive future generations from scarce resources, regardless of whether they could be replaced by alternative resources. In the view of the authors, the optimistic and pessimistic visions are not mutually exclusive but are in fact reconcilable; humanity will be able to resolve mineral depletion problems, e.g. by replacement of scarce resources and by increasing recycling, but it is also the case that the current generation should not take away geologically scarce resources from future generations.

Hence it is essential that minerals are extracted in a sustainable manner. In order to ensure this, a sustainable extraction rate must be determined. An important question, in this respect, is how large the Extractable Global Resources of a given mineral are. According to the UNEP International Panel on Sustainable Resource Management (2011, page 1), the *"Extractable Global Resources are the amount of a given metal in ore that is judged to be extractable over the long term."* According to Skinner (1976), the upper limit of the extractable global resources would be 0.01% of the total amount of a mineral in the crust. Erickson (1973) and Rankin (2011) also use 0.01% of the total amount of a metal in the crust for estimates of the extractable deposits. In line with these authors, the UNEP International Panel on Sustainable Resource Management believes that an amount of 0.01 % of the total amount available in the crust to 1 km depth is not an unreasonable upper limit of the Extractable Global Resources (EGR) of a mineral (UNEP, 2011, p 21 and 24).

According to calculations of the UNEP International Panel on Sustainable Resource Management, the EGR estimate of 0.01 % of the amount in the upper 1 km of the Earth's crust is, on average, 35 times as high as the latest *"reserve base"* figures of the United States Geological Survey (USGS). The *reserve base* (RB) is defined as the part of an identified resource that meets specific minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness and depth. USGS used to provide reserve base figures until this service was stopped in 2009. Reserves are that part of the reserve base that could be economically extracted or produced at the time of determination. Because the average EGR/RB ratio is 35, the authors of the present paper feel confident that the UNEP estimate of the extractable quantity of mineral resources is not unnecessarily alarming. Therefore, the UNEP approach is adopted in the framework of the elaboration of an operational definition of sustainable extraction.

It ought to be noted that, after the depletion of an extractable mineral resource, 99.99 % of that mineral still remains in the Earth's crust. However its extraction will be much more expensive than the extraction of the enriched top 0.01%. Enrichment factors of geologically scarce mineral resources are 100s to 1000s of times the average concentration of the mineral

in the Earth's crust (Rankin, 2011). Hence, the extraction of a mineral resource from normal rocks will be 100s to 1000s of times more expensive than for the enriched ores of that mineral (Steen and Borg, 2002).

Once the extractable quantity of a mineral resource is determined, it is essential to choose a basis from which to determine whether the extraction rate of a mineral is sustainable. An extraction rate is considered sustainable *"if a world population of 9 billion people can be provided with the resource for a period of at least 1000 years assuming that the average per capita consumption of the mineral is equally divided over the world's countries"* (Henckens et al. 2014). The assumption is made that the minimum conditions for an operational definition of sustainable extraction ought to take account of: (1) the long term continuity of delivery of the resource for a price that is in the same order of magnitude of the price that the current generation pays for the resource, (2) inter- and intra-generational equity and (3) knowledge on the amount of extractable global resources. 1000 years will be sufficient for humankind to organize a circular economy, in which the extraction of minerals from the Earth's crust will be minimal and sufficient resources are left for later generations. An order of magnitude smaller period (i.e. 100 years) would allow depleting certain mineral resources within a relatively short period of time depriving our grandchildren from those resources and without being certain that humanity is able to prepare for a fully circular economy so fast. On the other hand, a period of 10,000 years seems unnecessarily long. A population of 9 billion people has been used in the definition because, according to UN-estimates at the time of publication of the definition (2014) the expected world population in 2050 would be 9 billion and would be more or less stable from then on (United Nations, 2011). Of course, a higher world population makes the depletion issue more urgent.

After analyzing the geological scarcity of 65 minerals – mainly metals and metalloids (Henckens et al. 2014) – it was concluded that the extractable global resources of fifteen of these minerals will be depleted within about 350 years, with five due to be depleted within 100 years. Although for many mineral resources depletion is not imminent, for some minerals it is relatively nearby. Table 9-2 presents these 15 elements in order of geological scarcity. The mineral resources are subdivided in four groups according to their geological scarcity: (a) Very scarce, (b) Scarce, (c) Moderately scarce, and (d) Not scarce.

It should be noted that Table 9-2 may not be exhaustive. Only 65 minerals were included in the investigation. The selection has been derived from the work of the UNEP International Resource Panel on Sustainable Resource Management (2011). In the elaboration of an agreement on the conservation and sustainable use of geologically scarce mineral resources, all mineral resources need to be taken into consideration.

Table 9-2 Remaining years until depletion of 15 elements in a business-as-usual scenario (3% growth until 2050, where after stabilization). Necessary extraction reduction compared to the extraction in 2010 and to the estimated extraction in 2050 (Henckens et al. 2014)

Element	Remaining years after 2050 until depletion	Grouping according to geological scarcity	Necessary extraction reduction for average world citizen compared to 2010 extraction (%)	Necessary extraction reduction for average world citizen compared to extraction in 2050 after 3% annual growth between 2010 and 2050 (%)
Antimony	-9	Very scarce	96%	99%
Gold	6	Scarce	92%	98%
Zinc	50	Scarce	82%	95%
Molybdenum	50	Scarce	81%	94%
Rhenium	80	Scarce	74%	92%
Copper	120	Moderately scarce	63%	89%
Chromium	150	Moderately scarce	57%	87%
Bismuth	160	Moderately scarce	55%	86%
Boron	200	Moderately scarce	44%	83%
Tin	230	Moderately scarce	35%	80%
Silver	240	Moderately scarce	33%	80%
Lead	250	Moderately scarce	30%	79%
Nickel	320	Moderately scarce	12%	73%
Iron	330	Moderately scarce	11%	73%
Tungsten	330	Moderately scarce	10%	73%

9.3 OBJECTIVES OF AN INTERNATIONAL AGREEMENT ON THE CONSERVATION AND SUSTAINABLE USE OF GEOLOGICALLY SCARCE MINERAL RESOURCES

For a number of minerals, depletion of ores is relatively nearby, and a substantial extraction reduction is needed to make the use of these minerals sustainable. Therefore, it could be considered wise to create an international agreement on the conservation and sustainable use of geologically scarce mineral resources. The question arises why there has not been a similar urgency in the negotiation of an international agreement in response to the depletion of minerals as there has been with environmental issues such as biodiversity and climate change. The explanation might be that mineral resource depletion does not directly co-determine the *"safe operating space for humanity"* (terminology from Rockström et al., 2009), but it is primarily an economic problem (with the exception of mineral resources that are essential for life, such as phosphate). Nevertheless, this economic problem may become serious for future generations, if no action is taken. Once the ores of a mineral are depleted, extraction of this mineral from the Earth's crust will become 10-1000 times more expensive (Steen and Borg, 2002).

One could argue that the price mechanism of the free market system could lead automatically to a sufficient reduction of the use of geologically scarce mineral resources due to the inevitable price increase which results from growing scarcity (Dasgupta and Heal, 1979). However, so far, the increasing costs of extraction due to declining ore grades, increasing depths of the mines, more remote mining areas and smaller ore bodies, were neutralized by improving technology (Skinner, 2001; Bardi, 2013; Bleichwitz, 2010). For a long period of time the real prices of minerals have not increased. Moreover, according to USGS data (2015), the price development of geologically scarce minerals does not differ from the price development of geologically non-scarce minerals (Henckens et al., 2016c). The conclusion that real prices are not changing is supported by Krautkraemer (1998), Cuddington (2010) and Fernandez (2012). The market does not yet reflect the large differences of geological scarcity of mineral resources. It remains unclear how closely before depletion of a mineral resource the market will react on geological scarcity by structural and permanent price increases of the depleting mineral. It remains also unclear whether, at the near-depletion-stage, technological development will be able, again, to keep prices down at the same level as nowadays. It is also referred to the essay of Tilton (2003) in this respect. Summarizing, it is not certain whether or not the geologically scarcest mineral resources will be sufficiently saved for future generations, if humanity does not take measures to slow down the extraction of the geologically scarcest mineral resources.

It is for these reasons that an international agreement is proposed with the objective to achieve a situation of sustainable extraction and to equitably distribute geologically scarce mineral resources between the current and the future generations at the lowest cost. This section will discuss how this objective can be translated in concrete, implementable goals. Henckens et al. (2014) have elaborated what their definition of sustainable extraction of mineral resources would imply for 15 geologically scarce minerals (see Table 9-2 above). Comparing the two right columns of Table 9-2, the conclusion is that the longer humankind waits with starting-up extraction reduction, the more drastic the required extraction reduction will need to be; the sooner action is taken, the more gradual the necessary change can be.

Hence, based on the considerations in section 9.2, the objectives of an international agreement on the conservation and sustainable use of geologically scarce mineral resources must address: (1) the selection of minerals for which extraction reduction should be made a priority, (2) the sustainable extraction rate, including the required extraction reduction and the required time span within which the required extraction reduction of the selected priority minerals must take place and (3) the division of the extraction reduction over the various mineral producing countries. This will be elaborated in the following sub-sections.

9.3.1 Selection of priority mineral resources

In order to determine those minerals for which the reduction of the extraction rate is a priority, it is obvious to select the scarcest minerals as priority minerals: antimony, gold, molybdenum, rhenium and zinc which, according to our estimate, will be depleted within about 100 years. Indeed, geological scarcity is an important criterion because the essential purpose of the agreement is to ensure that future generations are not deprived scarce natural resources.

Other selection criteria could be relevant such as: the extent that a mineral is critical for our society, its economic importance, the stability of its delivery, its substitutability and its recycling potential. For an overview of criticality criteria, reference is made to an overview of criteria that have been used in 15 different criticality studies (Achzet and Helbig, 2013).

Elements which are essential for life and which cannot be substituted by other elements may need priority compared to elements which are not essential for life, for instance minerals used in fertilizer and micronutrients. Of the elements in Table 9-2, this concerns boron, molybdenum and zinc. In this framework, the exhaustion of phosphate, though not included in Table 9-2, will certainly need special attention as well. The majority of antimony's applications are in flame retardants. Hence, although antimony is a very scarce element, it can be relatively easily be substituted by other flame retardant systems. Molybdenum, on the other hand, is essential for the production of stainless steel and thus far, molybdenum seems to be hardly substitutable in this application. Therefore, even though molybdenum is less scarce than antimony, it may get more priority in view of a sustainable extraction than antimony (Henckens et al. 2016d, 2016b).

Another factor is the relative economic importance of an element for society in general or for specific countries. This depends on the strategic value of the applications. The overall weighing of these various factors is subjective and is influenced by the economic interests of the involved parties so the priority setting will necessarily be a political process. The political and societal insights with respect to priority setting of the minerals for extraction reduction may change over time. Therefore, an international agreement on the conservation and sustainable use of geologically scarce mineral resources will need to incorporate a priority setting procedure. Due to the potentially changing nature of the priority setting and the notoriously difficult processes involved in adopting amendments to treaties, the details of such a procedure are best elaborated in a separate protocol to ensure that it can be more easily altered to adapt to new realities.

9.3.2   *Extraction reduction goal and phasing down scheme*

How fast must, or can, the required extraction reduction take place? The answer depends on how fast society can change to production of substituting products, more material efficiency and a higher recycling rate without too much destruction of capital. Looking to history, relevant data may be derived from the phasing out of ozone depleting substances, the phasing out of asbestos, the ban of the use of certain chemicals in certain applications (e.g. PCBs and cadmium), the transition to cleaner and more economical cars, the emission reduction of greenhouse gasses and the emission reduction of acidifying air pollutants (e.g. SO_2 and NO_x). Without going into too much detail, one can say that a phasing down period will be in the order of 5 to 10 years, at a minimum. Determining factors are the time needed for the technical development of suitable substitutes and recycling technologies, plus the time needed to realize the necessary industrial facilities. Private companies must get sufficient time to amortize existing facilities in order to prevent too much financial loss. The feasibility of a phasing down scheme needs to be separately assessed for each selected mineral. Because phasing down schemes are specific and may differ per mineral, these schemes should be

elaborated in a separate protocol per mineral. This will need to be reflected in any framework agreement.

9.3.3 Allocation of annual extraction quota of priority minerals to resource countries

For the minerals that are selected for extraction reduction, the capped annual quantities that may be extracted will need to be allocated between the resource countries. The extraction reduction must – over a number of years – gradually arrive at the agreed level of sustainable extraction. For example, it is agreed that the extraction of a certain mineral resource must be reduced by 80% over a period of 10 years in steps of 8% of the original extraction. Assume that at the beginning there are 3 resource countries: A, B and C. The (known) reserves of the resource are respectively R_A, R_B and R_C, and their average annual extraction rates during the last x years are E_A, E_B and E_C. It appears obvious to allocate the extraction quota according to the known reserves in the resource countries. This starting point results in the following allocation A_{Ax} to country A in year x after the start of the extraction quota program:

$$A_{Ax} = (1-0.08x)*R_A*(E_A+E_B+E_C)/(R_A+R_B+R_C),$$

Now assume, new reserves are found in country D and country D decides to exploit the resource from year 8. In this case, the amount allocated to country D (A_D) in year 8 is equal to:

$$\frac{0.36R_D(E_A+E_B+E_C)}{(R_A+R_B+R_C+R_D)}$$

The globally agreed extraction reduction must go on, irrespective of the discovery of new reserves. This is necessary because the global extraction reduction scheme has already taken into account that most of the extractable resources have not yet been discovered (Henckens et al. 2014). That means that the quota of mineral extraction that have been allocated to the countries A, B and C will need to decrease proportionally to the new resource allocation to country D. 10 % extra allocation to country D means 10 % less allocation to the countries A, B and C.

To prevent the allocation system from being too restrictive, it must allow resource countries to trade within the allocated quotas. By allowing trading of allocated extraction quota, several objectives are achieved simultaneously: (1) flexibility of the system, (2) the final objectives are maintained and (3) extraction will take place in countries and mines with the lowest extraction costs. If resource country A cannot deliver, e.g. due to accidents, strikes or geopolitical events, then the other resource countries may be allowed to buy the extraction quota allocated to country A. Country A is allowed to buy back the quota again later on.

Extraction allocation pro rata of proven reserves is a rational approach, but other criteria might be taken into consideration as well, such as production capacity, historical production share, domestic consumption, production costs, dependence on export, population and external debt (see e.g. the discussion within the Organization of Oil Producing Countries (OPEC) on a quota system for oil production (Sandrea, 2003)).

The extractable reserves need to be evaluated regularly to assess whether these are still in accordance with the assumptions that were at the basis of the extraction reduction scheme. This is the task of a research body that must be installed as part of the international agreement on the conservation and sustainable use of geologically scarce mineral resources. The principle of annual extraction quota per resource country and the tradability of extraction quota amongst resource countries needs to be included in the framework agreement. The elaboration of the system requires further research and can be part of a separate protocol. In this framework the experience with existing quota systems, such as the OPEC system of quota for oil production, the United Nations Framework Convention on Climate Change (UNFCCC) CO_2 emission quota system, the emission trading arrangements in the framework of UNFCCC and the EU Emission Trading System, could provide a useful starting point.

9.4 POLICY INSTRUMENTS FOR REDUCING THE EXTRACTION OF GEOLOGICALLY SCARCE MINERAL RESOURCES

Once the geologically scarce mineral resources have been selected and the extraction reduction goals have been determined, technical measures must be defined to achieve these goals. Generally, the technical measures that are taken are: (1) substitution of the resource for another less scarce resource, (2) increasing material efficiency and (3) more recycling. In other publications the authors have demonstrated that the required reduction goals are technically achievable, even if they are very ambitious (Henckens et al, 2015, 2016d and 2016b). The question is which policy instruments are most appropriate. It is generally accepted that market oriented incentives are more efficient than a command and control approach which directly mandates what businesses or individuals should or should not do (Vogler, 2010; Helm et al., 2003; European Economics, 2008; Gerlagh and Van der Zwaan, 2006; Olmstead and Stavins, 2012; Molyneaux et al., 2010 and Goulder and Parry, 2008). The major market oriented incentives are taxing the production and/or use of geologically scarce mineral resources and "cap and trade" systems.

Applied on resource extraction, a cap and trade system fixes the maximum amount that is allowed to be extracted, but it allows for flexibility in the pricing of the extracted resource. A tax system fixes the price of the extracted resource but leaves the extracted quantity uncertain. There is much literature comparing the two systems with each other. This literature is mostly centered on the merits of either system for Green House Gas emission reduction. Criteria that are being used can be divided by the following three dimensions (i.e. Konidari and Mavrakis, 2007 and Mees et al, 2014)

- Performance (e.g. goal achievement, effectiveness etc.)
- Political acceptability (e.g. costs-efficiency, equity/fairness, flexibility, stringency for non-compliance, legal certainty/predictability/credibility, transparency controversy etc.)
- Ease of implementation (e.g. feasibility, accountability, transparency, complexity etc.)

Some authors come to the conclusion that cap and trade is better (Murray et al., 2009; Keohane, 2009). According to other authors taxing systems are better (Avi-Yonah and Uhlmann,

2009). Several authors plea for hybrid systems, combining taxes and cap and trade systems including price floors and price ceilings, banking and borrowing (Molyneaux et al., 2010; Mandell, 2008 and Vogler, 2010). According to others (Goulder and Perry, 2008 and Goulder and Schein, 2013), no instrument is best along all criteria. The conclusion is that a comparison of taxing systems and "cap and trade" systems does not unambiguously lead to a clear conclusion that either of the two systems is better.

The present publication elaborates on a global cap and trade system to achieve a sustainable extraction of geologically scarce mineral resources. The argumentation for this choice is that cap and trade offers greater certainty that the required extraction reduction is achieved. The cap and trade system is successfully applied in the framework of the US Acid Rain Program for the emission reduction of Sulfur Dioxide, and it is also already being applied at an international scale in the EU Emission Trading System for the reduction of the emission of greenhouse gases. Thus far, taxing systems for environmental purposes are only employed at a national scale.

Striving after a global cap and trade approach does not necessarily hamper or withhold concerned user countries to formulate and implement their own resource saving policies in advance. This will have the advantage of offering flexibility to States as to which policies they pursue, such as policies based on taxing or other instruments such as directly imposing or promoting substitution of geologically scarce mineral resources in selected applications and recycling and arranging (voluntary) agreements with or between sectors of industry or society. To the extent that a global cap and trade system would be implemented, such national or regional fall back options may be loosened or abolished again, may work in parallel or compliment a global regime.

Ideally, the approach for solving the problem of geologically scarce mineral resources is global. Geological scarcity is not a local or a regional problem; it is a problem of humanity as a whole, particularly for future generations. However, the climate change problem shows how difficult and time-consuming it can be to agree on a workable and practical solution that is acceptable for all countries despite the fact that the technical pathways are known and feasible. Nevertheless, a global approach is the ideal way to safeguard geologically scarce mineral resources for future generations. In addition, countries and regions may decide to go faster and implement unilateral measures to save geologically scarce mineral resources in advance of a global agreement.

A practical argument in favor of a global approach is the role of the resource countries. Without their cooperation, it will be very difficult or even impossible to substantially reduce the extraction of geologically scarce resources within a limited period of time. The system must include a mechanism that makes resource countries wholeheartedly stand behind an agreed extraction reduction. If not, there is a serious risk that an extraction reduction that is not supported by all resource countries leads to flooding of the market with scarce resources , decreasing their price and frustrating the objectives of the agreement.

9.5 PRINCIPLES OF AN AGREEMENT ON THE CONSERVATION AND SUSTAINABLE USE OF GEOLOGICALLY SCARCE MINERAL RESOURCES

The objectives of the international agreement discussed in section 9.4 refer to what Henckens et al. (2016a) would refer to as "goal orientated principles" of international environmental agreements. "Goal orientated principles" are the principles that are directly connected with the seriousness of the problem to be solved, such as the principle of sustainable use of resources. These can be distinguished from the "design oriented principles" of international environmental agreements which are related to the architecture and execution of the agreement, such as the sovereign right and equity principles (Henckens et al., 2016a). The present section deals with these "design oriented principles", hereinafter referred to as "*principles*".

Principles are preconditions of an agreement. Without adequate principles accepted by the parties of the agreement, the objectives of an agreement cannot be achieved. The aim of these principles is to satisfactorily comply with the justified interests of various partners of the agreement. Relevant principles for an agreement on the conservation and sustainable use of geologically scarce mineral resources are the sovereign right principle, the common concern of mankind principle, ethical principles (intra-generational equity, priority for the special situation and needs of developing countries and fairness), responsibility assignment principles (such as the common but differentiated responsibilities principle) and the polluter pays principle (Henckens et al., 2016a).

Most of these principles relate to burden sharing in connection with the agreement. The formulation and elaboration of these principles is essentially a political process and can therefore end up being a bottleneck of any agreement. The present section shall elaborate on the compensation of resource countries and how to address the special situation and needs of developing countries. In the Supplementary Information more background is provided on the "sovereign right to exploit own resources" principle, the "common concern of mankind" principle, the "common but differentiated responsibilities" principle and the "polluter pays" principle in relation with the issue of depletion of geologically scarce mineral resources.

9.5.1 *Compensation of resource countries and establishment of an annually fixed resource price*

When a resource country loses sovereignty over certain portions of its natural resources (and the related income) by being obliged to reduce the extraction of these resources for the purpose of serving a common concern of mankind, it should be compensated. Compensation of resource countries is justified because not only are their sovereign rights affected but also their income. The price increase that is probably caused by the obligatory extraction reduction of resources is not certain and may not be sufficient to compensate for the decreased production and export of resources. Without a guaranteed compensation for lost income, there is a substantial risk that resource countries may not want to participate in the international agreement, in which they play a crucial role.

The compensation principle is already being brought in practice in the UN REDD compensation program on Reducing Emissions from Deforestation and Forest Degradation which compensates (developing) nations for not logging their forests. The compensation for

extraction reduction of mineral resources is discounted in an increased resource price. To compensate the resource countries, the resource price needs to be increased proportionally to the decrease of the extraction rate. Therefore, from the moment on that extraction reduction is implemented, a resource tonnage price needs to be fixed annually, directly reflecting the imposed extraction decrease.

The compensation of resource countries must be such that their income *with* an agreement on the conservation and sustainable use of geologically scarce resources is equal to their income *without* such an agreement. A resource country should not get more compensation than the income that it would have received without international agreement. Corrections of the general approach may be necessary because the reserves in a country may be near to depletion. It is not necessary to compensate a country for lost income when this country would not have had this income anyway. The principle of the compensation mechanism needs to be part of the framework agreement. The detailed elaboration of the mechanism can be arranged in a separate protocol, since the outcome will be partly the result of political negotiations and may change over time.

9.5.2   Addressing the special situation and needs of developing countries

The solution of the geological scarcity problem may encompass substantial extra costs for all countries, including poor countries. Increasing scarcity of mineral resources is mainly caused by developed countries. Developed countries were able to generate welfare for their people and to build up a physical infrastructure co-based on the massive extraction and use of mineral resources. When limiting the further extraction of geologically scarce mineral resources, developing countries would be confronted with substantially higher costs for these resources, even though they have not yet been able to build up an infrastructure at the same level as developed countries and the majority of people in their societies have not yet been able to enjoy the services provided by these resources to the same extent of a citizen of the average developed country. It will be difficult to expect that developing countries would unconditionally agree with a system that leads to higher costs for their inhabitants without considering that they are not responsible for geological scarcity in the first place. Moreover, without the consent of these countries, an international agreement on the conservation and sustainable use of geologically scarce mineral resources cannot be globally ratified. This means that the role and position of developing countries needs special attention. The interest of the developing countries in this perspective is twofold: (a) that their access to geologically scarce mineral resources remains attainable and (b) that the costs for solving the scarcity problem are acceptable for the developing countries from a historical perspective.

(a) Equitable distribution of geologically scarce mineral resources

Geologically scarce mineral resources can be considered as part of the "*ecological space for humankind*". The right to equitably share the ecological space of mankind can be considered a fundamental human right (Hayward, 2006). From a certain point on, when a resource becomes very scarce, it looks justified to take steps to equitably share such a resource. There are

several ways in which geologically scarce mineral resources could be equitably distributed to countries, e.g.:

- Equal amount per capita
- Equal amount per unit of GDP
- Grandfathering: the distribution is based on the existing amount of resource that is used in a country in a reference year
- Contraction and convergence: convergence from the status quo to equal per capita emission rights over an agreed period of time
- Contraction and convergence with accounting of past use, e.g. from 1990. Countries that have used more than the global average use per capita until an agreed moment in time have to reduce their consumption by this amount in a later period

Pan et al. (2014) provide an overview of 20 alternative allocation schemes for CO_2 emission rights which – in principle – are also applicable for the ways in which geologically scarce mineral resources can be distributed. The distribution system will be the subject of bargaining during the genesis of the international agreement. The agreed distribution system will be laid down in a separate protocol.

(b)Lower costs for developing countries

Each of the user countries – developed or developing – will pay the same fixed tonnage price for the amount of resources that is distributed to it. This resource tonnage price is annually fixed by an international body in the framework of the agreement and is universal for all countries. User countries will be allowed to trade the allocated quota of mineral resources. They may sell the resource for a price that the market (usually mineral processing companies) is prepared to pay. Because of the global extraction reduction, scarcity is artificially increased during the phasing down period. The market price of the resource, that the user countries will be able to receive, will probably become higher than the fixed tonnage price that the user countries have paid. The gross effect of this system will be that the costs of the proposed system are relatively higher for countries with a high consumption of the scarce material and relatively lower for countries with a low consumption of the scarce material.

The per capita consumption of mineral resources is positively related to GDP (Graedel and Cao, 2010). The per capita consumption of mineral resources in developing countries is lower than the per capita consumption of mineral resources in developed countries. With an equal amount per capita distribution system this implies that – under the agreement – developing countries would get more mineral resources distributed to them than they actually use or need. This creates a net profit for these countries, as is demonstrated in detail in section E of the Supporting Material. In this way, developing countries are compensated for the higher costs of the services of the resource in the future and for their contribution to saving of geologically scarce mineral resources currently and in the past.

The extraction quota that are allocated to resources countries must be distinguished from the distribution quota of extracted resources that are allocated to user countries (see Figure 9-2). In our proposal both types of quota are tradable. The allocated quota that is extracted
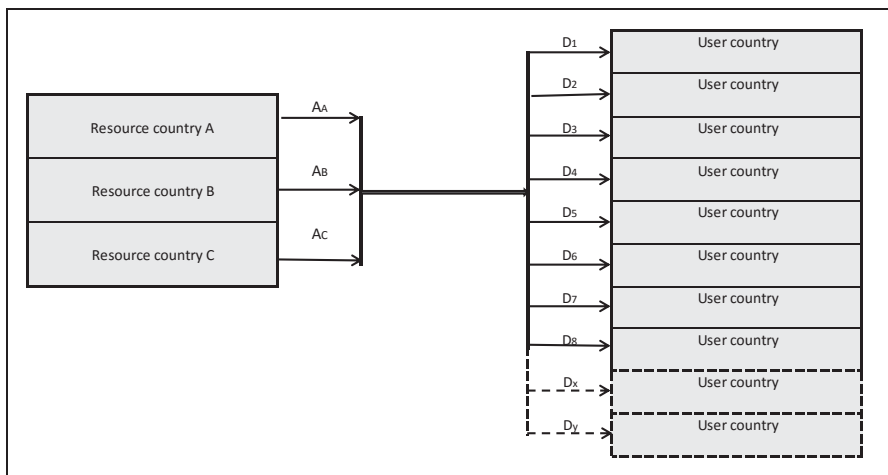
Figure 9-2 From extraction to distribution. A = allocated amount of resources that may be extracted by resource countries. D = distributed amount of resources to user countries.

by resource countries may be traded between resource countries; the resources that are distributed to user countries after extraction may be traded on the market.

Although geologically scarce mineral resources are equitably distributed to countries, it will remain the sovereign right of each country to determine how to manage the distribution of costs and benefits in its own country for its own citizens.

9.6   COSTS OF THE AGREEMENT AND FINANCIAL FLOWS

The costs of an international agreement on the conservation and sustainable use of geologically scarce mineral resources can be split up in three elements:

- The higher costs for substituents, increased recycling and better material efficiency compared to the current situation and the higher market price for the original resource. These costs will vary per mineral resource and per application and it is not easy to make a precise estimation of these costs in general. The optimal mix of substitution, material efficiency measures and recycling will differ per resource and per application. Moreover these costs will depend on the required reduction rate. The lower the required reduction of the extraction rate of a primary material is, the easier it will be to realize the necessary reduction of the use of that primary material and the less the market price of the original material will increase. These types of costs will be paid by the ultimate consumers of the products, within which the scarce resources are included. This is fair, because in this way the extra costs will be distributed according to the use of the resource. The economical consumer will incur fewer costs than the wasting consumer.

- The additional costs to compensate the resource countries for their loss of income. These costs will be incurred by the user countries and must be included in the annually fixed tonnage price that the user countries pay to the resource countries. The annually fixed tonnage price is paid to the administrative body that is in charge of the execution of the agreement and transferred by the administrative body to the resource countries. In return for the paid compensation costs, the user countries should gradually and proportionally become owner of the saved reserves. In this way, from a certain moment on, the remaining reserves are owned by the user countries and compensation does not need to be paid anymore.
- The costs for the international administrative bodies that will be in charge of the implementation and monitoring of the agreement. These are called the transaction costs. Usually these types of costs will not be permitted to exceed some percent of the total market value of the original amount of resources on an annual basis. These costs must be shared by the user countries in proportion to the amount of resource distributed to each
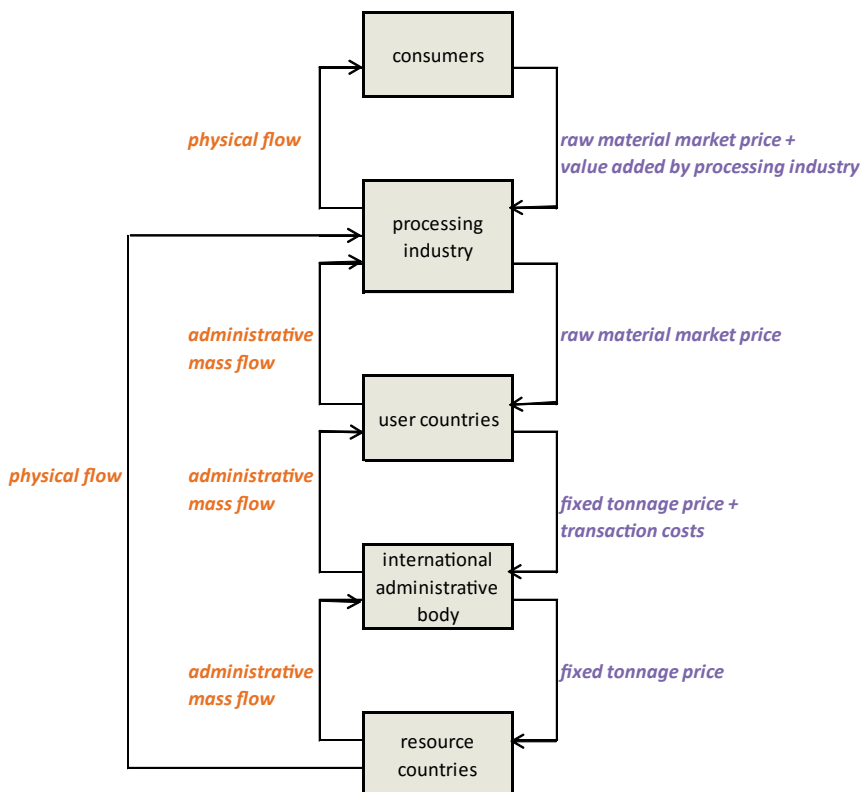
Figure 9-3 Physical mass flows, administrative mass flows and financial flows in the context of the proposed international agreement on the conservation and sustainable use of geologically scarce mineral resources

of them. These costs are paid together with the fixed tonnage price to the international body that is in charge with the execution of the agreement.

The buyers (the processing industry) will pay the market price to the user countries. However, it will be necessary to establish a minimum for the market price for preventing the market price to become lower than the annually fixed tonnage price. The minimum price should be equal to the annual fixed tonnage price plus the transaction costs. The purpose of setting a minimum price is to ensure that a user country, whatever the market price will be, will not suffer any costs if it sells any scarce resources that it received through the distribution system.

The mechanism is presented is Figure 9-3.

9.7 CORE ELEMENTS OF AN INTERNATIONAL AGREEMENT ON THE CONSERVATION AND USE OF GEOLOGICALLY SCARCE MINERAL RESOURCES

The present paper examines the set-up of an International Agreement on the Conservation and Sustainable Use of Geologically Scarce Mineral Resources. The focus is on the objectives, principles, set-up and mechanisms of the agreement.

Objectives
The objectives of an agreement on the conservation and sustainable use of geologically scarce mineral resources are:
- The sustainable use of geologically scarce mineral resources
- Equitable distribution of geologically scarce mineral resources between the current generation and future generations.

Principles
The principles, on which an agreement on the conservation and sustainable use of geologically scarce mineral resources is based, are:
- The sovereign right principle
- The concern to mankind principle
- Compensation of the resource countries for their willingness to reduce the extraction of geologically scarce mineral resources
- Equitable distribution of geologically scarce mineral resources to the world's countries

Set-up
The set-up is a cap and trade system and consists of:
- A priority setting methodology that results in a list of geologically scarce mineral resources, of which the extraction must be reduced with priority
- A procedure for the determination of an extraction reduction goal for the selected mineral resources and a phasing down scheme

- A system for setting annual extraction quota of the selected mineral resources and the allocation of these quota to the resource countries
- A system of equitable distribution of geologically scarce mineral resources to user countries for a fixed price per ton

Financial mechanisms

The financial mechanism of the proposed agreement consists of:

- A system of compensation of resource countries by user countries for reducing the extraction of geologically scarce mineral resources.
- A system to annually fix a resource price that includes the compensation for the resource countries and the transaction costs for the implementation of the international agreement
- A system that makes the user countries owner of the not extracted mineral resources to the extent that they have paid compensation to the resource countries
- The right for the resource countries to trade the extraction quota between the resource countries
- The right for the user countries to sell the distributed resources on the free market
- An international body for the conservation and sustainable use of geologically scarce resources that is responsible for the transfer and appropriate administration of the necessary payments to the extraction countries, and for inspection, monitoring, evaluation and research.

Protocols

For each of the above mentioned set-up elements and financial mechanisms, separate protocols will be needed to elaborate the agreed systems

Institutional Bodies

The following institutional bodies will need to be set-up:

a. Conference of Parties for international cooperation and decision taking
b. Secretariat
c. Administrative body for scientific and technological advice
d. Body on implementation, monitoring and evaluation

A draft of a framework Agreement on the Conservation and Sustainable Use of Geologically Scarce Mineral Resources is included in section F of the Supplementary Data.

9.8 RECOMMENDATIONS

In this paper the main lines of an international agreement on the conservation and sustainable use of geologically scarce mineral resources were laid out. The details of the proposed agreement need further research. This concerns especially:

- The factors that (may) hamper the genesis of an international agreement on the conservation and sustainable use of geologically scarce mineral resources and how these hampering factors could be addressed.
- An analysis of the interests of various partners to the agreement (resource countries and user countries, developed countries and developing countries) and other stakeholders (mining companies, processing industry)
- How to deal with countries that do not ratify the agreement. The draft framework agreement in the supplementary data contains a tentative article on this subject, but this approach needs more research
- The methodologies for priority setting of geologically scarce mineral resources for the determination of the extraction reduction goals and for the phasing down schemes
- The system for the allocation of annual extraction quota to resource countries
- The system of distribution of regulated mineral resources to user countries
- The system of compensation of resource countries for their loss of export opportunities. In this framework, existing compensation schemes, such as the REDD compensation scheme, need to be evaluated.
- The set-up of a system of periodic evaluation of extractable reserves per resource country
- The ownership system of non-extracted resources
- The lessons that may be drawn from the creation, the implementation and the execution of existing international environmental agreements and other relevant mechanisms, such as existing quota systems (oil-OPEC, CO_2-UNFCCC), emission trading schemes (UNFCCC and EU ETS) and compensation schemes (REDD)
- A study on how to harmonize an international agreement on the conservation and sustainable use of geologically scarce resources with existing WTO agreements.

REFERENCES

Achzet, B., Helbig, C., 2013, How to evaluate raw material supply risks – an overview. Resour. Policy, 38,435-47

Adelman, M.A., 1990, Mineral depletion, with special reference to petroleum. Rev. Econ. Stat. 72(1)1-10

Avi-Yonah, R.S., Uhlmann, D.M., 2009, Combating Global Climate Change: why a carbon tax is a better response to global warming than cap and trade, Stanf. Environ. Law J. 28(3) 1-50

Bardi, U., 2013, Plundering the Planet, 33rd report for the Club of Rome.

Barnett, H., Morse, C., 1963, Scarcity and Growth, the economics of natural resource availability. Johns Hopkins University Press, for Resources for the Future, Baltimore M.D.

Beckerman, W, (1995), Small is stupid, London, Duckworth

Bleichwitz R., 2010, International economics of resource productivity. Int. Econ. Policy 7,227-244

Craig, J.R., Vaughan, D.J., Skinner, B.J., 1988, Resources of the Earth, Prentice-Hall, Englewood Cliff, NJ

Cuddington, J.T., 2010, Long term trends in the *Real* real process of primary commodities: Inflation bias and the Prebisch-Singer hypothesis. Resour. Policy 35,72-76

Dasgupta, P., Heal, G., 1979, Economic Theory and Exhaustible resources, University Press, Cambridge.

Dasgupta, P., Heal, G., 1974, The optimal depletion of exhaustible resources, The Review of Economic Studies, Vol. 41, Symp.Econ. Exhaustible Resour.41, 99, 3-28

Diamandis, P.H., Kotler, S., 2012, Abundance, The future is better than you think, Free Press, New York

Diederen, A, 2009, Metal minerals scarcity: a call for managed austerity and the elements of hope, TNO

Erickson, R.L., 1973, Crustal occurrence of elements, mineral reserves and resources, USGS, Professional Paper 820, pp. 21-25

Europe Economics, 2008, A comparison of the costs of alternative policies for reducing UK carbon emissions, www.europe-economics.com, January 2008

Fernandez, V., 2012, Trends in real commodity prices: How real is real? Resour. Policy 37,30-47

Gaudet, G., 2007, Natural Resource Economics under the rule of Hotelling, Can.J. Econ. 40(4) 1033-1059

Gerlagh, R., Van der Zwaan, B., 2006, Options and instruments for a deep cut in CO_2 emissions: carbon dioxide capture or renewables, taxes or subsidies. Energy J. 27(3) 25-48

Goodland, R., 1995, The concept of sustainability, Annu.Rev. Ecol.Syst. 26,1-24

Goulder, H.L., Parry, W.H., 2008, Instrument choice in environmental policy. Rev.Envir.Econ.Policy, 2(2),152-174

Goulder, L.H., Schein, A., 2013, Carbon taxes vs. cap and trade: a critical review, Working Paper 19338 of the National Bureau of Economic Research, Cambridge, MA, http://www.nber.org/papers/w19338

Graedel, T.E., Cao, J., 2010, Metal spectra as indicators for development. Proc.Natl. Acad.Sc.2010, 107, 4920905-20910

Gunn, G., 2011, Mineral scarcity – a non-issue? British Geological Survey

Hayward, T., 2006, Human rights versus emission rights: climate justice and the equitable distribution of ecological space, Global Justice and Climate Change Conference. Institute for Ethics and Public Affairs, San Diego State University (April)

Heal, G., 1998, Valuing the future, Economic theory and sustainability, Columbia University Press

Helm, D., Hepburn, C., Mash, R., 2003, Credible carbon policy, Oxf. Rev. Econ. Policy 19,3

Henckens, M.L.C.M., van Ierland, E.C., Driessen, P.P.J, Worrell, E, 2016c, Mineral resources: geological scarcity, market price development and future generations, under review

Henckens, M.L.C.M., Driessen, P.P.J, Worrell, E., 2016d, How can we adapt to geological scarcity of antimony? Investigation of antimony's substitutability and other measures to achieve a sustainable use. Resour. Conserv. Recycl. 108, 54-62,

Henckens, M.L.C.M., Driessen, P.P.J, Worrell, E., 2014, Metal scarcity and sustainability, analyzing the necessity to reduce the extraction of scarce metals. Resour. Conserv. Recycl. 93,1-8

Henckens, M.L.C.M., Ryngaert, C., Driessen, P.P.J, Worrell, E., 2016a, The applicability of normative principles in existing international environmental agreements on the conservation and sustainable use of geologically scarce mineral resources, under review

Henckens, M.L.C.M., Driessen, P.P.J, Worrell, E., 2016b, The sustainable extraction of primary zinc and molybdenum. An investigation of measures to reduce primary zinc and molybdenum use to a sustainable level, unpublished results

Henckens, M.L.C.M., Driessen, P.P.J, Worrell, E., 2015, Towards a sustainable use of boron. Approach to a sustainable use of primary resources, Resour. Conserv. Recycl. 103, 9-18,

Hodges, C.A., 1995, Mineral resources, Environmental issues and Land use, 1995, Science 268 (5215) 1305-1312, new series)

Hotelling H., 1931, The economics of Exhaustible Resources. J. Polit. Econ. 39(2), 137-175

International Law Association, 2014, Legal Principles relating to Climate Change, Washington Conference

Keohane, N.O., 2009, Cap and trade, rehabilitated: using tradable permits to control U.S. greenhouse gases, Rev. Environ. Econ. Policy, 1-21

Kesler, S.E., 1994, Mineral resources, Economics and the Environment, Macmillan, New York

Konidari, P., Mavrakis, D., 2007, A multi-criteria evaluation method for climate change mitigation policy instruments. Energy Policy 35, 6235-57

Krautkraemer, J.A., 1998, Nonrenewable Resources Scarcity, J. Econ. Lit., 36(4), 2065-2107

Lomborg, B, 2001, The Skeptical Environmentalist, Cambridge University Press, United Kingdom

Maddison, 2010, www.ggdc.net/maddison/Historical_Statistics/horizontal-file_02-2010.xls

Malthus, T., 1798, An essay on the principles of population

Mandell, S., 2008, Optimal mix of emissions taxes and cap-and-trade, J. Environ. Econ. Manag 56,131-140

Maurice, C., Smithson, C.W., 1984, The doomsday myth, 10,000 years of economic crises, Hoover Institution Press, Stanford University

Meadows, D.H. et al., 1972, The limits to growth, New York, Universe Books

Meadows, D.H. et al., 1992, Beyond the limits, Chelsea Green Publishing, Post Mills, VT

Mees, H.L.P., Dijk, J., Van Soest, D., Driessen, P.P.J., Van Rijswick, M.H.F.M., Runhaar, H., 2014, A method for the deliberate and the deliberate selection of policy instrument mixes for climate change adaptation, Ecol. Soc. 19(2)58

Mill, J.S., 1848, Principles of Political Economy

Molyneaux, L., Foster, J., Wagner, L., 2010, Is there a more effective way to reduce carbon missions ?, Energy and management Group, School of Economics, University of Queensland, Brisbane

Murray, B.C., Newell, R.G., Pizer, W.A., 2009, Balancing cost and emissions certainty: an allowance reserve for cap-and-trade. Rev. Environ. Econ. Policy, 1-20

Olmstead, S.M., Stavins, R.N., 2012, Three key elements of a post-2012 international climate policy architecture, Rev. Environ. Econ. Policy, 6(1) 65-85

Pan, X., Teng, F., Ha, Y., Wang, G., 2014, Equitable access to sustainable Development: Based on the comparative study of carbon emission rights allocation schemes. Appl. Energy 130,632-640

Perman, R., Ma, Y, McGilvray, J., Common, M., 2003, Natural Resource and Environmental Economics, Pearson Education Limited

Rankin, W.J., 2011, Minerals, metals and sustainability, CSIRO

Ricardo, D., 1817, Principles if political economy and taxation

Rockström, J., Steffen, W., Noone, K, Persson, A, Stuart Chapin, F III, Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B, de Wit, C.A., Hughes, T, van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A., 2009, A safe operating space for humanity, Nature, 461, 24

Sandrea, R., 2003, OPEC's challenge: Rethinking its quota system, Oil and Gas Journal, 07/28/2003, http://www.ogj.com/articles/print/volume-101/issue-29/general-interest/opecs-challenge-rethinking-its-quota-system.html, 29-1-2016

Simon, J.L., 1980, Resources, population, environment: an oversupply of false bad news, Science 208, 1431-1438

Simon, J.L., 1981, The ultimate resource, Princeton, NJ, Princeton University Press

Skinner, B.J., 2001, Long run availability of minerals, keynote talk at a workshop "Exploring the resource base", in Washington DC, Resources for the Future, April 22-23

Skinner, B.J., 1976, A second iron age ahead? Am. Sci. 64, 158-169

Smith, K., 1979, Scarcity and growth reconsidered, Resources for the Future Inc. John Hopkins Press, Ltd London

Solow, R.M., 1974, Equity and exhaustible resources, The Review of economic studies, Symp. Econ. Exhaustible Resour. 41, 29-45

Solow, R.M., 1974, Equity and exhaustible resources, The Review of economic studies, 41, Symp.Econ. Exhaustible Resour. 29-45

Steen, B., Borg, G., 2002, An estimation of the cost of sustainable production of metal concentrates from the earth's crust, Ecol. Econ. 42, 401-413

Tilton, J.E., 2001, Manuscript for the workshop on the long-run-availability of mineral commodities, sponsored by Mining, Minerals and Sustainable Development Project and Resources for the Future, Washington DC, April21-23

Tilton, J.E., 2003, On borrowed time? Assessing the threat of mineral depletion, Miner. Energy-Raw Mater. Rep., 18(1), 33-42

UNEP International Panel on Sustainable Resource Management, 2011a, Working Group on Geological Stocks of Metals, Working Paper, April 6

United Nations, 1999, The world at six billion

United Nations, 2015, World Population Prospects, the 2015 Revision, Population Division, Department of Economic and Social Affairs

United Nations Statistics Division, 2014, National Accounts, December

United Nations, 2011, World Population Prospects, The 2010 Revision, Population Division, Department of Economic and Social Affairs

United States Geological Survey, 2015, Historical statistics for mineral and material commodities in the United States

Vogler, N., 2010, Policy option issues for CO_2 emissions, 2010, Nova Science Publishers, Inc. New York

Chapter 10

Conclusions, reflection and recommendations

10.1   CONCLUSIONS

Scarcity and sustainability
The following definition was formulated for the concept of sustainable extraction rate: the extraction rate of a mineral is sustainable if a world population of 9 billion people can be provided with that resource for a period of 1000 years, assuming that the average per capita consumption is equally divided over the world's countries. On the basis of this definition, the conclusion is that, at present, of the 65 mineral resources investigated, the extraction rate of 17 mineral resources is not sustainable. The following minerals should receive highest priority in view of reduction of their extraction rate: antimony, gold, molybdenum, zinc, rhenium, copper, chromium, bismuth, and boron. The extraction of these mineral resources must be reduced by between about 40% (boron) and about 95% (antimony) to become sustainable. The added value of our study is that geological scarcity has been made concrete and specific. Using our definition for sustainable extraction, mineral resources can be ranked according to their geological scarcity.

Technical solutions to address geological scarcity
In general, the consumption of a material can be reduced (1) by substituting for the material, (2) by increasing material efficiency and (3) by recycling. Different mixes of substitution, material efficiency improvement, and recycling may be applied to achieve a sustainable level of extraction. We have developed a method that starts with the assessment of the substitution potential of the geologically scarce material by suitable alternatives, followed by the opportunities for material efficiency improvement in production and processing of the non-substituted part. Finally, the recycling potential of the remainder must be explored. We have applied this methodology to investigate whether a sustainable level of extraction is feasible for four mineral resources: antimony, boron, molybdenum, and zinc. The general conclusion and added value of our study is that with currently existing substitutes and recycling technologies it seems feasible to achieve the required sustainable level of extraction of the four minerals mentioned, although for molybdenum this will require a big effort.

Geological scarcity in a free market system
We have compared the real price development of 34 different mineral resources and groups of mineral resources (including Rare Earth Elements and Platinum Group Metals) over a period of 113 years with the geological scarcity of these resources. The conclusion is that, thus far, there is not a statistically significant relationship between geological scarcity of mineral resources and their price. Thus far, the price trend of an abundant resource with geological reserves for 1000s of years does not differ significantly from the price trend of a geologically scarce mineral resource, of which the ores may be depleted within decades or a century. We have demonstrated that geological scarcity of mineral resources is not yet a driving force, through the price mechanism, for more substitution and recycling and better material efficiency. Thus it is not certain that the price mechanism of the free market system will automatically lead to a timely and sufficient conservation of scarce non-renewable resources for

future generations. We expect that the market will ultimately react to geological scarcity, but that may be only at the stage at which ores are near depletion. If humanity does not accept this uncertainty or finds this conclusion alarming, then steps need to be taken to anticipate a future with depleting mineral resources.

The approach used to investigate the relationship between geological scarcity and price development of mineral resources is an added value of our study.

Normative principles for an international agreement on the conservation and sustainable use of geologically scarce mineral resources

Thus far, the problem of depletion of geologically scarce mineral resources is apparently not perceived as grave enough for an international agreement on this subject. Therefore, we have investigated whether normative principles from existing international environmental agreements could also be applied to the problem of depleting mineral resources. On the basis of the gravity of the problem of depletion of geologically scarce mineral resources, as compared to the gravity of problems for which international agreement has already been reached, we conclude that two normative principles from existing international environmental agreements justify an international agreement on the conservation and sustainable use of geologically scarce mineral resources as well: (1) the principle of "Conservation and Sustainable Use of Resources" and (2) the "Inter-Generational Equity" principle.

The set-up of an international agreement on the conservation and sustainable use of geologically scarce mineral resources

Based on the findings of our research it is recommended to draft and conclude an international agreement on the conservation and sustainable use of geologically scarce mineral resources. Key elements of such an agreement are:
- A priority setting methodology that results in a list of geologically scarce mineral resources, of which the extraction must be reduced with priority
- A procedure for the determination of an extraction reduction goal for the selected mineral resources and a phasing down scheme
- A system for setting annual extraction quota of the selected mineral resources and the allocation of these quota to the resource countries
- A system of equitable distribution of geologically scarce mineral resources to user countries for a fixed price per ton
- A system of compensation of resource countries by user countries for reducing the extraction of geologically scarce mineral resources.
- A system to annually fix a resource price that includes the compensation for the resource countries and the transaction costs for the implementation of the international agreement
- A system that makes the user countries owner of the not extracted mineral resources to the extent that they have paid compensation to the resource countries

- The right for the resource countries to trade the extraction quota between the resource countries
- The right for the user countries to sell the distributed resources on the free market
- An international body for the conservation and sustainable use of geologically scarce resources that is responsible for the transfer and appropriate administration of the necessary payments to the extraction countries, and for inspection, monitoring, evaluation and research.

Overall conclusion

The overall conclusion of our investigation is that it is not certain that the price mechanism of the free market system will automatically lead to a timely and sufficient reduction of the extraction of geologically scarce mineral resources. Effective steps to achieve a sustainable level of extraction of geologically scarce mineral resources are necessary and technically possible. This can be achieved by the creation of an international agreement on the conservation and sustainable use of geologically scarce resources.

10.2   REFLECTION AND RECOMMENDATIONS

Extractable global resources and the concept of sustainable extraction

We have clarified that it is necessary to define an operational concept of "sustainable extraction". Without such an operational definition, it is not possible to make the distinction between scarce and non-scarce mineral resources and to determine priorities and urgencies. According to our definition, extraction of mineral resources is sustainable if a world population of 9 billion people can be provided with the resource for a period of at least 1000 years, assuming that the average per capita consumption of the mineral is equally divided over the world's countries.

The definition implies that mineral resources are scarce if their extractable global reserves are depleted within 1000 years. This *depletion period of 1000 years* is arbitrary of course. Why opt for such a long (or short) period? The first reason is the concept of sustainability as such. A situation or an action is sustainable, if it can be continued forever. However, per definition, the extraction of ores cannot be sustainable, because the amount of ores in the earth's crust is not unlimited. For some minerals it can be considered quasi unlimited, because of the huge amount of ore compared to the annual extraction, but of other minerals the extractable resources are limited to some decades or some centuries. Even in this perspective, one may consider not restricting the extraction of minerals. However, it is international environmental policy to limit the extraction rate of geologically scarce mineral resources to a rate that takes the interest of future generations into consideration. So it is necessary to choose for an approximation of the concept of sustainability. Though not permanent, the sustainability period should be sufficiently long. What is sufficiently long? 50 years, 100 years, 200 years, 500 years, 1000 years, 10000 years? When considering different time periods, two

factors are important: (1) the capability of mankind to adapt timely to a situation with a much scarcer resource, (2) the possible utility of the resource for future generations. We are positive regarding the capability of mankind to adapt to a situation of a depleting scarce resource. The chapters 3 to 6 show that a situation with (almost) exhausted resources of antimony, boron, zinc or molybdenum, would not be disastrous. Technologically, mankind would be able to adapt and generate the same services as generated now by these resources by substitution, dissipation reduction, a better material efficiency and recycling. In view of the second factor, it is relevant considering that the current generation is taking away irreplaceable resources from future generations without knowing the value that these resources may have for those generations. New applications will continue to be developed. Therefore, according to international environmental policy, it is necessary to deal economically with scarce mineral resources and to save these resources as long as possible. In this perspective we consider a sustainability period of 100 years as too short. That would allow this and the next few generations to completely exhaust resources such as antimony, molybdenum, zinc , gold and rhenium. We propose a sustainability period of 1000 years. Such a period is long enough to be considered as prudent. If scientific or policy views change, then adaptation will not be too drastic. It is clear that the interests of future generations are taken into consideration in this way. Furthermore, the necessary reduction of the concerned resources seems feasible, although for some resources this still needs to be confirmed. We consider a sustainability period of 10,000 years as unnecessarily long, because the steps to be made now would be very drastic in view of such a long time period and the interest of the current generation would be affected too much. In a sensitivity analysis in chapter 2, we have investigated the impact, if we allow a 200 year depletion period (after 2050) instead of 1000 years. The result is that the citizens of industrialized countries still need to reduce the use of 8 mineral resources with more than 50 % compared to the present use of those resources by these citizens.

As for the amount of *extractable global resources* (EGR), two points of departure can be considered : (1) the so called Reserve Base data of the United States Geological Survey and (2) the approach of the UNEP International Resource Panel on Sustainable Resource Management (2011).

The Reserve Base of a mineral, according to the United States Geological Survey, is that part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices including those for grade, quality thickness and depth. Identified resources are resources whose location, grade, quality and quantity are known or estimated from specific geologic evidence. Identified resources include economic, marginally economic and sub-economic components. Since 2009, reserve base data are no longer updated by USGS. Reserve Base data were provided to USGS by national governments. We have used the UNEP approach for the upper limit of the Extractable Global Resources. This is 0.01 % of the amount of a mineral in the upper 1 km of the continental earth's crust. Although the UNEP estimation is rough and categorical, there are strong indications that the total quantity of an element that can be found in anomalies in the earth crust (ores), *"is directly proportional to the crustal abundance of the element"* (Rankin, 2011, p 302):

" - the size of the largest known deposit of each scarce mineral is proportional to the average crustal abundance of the element (Skinner, 1976)

- *The number of known deposits of over 1 million tons of a given metal is proportional to the average crustal abundance of the element (Skinner, 1976)*
- *The known reserves of the elements are proportional to their crustal abundance (McKelvey, 1960, Nishiyama and Adachi, 1995)"* (cited from Rankin, 2011, p 302)

Therefore, Rankin (2011) assumes that data on the extractability of copper (between 0.001 % and 0,01 % of the total quantity of copper in the accessible earth's crust), as provided by Skinner (1976), can be applied to other minerals as well.

According to the UNEP working group, *"the EGR estimates"* (of 0.01 % of the amount of an element in the upper 1 km of the continental earth's crust) *"are not unreasonable upper limits"* to the EGR probability distributions as hypothesized by the working group. *"Second, the Reserve*
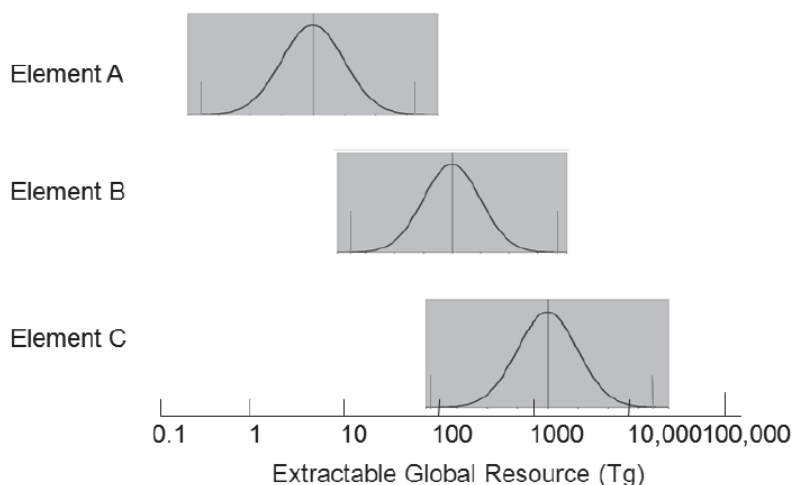
Figure 10.1 Hypothetical EGR probability distributions. The vertical lines at the edges of the distributions indicate lower and upper estimates for the Extractable Global Resources (UNEP, 2011)

Base estimates are not unreasonable lower limits". See Figure 10.1, which is derived from UNEP, 2011.

This means that the UNEP working group supposes that the most probable value for the amount of extractable global resources is somewhere between the Reserve Base figures as provided by USGS as lower limit and 0.01 % of the amount of the mineral in the upper 1 kilometer of the continental earth's crust as upper limit. In order to make our argument on the necessity of sustainable extraction as strong as possible, we have used the most optimistic figure for the amount of Extractable Global Resources. Additionally we have carried out a sensitivity analysis supposing the availability of an amount of EGR of 0.02 % instead of 0.01 %.

The result of this analysis shows that - supposing an amount of extractable global resources of 0,02 % (instead of 0.01 %) of the total amount in the upper 3 km of the earth's crust (instead of the upper 1 km)in combination with a depletion period of 500 years (instead of 1000 years) - the existing geological scarcity still results in a necessary reduction of 86 % of antimony use, 89 % of gold use, 36 % of rhenium use and 38 % of zinc use by citizens of the industrialized countries compared to the present use by these citizens. See chapter 2.

The depletion period of 1000 years in the sustainability definition is arbitrary and the estimation of the global extractable reserves is very rough. But we are unaware of other, possibly better, approaches. We did not find an operational definition of *"sustainable extraction"* in the literature. The assumption for the global extractable resources and the approach for the allowed depletion period of 1000 years are both basic and important. We recommend further research and debate on these two issues.

Geological stock vs anthropogenic stock

One may argue that the anthropogenic (including the in- use-) stock of some minerals is large and can be used as source of minerals in the future. The anthropogenic stock includes the minerals in buildings, machinery, infrastructure and, via disposal of end-of-life products, in landfills. The question is whether the anthropogenic stock of minerals could (partly) compensate for geological scarcity of minerals. The length of a mineral's usage time depends on product life time and the product life time depends on the type of use. Application in cars leads to a usage time of 10 to 15 years, in buildings this can be 40 to 80 years and in electronic appliances 5 years. Given an annual use of 700 kg of primary iron per year per capita in industrialized countries (Halada 2008) and an anthropogenic stock of iron in industrialized countries of about 10 tons per capita (Graedel 2015) , the average residence time of iron in the usage phase is about 15 years. Whereas in industrialized countries , the further accumulation of minerals in the anthropogenic stock, both in the usage phase and in landfills, is decreasing, it still increases in developing countries. To the extent the further build-up of a mineral in the anthropogenic stock is decreasing, recycling and reuse of the mineral will increase accordingly, because more products reach their end-of-life stage. So, when calculating the sustainable extraction rate, one needs to depart from a stabilized anthropogenic stock . Sustainable extraction according to our definition is meant as net extraction of primary resources after stabilization of the anthropogenic stock as clarified in chapter 5 and 6. In a stable situation, without further build-up of anthropogenic stock (either in the usage phase or in landfills), the net extraction of a mineral will be equal to dissipation. The more economical a mineral resource is used, the larger the in-use-stock of this mineral will be, due to a higher material efficiency, such as a longer product-life-time. The conclusion is that a relatively high in- use- stock of a mineral cannot be considered being a resource as such, but a side-effect of an economical use of the primary resource.

The price mechanism

Warnings on depleting resources have been repeatedly given in the past. The objection has always been that the price mechanism of the free market system will automatically lead to a

reduction of the use of scarce resources. Scarcity will result in higher prices, which will lead to replacement of the scarce resource by substitutes and to increased recycling. In general, we share the point of view that the innovativeness of humankind will be able to cope with scarcity of specific raw materials. However, we must also consider that it is uncertain when the market will react to geological scarcity and whether this will be timely enough to prevent future generations from being deprived of certain raw materials and connected services and of the opportunities available to the current generation.

We have demonstrated that, thus far, price development of mineral resources does not reflect their geological scarcity. The price development of a scarce mineral resource does not differ significantly from the price development of abundant mineral resources. This means that prices may only really react to geological scarcity when total depletion is imminent.

We believe that increasing prices will reduce the extraction and use of a mineral resource. By limiting the extraction rate, the proposed international agreement on the conservation and sustainable use of geologically scarce mineral resources will increase scarcity artificially. Through the price mechanism this will result in higher prices of the geologically scarce resource long before this would have happened if there had been no intervention. This will generate greater pressure to use substitutes for the resource and to use the resource more economically.

The price formation and development of by-product minerals needs special attention. The offer of by-product minerals depends on the quantity of main-product minerals extracted, not on the demand for by-product minerals. If, compared to the quantities produced, the demand for the by-product is higher than the demand for the main product, the price of the by-product will normally rise faster than the price of the main product. That does not necessarily mean that the by-product is geologically scarce—the reverse may also be the case. We recommend examining the price development of by-product minerals in relation to the price movements of main-product minerals from a point of view of geological scarcity.

Other geologically scarce mineral resources

Based on our definition of sustainable extraction, the conclusion is that some mineral resources will be depleted within a relatively short period of time, if their extraction rate is not reduced. We did not investigate all mineral resources. We recommend extending the scarcity analysis to additional mineral resources, i.e. phosphate.

Thus far, the discussion on scarcity and depletion of mineral resources has been general and has resulted in general calls to deal economically with resources. It has not been explored what reduction of the extraction rate to a sustainable level would mean in practice. In our investigation we have specified which measures would need to be taken for four geologically scarce mineral resources (antimony, boron, molybdenum, and zinc). We recommend carrying out similar investigations for the other geologically scarce mineral resources. This includes further research on the substitutability of all geologically scarce minerals, the possibilities of increasing their material efficiency, and their recycling potential. Sometimes it is possible to achieve the required reduction goal in several ways: e.g. by combining a relatively low substitution rate with a relatively high recycling rate, or vice versa: for instance, for the case of

zinc. For such cases we recommend determining the economically optimal mix of measures that will achieve the required extraction reduction. The optimal mix of measures will vary per commodity.

Normative principles
On the basis of an analysis of normative principles in existing international environmental agreements, we argue that the same principles would justify the creation of an international agreement on the conservation and sustainable use of geologically scarce mineral resources as well. However, a real sense of urgency for such an agreement seems to be lacking, in contrast to the situation regarding agreements on the conservation of living resources. We recommend carrying out an investigation into the background to this discrepancy.

Factors hampering the genesis of an international agreement
We have formulated the key elements of an international agreement on the conservation and sustainable use of mineral resources. The essence of the proposed agreement is that the extraction of the scarcest mineral resources has to be reduced to a much lower level than is currently the case. Many people are skeptical about the effectiveness of international agreements. However, two arguments plea for an international agreement on the conservation and sustainable use of geologically scarce mineral resources:

- Without international agreement it is impossible to limit the extraction of geologically scarce mineral resources to a sustainable level in a controlled way and at a global level.
- In an evaluation project of a large number of international environmental regimes it was concluded that *"International regimes matter in the sense that they …make a difference"* (Breitmeier et al. 2006, p 230), meaning that without international regimes, the intended (positive) outcome for the environment would have been attained to a lesser extent.

For the creation of an international agreement on the conservation and sustainable use of geologically scarce mineral resources it will be of critical importance that the resource countries agree and participate. Therefore, an adequate compensation arrangement for these countries will be crucial.

A pitfall is to make the phasing-down period for the extraction reduction of a geologically scarce mineral too long or too short. A phasing-down period that is too long will lead to an unnecessarily premature depletion of a scarce mineral resource. A phasing-down period that is too short will lead to unnecessary economic losses.

We recommend investigating the factors that can or may hamper the genesis of an international agreement on the conservation and sustainable use of geologically scarce mineral resources and how these factors could be addressed. Parties may differ in their degree of interest in an international agreement on geologically scarce resources. The more the various interests are taken into account, the greater the chance that an international agreement will be successfully created.

REFERENCES

Breitmeier, H., Young, O.R., Zürn, M., 2006, Analyzing International Environmental Regimes, from case study to database, MIT Press

McKelvey VE, Relations of reserves of the elements to their crustal abundance, American Journal of Science, 258(A); 234-241, 1960

Nishiyama T, Adachi T, Resource depletion calculated by the ratio of the reserve plus accumulative consumption to crustal abundance for gold, Natural Resources Research 4(3): 253-261, 1995

Rankin WJ. Minerals, metals and sustainability, CSIRO 2011

Skinner BJ. A second iron age ahead? Am Sci 1976; 64, 158-69

UNEP International Resource Panel on Sustainable Resource Management, 2011Estimating long-run geological stocks of metals, Working group on geological stocks of metals, Working Paper, April 6, 2011

SUMMARY

Mineral resources are the physical foundation of society. Without mineral resources there would be no wealth or progress. Since the beginning of the 20th century the use of mineral resources increased faster than ever before.

Will the earth be able to keep on providing future generations of sufficient mineral resources, given the growing world population in combination with a growing GDP per world citizen?

The research objective was to enable soundly-based recommendations to be made on whether humankind needs an international agreement on the conservation and sustainable use of geologically scarce mineral resources and, if so, to identify the key elements of such an agreement.

The main research question was: what are the concrete objectives, the time framework, the technical steps, and the policy approach needed to achieve a sustainable level of extraction of geologically scarce mineral resources? The sub-questions were:

- What does geological scarcity mean, which mineral resources are geologically scarce and how can the concept of sustainable rate of extraction be made operational?
- Which technical options are available for making the extraction rate sustainable from the point of view of depletion?
- What is the role of the price mechanism of the free market system in view of geological scarcity of mineral resources?
- Is there a normative justification for an international agreement on the conservation and sustainable use of mineral resources?
- What are the key elements of an international agreement on the conservation and sustainable use of mineral resources?

Geological scarcity reflects the amount of extractable mineral resources in the earth's crust compared to the extraction rate of that mineral resource. Not all minerals are equally scarce from a geological point of view. In the current investigation, 65 mineral resources were divided into four groups according to their geological scarcity. The geologically scarcest mineral resources are (in order of increasing scarcity): antimony, gold, zinc, molybdenum, rhenium, copper, chromium, bismuth, and boron.

According to this study, the resources of these nine minerals will be depleted within a period ranging from about 30 years from now (antimony) to about 200 years from now (boron). The depletion periods of all the other minerals investigated are estimated to be longer. If the depletion period is longer than 1000 years, the mineral resource is characterized as not being geologically scarce.

In this study the following operational definition for the sustainable extraction rate of geologically scarce mineral resources was used: the extraction rate of a mineral is sustainable if a world population of 9 billion people can be provided with that resource for a period of 1000

years, assuming that the average per capita consumption is equally divided over the world's countries. Based on this definition we investigated for which of the 65 mineral resources the extraction needs to be reduced and by how much. The conclusion is that extraction reduction is needed for 15 of the 65 mineral resources investigated. See Table 1.

Table 1 The reduction in extraction (relative to 2010) necessary to achieve a sustainable extraction rate of the 15 geologically scarcest mineral resources

	Necessary extraction reduction as % of average per capita extraction in 2010
Antimony	96%
Gold	92%
Zinc	82%
Molybdenum	81%
Rhenium	74%
Copper	63%
Chromium	57%
Bismuth	55%
Boron	44%
Tin	35%
Silver	33%
Lead	30%
Nickel	12%
Iron	11%
Tungsten	10%

For four mineral resources (antimony, zinc, molybdenum, and boron) we investigated whether their extraction could be reduced to a sustainable level without losing any of the services they currently provide. To do so, we designed a generally applicable approach for investigating whether and, if so, to what extent a combination of substitution, material efficiency, and recycling could reduce the use of a primary material to a sustainable level. The conclusion is that on the basis of existing knowledge on substitutability, material efficiency, and recycling potential, it seems that reducing extraction to a sustainable level would be feasible for all four minerals investigated, although for molybdenum this will require a big effort. One of the recommendations of the present investigation is that similar research is needed for other geologically scarce mineral resources.

But maybe future generations do not need to worry whether enough mineral resources will be safeguarded for them, because the price mechanism of the free market system might lead to an automatic, timely, and sufficient conservation of geologically scarce mineral resources. The present investigation makes clear that, thus far, there is no statistically significant correlation between the geological scarcity of a mineral resource and its price development. The historical price development of a resource that is geologically scarce does not significantly

differ from the price development of an abundant resource. Although we expect that the price of a resource will eventually increase, this may only be at the moment that the resource is nearly depleted and little remains for future generations. The conclusion is that on the basis of the present knowledge and facts it is not certain that the price mechanism of the free market system will work in time and sufficiently. Therefore, it would seem to be wise to follow a precautionary approach, to ensure that geologically scarce mineral resources will remain available for future generations.

It is argued that normative principles in existing international environmental agreements are also applicable to the problem of depletion of geologically scarce mineral resources. On the basis of the gravity of the depletion problem, two normative principles from existing international environmental agreements justify an international agreement on the conservation and sustainable use of geologically scarce mineral resources:
(1) the principle of *"Conservation and Sustainable Use of Resources"*.
(2) the *"Inter-Generational Equity"* principle.
Both principles reflect the tenet that future generations have a legitimate expectation of equitable access to planetary resources.

Based on the findings of the current research it is recommended to create an international agreement on the conservation and sustainable use of geologically scarce mineral resources. Key elements such an agreement are:
- A priority setting methodology that results in a list of geologically scarce mineral resources, of which the extraction must be reduced with priority
- A procedure for the determination of an extraction reduction goal for the selected mineral resources and a phasing down scheme
- A system for setting annual extraction quota of the selected mineral resources and the allocation of these quota to the resource countries
- A system of equitable distribution of geologically scarce mineral resources to user countries for a fixed price per ton
- A system of compensation of resource countries by user countries for reducing the extraction of geologically scarce mineral resources.
- A system to annually fix a resource price that includes the compensation for the resource countries and the transaction costs for the implementation of the international agreement
- A system that makes the user countries owner of the not extracted mineral resources to the extent that they have paid compensation to the resource countries
- The right for the resource countries to trade the extraction quota between the resource countries
- The right for the user countries to sell the distributed resources on the free market
- An international body for the conservation and sustainable use of geologically scarce resources that is responsible for the transfer and appropriate administration of the necessary payments to the extraction countries, and for inspection, monitoring, evaluation and research.

SAMENVATTING

Minerale bronnen zijn het fysieke fundament van de samenleving. Zonder minerale hulp-
bronnen zou er geen welvaart of vooruitgang zijn. Vanaf het begin van de 20e eeuw is het
gebruik van minerale hulpbronnen sneller gestegen dan ooit tevoren. De vraag is of de
aarde in staat zal zijn om ook toekomstige generaties van voldoende minerale hulpbronnen
te blijven voorzien, gezien de groeiende wereldbevolking in combinatie met een groeiend
bruto nationaal product per wereldburger.

Het doel van het onderzoek is om onderbouwde aanbevelingen te kunnen doen of het nodig
en nuttig is om een internationale overeenkomst betreffende het behoud en duurzaam ge-
bruik van geologisch schaarse delfstoffen te ontwikkelen en te implementeren en, zo ja, wat
dan de hoofdelementen van een dergelijke overeenkomst zouden moeten zijn.

De centrale onderzoeksvraag is wat de concrete doelstellingen zouden moeten zijn, het
tijdpad, de technische stappen en de beleidsaanpak om een duurzaam winningsniveau van
geologisch schaarse delfstoffen te bereiken.

De sub-vragen zijn:
- Wat betekent geologische schaarste en welke minerale hulpbronnen zijn geologisch
  schaars?
- Wat zijn de technische mogelijkheden om het tempo van winning van delfstoffen duur-
  zaam te maken?
- Wat is de rol van het prijsmechanisme van het vrije marktsysteem met het oog op geolo-
  gische schaarste van minerale hulpbronnen?
- Is er een normatieve rechtvaardiging voor een internationale overeenkomst betreffende
  het behoud en duurzaam gebruik van minerale hulpbronnen?
- Wat zijn de belangrijkste elementen van een internationale overeenkomst betreffende
  het behoud en duurzaam gebruik van minerale hulpbronnen?

Geologische schaarste van een delfstof weerspiegelt de winbare hoeveelheid van deze
delfstof in de aardkorst ten opzichte van de thans gewonnen hoeveelheid per jaar. Niet alle
mineralen zijn even schaars vanuit een geologisch oogpunt. In dit onderzoek zijn 65 minerale
delfstoffen verdeeld in vier groepen naar gelang hun geologische schaarste. De geologische
meest schaarse minerale grondstoffen (in volgorde van schaarste) zijn: antimoon, goud, zink,
molybdeen, rhenium, koper, chroom, bismut en borium.

Volgens de onderhavige studie zullen de winbare voorkomens van deze negen mineralen
zijn uitgeput binnen een periode van ongeveer 30 jaar vanaf nu (antimoon) tot ongeveer 200
jaar vanaf nu (borium). De uitputtingsperiode van de andere minerale delfstoffen worden
langer ingeschat. Indien de uitputtingsperiode langer dan 1000 jaar is, wordt het mineraal
niet gekarakteriseerd als geologisch schaars.

In dit onderzoek wordt de volgende operationele definitie voor de duurzame winning van
geologisch schaarse minerale delfstoffen gebruikt: de winning van een minerale delfstof is

duurzaam, als een wereldbevolking van 9 miljard mensen kan worden voorzien van die delf-stof gedurende een periode van 1000 jaar aangenomen dat de per hoofd van de wereldbe-volking gewonnen hoeveelheid gelijkelijk wordt verdeeld over alle landen van de wereld. Op basis van deze definitie hebben we onderzocht van welke van de 65 onderzochte mineralen de winning moet worden verminderd en met hoeveel. De conclusie is dat vermindering van

Tabel 1 Noodzakelijke vermindering van de winning van schaarse delfstoffen om een duurzame situatie te bereiken

	Noodzakelijke verlaging van de winning per wereldburger ten opzichte van 2010 %
Antimoon	96%
Goud	92%
Zink	82%
Molybdeen	81%
Rhenium	74%
Koper	63%
Chroom	57%
Bismuth	55%
Borium	44%
Tin	35%
Zilver	33%
Lood	30%
Nikkel	12%
IJzer	11%
Wolfraam	10%

de winning nodig is voor 15 van de 65 onderzochte bodemschatten. Zie tabel 1.

Voor vier minerale delfstoffen (antimoon, zink, molybdeen en borium) is onderzocht of de winning kan worden teruggebracht tot een duurzaam niveau zonder verlies van de huidige diensten die door deze bodemschatten worden geleverd. In dat kader is een algemeen gel-dende aanpak ontwikkeld voor het onderzoeken òf en zo ja, in welke mate een combinatie van vervanging, materiaal efficiency en recycling het gebruik van een primair materiaal zou kunnen verminderen tot een duurzaam niveau. De conclusie is dat de vermindering van de winning tot een duurzaam niveau haalbaar is voor alle vier de onderzochte minerale delfstoffen op basis van de bestaande kennis over de vervangbaarheid, materiaal efficiency en recycling potentieel. Eén van de aanbevelingen is dat dit onderzoek ook moet worden uitgebreid naar de andere geologisch schaarse bodemschatten.

Maar misschien hoeven toekomstige generaties zich wel geen zorgen te maken of er al dan niet voldoende minerale hulpbronnen voor hen zullen zijn, omdat het prijsmechanisme van de vrije markt zal leiden tot een automatische, tijdige en voldoende vermindering van het

gebruik van geologisch schaarse delfstoffen. Uit deze studie blijkt evenwel dat er tot dusver geen significante relatie is tussen de geologische schaarste van een mineraal en de prijsontwikkeling. De prijsontwikkeling van een delfstof die geologisch schaars is, wijkt niet significant af van de prijsontwikkeling van een niet-schaarse delfstof. Hoewel we verwachten dat de prijs van een delfstof uiteindelijk wel zal toenemen, wanneer deze geologisch echt schaars begint te worden, zou het kunnen zijn dat dit pas gebeurt op een moment dat de delfstof bijna is uitgeput en er niet veel meer over is voor toekomstige generaties. De conclusie is dat het op basis van de huidige kennis en feiten niet zeker is dat het prijsmechanisme van het vrije marktsysteem tijdig en in voldoende mate zal werken. Daarom lijkt het verstandig om voorzorgsmaatregelen te nemen om te waarborgen dat geologisch schaarse delfstoffen ook beschikbaar zullen blijven voor toekomstige generaties.

In deze studie wordt beargumenteerd dat normatieve beginselen in bestaande internationale milieu-overeenkomsten ook van toepassing zijn op het probleem van de uitputting van geologisch schaarse delfstoffen. Op basis van de ernst van het uitputtingsprobleem rechtvaardigen twee normatieve beginselen uit bestaande internationale milieu-overeenkomsten een internationale overeenkomst betreffende het behoud en duurzaam gebruik van geologisch schaarse delfstoffen:
(1)	Het beginsel van "het behoud en duurzaam gebruik van hulpbronnen".
(2)	Het "intergenerationele gelijkheids"-beginsel.
Beide beginselen waarborgen het legitieme recht van toekomstige generaties op een eerlijk deel van natuurlijke hulpbronnen.

Op basis van de bevindingen van het onderhavige onderzoek wordt aanbevolen om een internationale overeenkomst betreffende het behoud en duurzaam gebruik van geologisch schaarse delfstoffen te creëren.
De belangrijkste elementen een dergelijke overeenkomst zijn:
-	Een prioriteitstellingsmethode die resulteert in een lijst van geologisch schaarse minerale delfstoffen, waarvan de winning met voorrang moet worden verminderd.
-	Een procedure voor de bepaling van een doelstelling voor de mate van vermindering van de geselecteerde minerale delfstoffen en een fasering van die vermindering.
-	Een systeem voor het vaststellen van een jaarlijkse quota voor de winning van de geselecteerde minerale delfstoffen en de verdeling van die quota over de delfstoflanden.
-	Een systeem van eerlijke verdeling van geologisch schaarse delfstoffen over de gebruikslanden voor een vastgestelde prijs per ton.
-	Een systeem van compensatie van de delfstoflanden door gebruikslanden voor het verminderen van de winning van geologisch schaarse delfstoffen.
-	Een systeem om jaarlijks de prijs van een schaarse delfstof vast te stellen, waarin de compensatie van delfstoflanden en de transactiekosten voor de uitvoering van de internationale regeling zijn verdisconteerd.

- Een systeem dat de gebruikslanden mede-eigenaar van de niet gewonnen minerale hulpbronnen maakt, al naargelang dat deze landen compensatie hebben betaald aan delfstoflanden.
- Een systeem van verhandelbaarheid van de winningsquota en verdelingsquota.
- Een internationaal orgaan voor het behoud en duurzaam gebruik van geologisch schaarse delfstoffen, dat verantwoordelijk is voor het regelen van de noodzakelijke betalingen aan de delfstoflanden, en voor inspectie, monitoring, evaluatie en onderzoek.

CURRICULUM VITAE

Theo Henckens was born in Hunsel in The Netherlands on 20 November 1948. He completed his secondary education (Gymnasium β) at the Bisschoppelijk College in Roermond in 1966. He studied Chemical Technology at Eindhoven Technical University from 1966 and got his MSc degree in 1972. After a two year stay in Algeria as teacher in chemistry and physics at the Lycee Ben Boulaid in Batna, he joined DHV Consultants in Amersfoort, The Netherlands, in 1974. From that year on, Theo Henckens worked in the field of environmental protection. First he was a designer of wastewater treatment plants, both for municipal wastewater and industrial wastewater. Thereafter, between 1976 and 1982, he was expert and team leader of many environmental projects, including environmental impact assessments, and air pollution control studies. Clients were local, regional and central government and the private sector. Between 1982 and 1990 Theo Henckens was employed by the Netherlands Ministry of the Environment in the Regional Inspectorate for the Environment in the province of North Brabant. His main task in the inspectorate was the improvement and promotion of enforcement of the environmental legislation in the province of North Brabant. In the first period as inspector, later as deputy head of the regional inspectorate for the environment. In 1990 Theo Henckens joined DHV again. This move of his personal career was triggered by the changes in the world. Eastern Europe was opening up and from an environmental point of view much needed to be improved. Between 1990 and 1999, Theo Henckens had a position as project director for DHV's water and environment projects in Eastern Europe. In this framework he acquired and managed projects in the Czech Republic, Ukraine, Poland, Romania, Croatia, Bulgaria, Russian Federation, Estonia, Lithuania, Hungary, Bosnia-Hercegovina, Slovenia, Slovakia, Morocco, Tunisia, China and India. Mostly the projects were financed by international financiers such as the World Bank and the European Union. Between 1999 and 2004 Theo Henckens was head of the Environmental Policy Department of DHV. The projects of this 25 staff department were in the field of environmental policy and strategy, environmental permitting and enforcement, juridical advise and procedure management related to the environment, climate and energy. In 2004 Theo Henckens returned to his previous position as project director of international water and environment projects. He acquired and managed projects in Poland, Romania, Caspian Sea Region, Serbia, Russian Federation, Bulgaria and Montenegro. Between 2007 and 2010, Theo Henckens had the function of team leader of the EU financed EU-China River Basin Management Program. This 13.9 million Euro project focused on assisting the competent Chinese authorities to further improve integrated water management in the middle reaches of the Yellow River basin and the Yangtze river basin. In 2010 Theo Henckens assisted DHV Vietnam in the framework of a number of wastewater and drinking water projects. From 2010 until his retirement in 2011 Theo Henckens remained employed by DHV Asia. Beginning 2013 Theo Henckens started a PhD research with respect to geologically scarce mineral resources.

NAWOORD EN DANKBETUIGING

Al in mijn studententijd intrigeerde me de vraag hoe een exponentiële groei van het gebruik van grondstoffen op langere termijn te rijmen is met de beperkingen die de aarde nu eenmaal heeft. Of is de toekomstige schaarste van grondstoffen wellicht een schijnprobleem? Zal het vrije marktsysteem vanzelf tot een oplossing van het probleem leiden, zo er al een probleem is?

Ik prijs me dan ook gelukkig dat ik de gelegenheid heb gekregen om me na mijn professionele loopbaan, die vrijwel helemaal in het teken stond van milieubescherming, verder te verdiepen op het gebied van schaarse grondstoffen. Ik voel dit als een completering van mijn kennis op het gebied van milieu. Milieubescherming en grondstoffenbesparing zijn immers twee kanten van dezelfde medaille. Milieuvervuiling is het gevolg van een verkeerd gebruik van grondstoffen. Teveel grondstoffen komen terecht op plekken, waar ze niet thuis horen. Aantasting van de kwaliteit van lucht, water en bodem is het gevolg, met in het kielzog een reeks van negatieve consequenties, zoals aantasting van de gezondheid van mensen, dieren en planten en aantasting van de biodiversiteit.

Milieuvervuiling kan worden voorkomen of tegengegaan door beschermingsmaatregelen, zoals rioolstelsels en daaraan gekoppelde waterzuiveringsinstallaties, afgasbehandeling in fabrieken, katalysatoren in auto's, gescheiden inzameling en hergebruik van afvalstoffen, gebruik van alternatieve grondstoffen en processen met minder negatieve consequenties. Een doeltreffende milieubescherming leidt automatisch tot een efficiënter gebruik van grondstoffen.

De optiek in dit proefschrift is echter niet die van de bescherming van het milieu, maar die van een blijvende beschikbaarheid van grondstoffen voor toekomstige generaties. Het voorstellen van maatregelen ten aanzien van een probleem dat pas ergens in de toekomst concreet wordt, en vooral het daadwerkelijk nemen van de voorgestelde maatregelen, is een weerbarstige materie. Temeer in een tijdsgewricht waarin al zoveel andere grote problemen wachten op een oplossing zal de mensheid de neiging hebben om de problemen, die samenhangen met uitputting van grondstoffen, voor zich uit te schuiven. Niettemin is het mijns inziens de plicht van de huidige generatie om ook oog te hebben voor de belangen van toekomstige generaties. Ik hoop dat dit proefschrift daaraan zal bijdragen.

Mijn dank gaat in de eerste plaats uit naar de Nederlandse belastingbetaler, die het mogelijk maakte dat mijn promotoren tijd konden besteden om mij te begeleiden bij het onderzoek en mij toegang gaven tot de wetenschappelijke literatuur via de faciliteiten van de Universiteit Utrecht. Mijn beide promotoren, Prof. Dr. Peter Driessen en Prof. Dr. Ernst Worrell, wil ik heel hartelijk danken voor de onmisbare en onschatbare inspiratie en feedback die ze mij schonken bij alle onderdelen van het proefschrift.

Mijn dank gaat verder uit naar Prof. Dr. Cedric Reyngaert, die mij voorzag van adviezen en suggesties bij de onderdelen met betrekking tot de toepasbaarheid van normatieve begin-

selen en de opzet van een internationale regeling op het gebied van de conservering en het gebruik van geologisch schaarse grondstoffen.

Prof. Dr. Ekko van Ierland dank ik voor zijn steun en adviezen bij het schrijven van het onderdeel over de rol van het prijsmechanisme van de vrije markt ten aanzien van geologisch schaarse grondstoffen.

Joy Burrough, Ben Thompson en Anni Joosten wil ik bedanken voor hun ondersteuning om het proefschrift in het Engels te verwoorden. Resterende grammatica fouten of kromme, door het Nederlands geïnspireerde, zinnen blijven niettemin mijn verantwoordelijkheid, omdat niet alle hoofdstukken door genoemde personen zijn nagekeken.

Ik draag dit proefschrift op aan mijn echtgenote Nelleke Rögels, die in 2014 is overleden. Nelleke vond het prachtig dat ik na mijn pensionering het plan opvatte om dit promotietraject te starten. Zij werkte eveneens aan een boek, over levenslooppsychologie. Wat was het fijn om gezamenlijk bezig te zijn en bij een kopje koffie aan de keukentafel elkaar bij te praten over de voortgang, de successen en de moeilijkheden. Nelleke heeft me tot de laatste dag van haar leven geïnspireerd om door te gaan en het proefschrift af te maken.

Ik draag het proefschrift ook op aan mijn kinderen Josée en Guy en mijn kleinkinderen Elof, Floris, Reinout, Quintijn en Friso. Zij maken deel uit van volgende generaties, wier belang een centrale rol speelt in mijn proefschrift.

In dit kader wil ik zeker mijn 93-jarige moeder niet vergeten. Zij was degene die mij het leven schonk en die mij op zeer jonge leeftijd leerde lezen. Zij stond aan het begin van een levenslange leespassie en heeft daarmee voor mij de toegangspoort tot de wetenschap geopend.

Tenslotte, maar niet in het minst, dank ik mijn huidige levenspartner Anni Joosten. Niet alleen gaf ze me weer zin in het leven, maar ook stimuleerde ze me met een niet aflatende interesse in mijn verhalen over schaarse grondstoffen.

Annex I

Supplementary information to Chapter 4 (antimony)

A. Materials and applications with antimony-containing flame retardants and their possible substitutes and replacements

Derived from Lassen C., Lokke S., Andersen L.I., Brominated flame retardants – Substance flow analysis and assessment of alternatives, Danish Environmental Protection Agency, 1999, Environmental project no 494

Materials	Electric and electronic equipment		Building and construction		Textiles		Transportation	
	Major applications	Possible substitutes of antimony-containing flame retardants and replacements of material S=other Synergist FR=other Flame Retardant AM=Alternative Material	Major applications	Possible Substitutes of antimony-containing flame retardants and replacements of material S=other Synergist FR=other Flame Retardant AM=Alternative Material	Major applications	Possible substitutes for antimony-containing flame retardants and replacements of material S=other Synergist FR=other Flame Retardant AM=Alternative Material	Major applications	Possible substitutes for antimony-containing flame retardants and replacements of material S=other Synergist FR=other Flame Retardant AM=Alternative Material
General		Zinc-stannate (S) Zinc-hydroxy-stannate (S) Bismuthtrioxide (S)		Zinc-stannate (S) Zinc-hydroxy-stannate (S) Bismuthtrioxide (S)		Zinc-stannate (S) Zinc-hydroxy-stannate (S) Bismuthtrioxide (S)		Zinc-stannate (S) Zinc-hydroxy-stannate (S) Bismuthtrioxide (S)
PE Polyehtylene	cable covering; mounting boxes, plugs	- aluminum trihydroxide FR - red phosphorus (FR); - magnesiumhydroxide (FR)	pipes, construction sheets; mounting boxes, wall sockets; Foils	- ammonium-polyphosphate(FR); - HDPE with magnesium hydroxide (FR); - ammonium polyphosphate (FR)			cable covering in cars	- aluminumtrihydroxide(FR) - red phosphorus(FR)
PP Polypropylene	appliances, switch gears, film, IT-housing, wall sockets, switch boxes; wiring material	- magnesium hydroxide (FR) - red phosphorus (FR) - intumescent systems(FR); ammoniumpolyphosphate(FR)	pipes, construction sheets, flooring; Foils	- ammoniumphosphate (FR); - ammonium-polyphosphate (FR)			electric and electronic appliances	- magnesium hydroxide(FR) - red phosphorus(FR) - intumescent systems(FR)
ABS Acrylonitrile-butadiene-styrene	Housing of electric and electronic appliances	- ABS/PC blends with triphenyl phosphate (AM); - PPE/PS blends with organic phosphorus compounds (AM); - PC containing organic phosphorus compounds (AM); - separation of housing and electronic and electric parts(AM)					audio and video components, GPS systems, electrical and electronic equipment	- ABS/PC blends with triphenyl phosphate (AM); - PPE/PS blends with organic phosphorus compounds (AM); - PC containing organic phosphorus compounds (AM); - separation of housing and electronic and electric parts(AM)

Materials	Electric and electronic equipment		Building and construction		Textiles		Transportation	
	Major applications	Possible substitutes of antimony-containing flame retardants and replacements of material. S=other Synergist, FR=other Flame Retardant, AM=Alternative Material	Major applications	Possible Substitutes of antimony-containing flame retardants and replacements of material. S=other Synergist, FR=other Flame Retardant, AM=Alternative Material	Major applications	Possible substitutes for antimony-containing flame retardants and replacements of material. S=other Synergist, FR=other Flame Retardant, AM=Alternative Material	Major applications	Possible substitutes for antimony-containing flame retardants and replacements of material. S=other Synergist, FR=other Flame Retardant, AM=Alternative Material
HIPS — High Impact Polystyrene	housing of electric and electronic appliances, wiring parts	- Organic phosphorus compounds (FR) - PE with magnesium hydroxide (AM) - PS-PPO blends with phosphate esthers (AM)	mounting boxes, wall sockets	- HDPE with magnesium hydroxide			electric and electronic appliances	- Organic phosphorus compounds (FR) - PE with magnesium hydroxide (AM) - PS-PPO blends with phosphate esthers (AM)
EPS,XPS — Polystyrene, expanded or extruded			insulation panels	- mineral wool (AM) - foam glass (AM)			insulation panels	- mineral wool (AM) - foam glass (AM)
UP — Unsaturated Polyesthers	Technical laminates	- ammonium polyphosphate + aluminumtrihydroxide (FR) - red phosphorus + aluminumtrihydroxide (FR) - ceramic laminates (AM)					overhead compartments, side wall and ceiling panels,internal structures, dashboards, instrument panels, battery cases and trays	- ammonium phosphate (FR) - aluminumtrihydroxide (FR)
PET/PBT — Polyethylene Terephtalate/Polybuthylene terephtalate	relays, switches, sockets, mounting boxes	- polyketone with magnesium hydroxide (AM) - diarylphosphonate (FR) - melaminecyanurate (FR) - red phosphorus (FR) - halogen free polyamide - ceramics - self-extinguishing plastics	lighting, relays, contactors, starters	- porcelain (AM) - bakelite (AM) - halogen free PA (AM)			electric and electronic equipment	- polyketone with magnesium hydroxide (AM) diarylphosphonate (FR) melaminecyanurate (FR) red phosphorus (FR) - halogen free polyamide - ceramics - self-extinguishing plastics

Materials	Electric and electronic equipment		Building and construction		Textiles		Transportation	
	Major applications	Possible substitutes of antimony-containing flame retardants and replacements of material S=other Synergist FR=other Flame Retardant AM=Alternative Material	Major applications	Possible Substitutes of antimony-containing flame retardants and replacements of material S=other Synergist FR=other Flame Retardant AM=Alternative Material	Major applications	Possible substitutes for antimony-containing flame retardants and replacements of material S=other Synergist FR=other Flame Retardant AM=Alternative Material	Major applications	Possible substitutes for antimony-containing flame retardants and replacements of material S=other Synergist FR=other Flame Retardant AM=Alternative Material
Polyamide, nylon PA	switch gear, fuse boxes, terminal blocks, print connectors	- zinc compounds (oxide, borate, sulphide, stannate, phosphate) (S) - melamine-cyanurate (FR) - red phosphorus (FR) - magnesium hydroxide (FR) - melamine polyphosphate (FR) - polyketone with - magnesium hydroxide (AM) - self-extinguishing plastics (AM)	lighting, relays, contactors, starters	- porcelain(AM) - bakelite(AM)			electric and electronic equipment	- zinc compounds (oxide, borate, sulphide, stannate, phosphate) (S) - melamine-cyanurate (FR) - red phosphorus (FR) - magnesium hydroxide (FR) - melamine polyphosphate (FR) - polyketone with magnesium hydroxide (AM) self-extinguishing plastics (AM)
Polycarbonate PC	electric and electronic equipment	- organic phosphorus compounds (FR) - phosphate ester with polytetrafluoroethylene (FR)					electric and electronic equipment	- organic phosphorus compounds (FR) phosphate ester with polytetrafluoroethylene (FR)
Epoxies	printed circuit boards, technical laminates, encapsulates	- reactive nitrogen and phosphorus components - aluminum trihydroxide +ammoniumpolyphosphate(FR) - polyphenylene sulphide(AM) - resins of epoxy and unsaturated polyester with red phosphorus (AM) aluminumtrihydroxide + red phosphorus					electric and electronic equipment	- reactive nitrogen and phosphorus components - aluminum trihydroxide +ammoniumpolyphosphate(FR) - polyphenylene sulphide(AM) - resins of epoxy and unsaturated polyester with red phosphorus (AM) aluminumtrihydroxide + red phosphorus
Polyurethane PUR			insulation panels	- ammonium-polyphosphates(FR) - red phosphorus(FR) - mineral wool(AM)			insulation panels	- ammonium-polyphosphates(FR) - red phosphorus(FR) - mineral wool(AM)
Phenolic resins	printed circuit boards, technical laminates	- nitrogen and phosphorus constituents(FR) - aluminum trihydroxide(FR) - ceramic laminates (AM)					printed circuit boards, technical laminates	- laminates with nitrogen and phosphorus constituents - aluminum trihydroxide ceramic laminates

Materials	Electric and electronic equipment		Building and construction		Textiles		Transportation	
	Major applications	Possible substitutes of antimony-containing flame retardants and replacements of material S=other Synergist FR=other Flame Retardant AM=Alternative Material	Major applications	Possible Substitutes of antimony-containing flame retardants and replacements of material S=other Synergist FR=other Flame Retardant AM=Alternative Material	Major applications	Possible substitutes for antimony-containing flame retardants and replacements of material S=other Synergist FR=other Flame Retardant AM=Alternative Material	Major applications	Possible substitutes for antimony-containing flame retardants and replacements of material S=other Synergist FR=other Flame Retardant AM=Alternative Material
Polyvinylchloride PVC			pipes, fittings, window profiles	aluminumtrihydroxide (FR) magnesiumhydroxide (FR) zincborate(FR)				
			foils	ammoniumpolyphosphate				
Rubber	wiring	- aluminum trihydroxide + zincborate + ethylene vinylacetate (FR)	cables,wires	- aluminum trihydroxide + zincborate + ethylene vinylacetate (FR)			cables, wiring, car bumpers	- aluminum trihydroxide + zincborate + ethylene vinylacetate (FR)
		ethylenevinylacetatepolymer with aluminum trihydroxide		ethylenevinylacetatepolymer with aluminum trihydroxide				ethylenevinylacetatepolymer with aluminum trihydroxide
Wool					furniture, clothing, interiors, technical textiles, furniture upholstery	phosphorus constituents (FR) - zirconium constituents (FR)	seat upholstery	- phosphorus constituents(FR) - zirconium constituents (FR)
					Backing of carpets	- aluminum trihydroxide(FR)	Backing of carpets	- aluminum trihydroxide(FR)

Materials	Electric and electronic equipment		Building and construction		Textiles		Transportation	
	Major applications	Possible substitutes of antimony-containing flame retardants and replacements of material S=other Synergist FR=other Flame Retardant AM=Alternative Material	Major applications	Possible Substitutes of antimony-containing flame retardants and replacements of material S=other Synergist FR=other Flame Retardant AM=Alternative Material	Major applications	Possible substitutes for antimony-containing flame retardants and replacements of material S=other Synergist FR=other Flame Retardant AM=Alternative Material	Major applications	Possible substitutes for antimony-containing flame retardants and replacements of material S=other Synergist FR=other Flame Retardant AM=Alternative Material
Cotton					furniture, clothing, interiors, technical textiles	- ammonium polyphosphate(FR) - diammonium phosphate(FR) - cellulose reactive methylated phosphonamides(FR) - polymeric phosphonium salt condensates(FR)	seats, interior, technical textiles	- ammonium polyphosphate - diammonium phosphate - cellulose reactive methylated phosphonamides - polymeric phosphonium salt condensates
					furniture upholstery	phosphorus(FR)	seat upholstery	phosphorus(FR)
					backing of carpets	aluminum trihydroxide(FR)	Carpets	aluminum trihydroxide(FR)
Polyester fibers					furniture, clothing, interiors, technical textiles	Substitutes for flame retardants phosphinic acid derivate co-monomer(FR) bisphenol(FR) cyclic phosphonate(FR) chlorophosphates (AM)	curtains, seat covers	Substitutes for flame retardants phosphinic acid derivate co-monomer(FR) bisphenol(FR) cyclic phosphonate(FR) chlorophosphates (AM)
					furniture upholstery	phosphorus(FR)	seat upholstery	- phosphorus
					backing of carpets	aluminum trihydroxide(FR)	Carpets	- aluminum trihydroxide

B.   Experts' opinion on the substitutability of antimony-containing flame retardants in electric and electronic equipment

Antimony-containing flame retardants are applied in various plastics that are used in electric and electronic equipment. The scientific literature provides information on possible substitutes for antimony in these applications. Three main alternatives can be distinguished:

-    Antimony trioxide is replaced by another synergist. The halogenated hydrocarbon in the flame retardant is not replaced
-    The halogenated flame retardant, including antimony trioxide is replaced
-    The base material in which the flame retardant is applied, is replaced by another material

Three experts in this field have given their independent opinion about the various substitutes. It concerns

-    the performance of the substitute
-    the environment, health and safety impacts of the substitute
-    the costs of the substitute

Furthermore we have asked the expert's opinions on the question whether a 100 % substitution or replacement of the antimony-containing flame retardancy systems would be feasible within 10 years without compromising the required flame retardant quality.

The below table provides an overview of the results.

Summarized, the expert's opinion on the substitutability of antimony-containing flame retardants in electric and electronic equipment is as follows:

In an average of 58 % of the applications the original antimony-containing system can be adequately substituted by a non-antimony-containing system

The expert's opinion is that in an average of 96% of the applications substitution or replacement would be feasible within 10 years without compromising the required flame retardant quality.

Regarding the EHS (environment, health and safety) aspects of the substitutes, the expert's opinion is that in 12 % of the cases the substitute's EHS properties are at least in one regard negative compared to the original. In 88 % of the cases the substitute's EHS properties are considered equal or positive compared to the original

Regarding the costs of the substitutes the expert's opinion is that in 57 % of the cases the substitute is equal in price or cheaper than the original. The other 43 % of the substitutes is deemed costlier. In 15 % of the cases the substitutes are labeled as very negative in this respect (costs of the substitute > 200% of the costs of the original).

Expert's opinion on the substitutability of antimony-containing flame retardants in electric and electronic equipment

The below table shows the average outcome of the experts replies per application/substitute. In case the result was exactly between two columns, the outcome has been rounded to the negative side. The explanation of the scoring system is given at the end of the table.

1	2	3	4	5 Combined substitutes applicability (— = very poor, - = poor, 0 = moderate, + = good, ++= very good, U = unknown)						6 Substitutes environment, health and safety impact (— = very negative, - = negative, 0 = equal, + = positive, ++= very positive, U = unknown)						7 Substitutes costs (— = >200 % of original, - = 120-200 % of original, 0 = 80-120% of original, + = 50-80% of original, ++ = < 50 % of original, U = unknown)						8
Materials	Major applications	Possible substitutes of antimony-containing flame retardants or replacement of material. S=other Synergist FR=other Flame Retardant AM=Alternative Material	100% substitution or replacement of antimony would be feasible within 10 years, without compromising required flame retardancy quality	—	-	0	+	++	U	—	-	0	+	++	U	—	-	0	+	++	U	- Comments -Other applications -Other synergists, FR substitutes or replacing materials
All below mentioned materials	All below mentioned applications	- Zinc stannate (S)						■				■							■			
		- Zinc hydroxy stannate (S)	50%					■				■							■			
		- Bismuth trioxide (S)													■							■	
PE Polyethylene	Cable covering	- aluminum trihydroxide (FR)	100%				■						■					■				
	Mounting boxes, plugs	- red phosphorus (FR)	100%				■					■					■					
		- magnesiumhydroxide(FR)	100%			■						■						■				
PP Polypropylene	appliances, switch gears, film, IT-housing, wall sockets, switch boxes	- magnesium hydroxide(FR)	100%			■						■						■				
		- red phosphorus(FR)				■					■						■					
		- intumescent systems(FR)				■						■						■				
	Wiring material	ammoniumpolyphosphate(FR)	100%			■						■						■				
ABS Acrylonitrile-butadiene-styrene	Housing of electric and electronic appliances	- ABS/PC blends with triphenyl phosphate(AM)							■		■							■				
		- PPE/PS blends with organic phosphorus compounds(AM)				■						■					■					
		- PC containing organic phosphorus compounds(AM)	100%			■						■						■				
		- separation of housing and electronic and electric parts(AM)							■				■					■				
HIPS High Impact Polystyrene	housing of electric and electronic appliances, wiring parts	- Organic phosphorus compounds(FR)	100%			■						■						■				
		- PE with magnesium hydroxide(AM)				■						■						■				
		PS-PPO blends with phosphate esters (AM)				■						■					■					

1	2	3	4	5	6	7	8
Materials	Major applications	Possible substitutes of antimony-containing flame retardants or replacement of material. S=other Synergist FR=other Flame Retardant AM=Alternative Material	100% substitution or replacement of antimony would be feasible within 10 years, without compromising required flame retardancy quality	Combined substitutes applicability — = very poor - = poor 0 = moderate + = good ++= very good U = unknown	Substitutes environment, health and safety impact — = very negative - = negative 0 = equal + = positive ++= very positive U = unknown	Substitutes costs — = >200 % of original - = 120-200 % of original 0 = 80-120% of original + = 50-80% of original ++ = < 50 % of original U = unknown	- Comments -Other applications -Other synergists, FR substitutes or replacing materials

UP — Unsaturated Polyesthers
Major applications: Technical laminates
Column 4: 100%
- ammonium polyphosphate + aluminumtrihydroxide(FR)
- red phosphorus + aluminumtrihydroxide(FR)
- ceramic laminates (AM)

PET/PBT — Polyethylene Terephtalate/ Polybuthylene Terephtalate
Major applications: relays, switches, sockets, mounting boxes
Column 4: 100%
- polyketone with magnesium hydroxide(AM)
- diarylphosphonate(FR)
- melamine-cyanurate(FR)
- red phosphorus(FR)
- halogen free polyamide(AM)
- ceramics(AM)
- self-extinguishing plastics (PPS,PSu,PAEK,PES)(AM)

PA — Polyamide, Nylon
Major applications: switch gear, fuse boxes, terminal blocks, print connectors
Column 4: 100%
- Zinc compounds(oxide, borate, sulphide, stannate, phosphate)(S)
- melamine-cyanurate(FR)
- red phosphorus(FR)
- magnesium hydroxide(FR)
- melamine polyphosphate(FR)
- polyketone with magnesium hydroxide(AM)
- self-extinguishing plastics (PPS,PSu,PAEK,PES)(AM)

1 Materials	2 Major applications	3 Possible substitutes of antimony-containing flame retardants or replacement of material. S=other Synergist FR=other Flame Retardant AM=Alternative Material	4 100% substitution or replacement of antimony would be feasible within 10 years, without compromising required flame retardancy quality	5 Combined substitutes applicability — = very poor - = poor 0 = moderate + = good ++= very good U= unknown						6 Substitutes environment, health and safety impact — = very negative - = negative 0 = equal + = positive ++= very positive U = unknown						7 Substitutes costs — = >200 % of original - = 120-200 % of original 0 = 80-120% of original + = 50-80% of original ++= < 50 % of original U = unknown						8 Comments -Other applications -Other synergists, FR substitutes or replacing materials
				—	-	0	+	++	U	—	-	0	+	++	U	—	-	0	+	++	U	
PC Polycarbonate	electric and electronic equipment	- organic phosphorus compounds(FR)																				
		- phosphate ester with polytetrafluoroethylene (FR)	100%																			
Epoxies	printed circuit boards, technical laminates, encapsulates	- reactive nitrogen and phosphorus components(FR)																				
		- aluminum trihydroxide +ammoniumpolyphosphate(FR)	100%																			
		- polyphenylene sulphide(AM)																				
		- resins of epoxy and unsaturated polyester with red phosphorus(AM)																				
		- aluminumtrihydroxide+red phosphorus																				
Phenolic resins	printed circuit boards, technical laminates	- nitrogen and phosphorus constituents(FR)																				
		- aluminum trihydroxide(FR)	100%																			
		- ceramic laminates(AM)																				
Rubber	Wiring	- aluminum trihydroxide +zincborate+ethylene vinylacetate(FR)	100%																			
		- ethylenevinylacetate polymer with aluminum trihydroxide(AM)																				

Missing materials in electric and electronic equipment with halogenated flame retardants

Explanation of the scoring system

1. Performance of the combined substitutes compared to the performance of the original

The performance of the substitutes is expressed as the total percentage of the original antimony-containing uses, in which substitutes can replace antimony with an adequate/sufficient performance.

Applicability scoring scale: — / - / 0 / + / ++ (very poor to very good)

—	Very poor:	Antimony can be adequately substituted by alternatives in 0-20 % of the uses
-	Poor:	Antimony can be adequately substituted by alternatives in 20 – 40 % of the uses
0	Moderate:	Antimony can be adequately substituted by alternatives in 40 – 60 % of the uses
+	Good:	Antimony can be adequately substituted by alternatives in 60 – 80 % of the uses
++	Very good:	Antimony can be adequately substituted by alternatives in 80 – 100 % of the uses
U	Unknown	The applicability of the substitute or replacement is not (sufficiently) known

2. Environment, health and safety (EHS) properties of the substitute

The EHS-properties of the substitute and the original are supposed to encompass all aspects, from cradle to grave, in all stages, from the extraction of the involved elements until the waste stage. To be able to score this item it will be necessary to focus on the most striking EHS properties of the substitute and the original.

EHS scoring scale: — / - / 0 / + / ++ (very negative to very positive compared to the original)

— Very negative:	In at least one regard the substitute's EHS properties are very negative compared to the original
- Negative:	In at least one regard the substitute's EHS properties are negative compared to the original
0 Equal:	Overall the substitute's EHS properties are about equal to the one of the original
+ Positive:	Overall the substitute's EHS properties are positive compared to the original
++ Very positive:	Overall the substitute's EHS properties are very positive compared to the original
U Unknown	The EHS properties of the substitute or the replacement are not (sufficiently) known

If the EHS score of the substitute is negative or very negative, and cannot be mitigated, the applicability of the candidate substitute might be reconsidered.

3. The substitute's extra costs

The extra costs of a substitute or alternative material will vary with its availability, technology and with the overall economic situation in the world.

Finance scoring scale: — / - / 0 / + / ++ (very negative to very positive compared to the original)

—	very negative	The costs of the substitute or the replacement are >200 % of the costs of the original antimony-containing flame retardant <u>or</u> the costs of the alternative material are > 120 % of the costs of the original material. For the specification of "alternative materials", it is referred to column 3 of the table.
-	Negative	The costs of the substitute or the replacement are 120%-200% compared to the costs of the original antimony-containing flame retardant <u>or</u> the cost of the alternative material are between 105% and 120 % of the costs of the original material. For the specification of "alternative materials", it is referred to column 3 of the table.
0	Equal	The costs of the substitute or the replacement are 80 – 120 % compared to the costs of the original antimony-containing flame retardant <u>or</u> the costs of the alternative material are between 95% and 105 % of the costs of the original material. For the specification of "alternative materials", it is referred to column 3 of the table.

+	Positive	The costs of the substitute or replacement are 50-80 % compared to the original antimony-containing flame retardant <u>or</u> the costs of the alternative material are between 80% and 95 % of the costs of the original material. For the specification of "alternative materials", it is referred to column 3 of the table.
++	very positive	The costs of the substitute or replacement are < 50 % compared to the original antimony-containing flame retardant <u>or</u> the cost of the alternative material are less than 80 % of the costs of the original material. For the specification of "alternative materials", it is referred to column 3 of the table.
U	Unknown	The costs of the substitute or replacement are not (sufficiently) known

The costs are meant as <u>total costs</u> for adequate flame retardancy compared to the original, so not the (extra or less) costs per kg of flame retardant. (The substitute may be costlier per kg, but the needed quantity may be less.) If the total costs of the substitute or of the alternative are much higher than the costs of the antimony-containing original, the substitutability becomes questionable.

C.   Experts' opinion on the substitutability of antimony-containing flame retardants in textiles

Antimony-containing flame retardants are applied in various applications of wool, cotton and polyester fibers. The scientific literature provides information on possible substitutes for antimony in each of these applications. Three main alternatives can be distinguished:

-   Antimony trioxide is replaced by another synergist. The halogenated hydrocarbon in the flame retardant is not replaced
-   The halogenated flame retardant, including antimony trioxide is replaced
-   The base material in which the flame retardant is applied, is replaced by another material

We have asked experts in this field to give their opinion about the various substitutes.

It concerns

-   the performance of the substitute
-   the environment, health and safety impacts of the substitute
-   the costs of the substitute

Furthermore we have asked the expert's opinions on the question whether a 100 % substitution or replacement of the antimony-containing flame retardancy systems would be feasible within 10 years without compromising the required flame retardant quality.

The below table provides an overview of the detailed results.

Summarized, the expert's opinion on the substitutability of antimony-containing flame retardants in textiles is as follows:

In an average of 55 % of the applications the original antimony-containing system can be adequately substituted by a non-antimony-containing system

As for the future the expert's opinion is that in an average of 96% of the applications substitution or replacement would be feasible within 10 years without compromising the required flame retardant quality.

Regarding the EHS (environment, health and safety) aspects of the substitutes, the expert's opinion is that in 13 % of the cases the substitute's EHS properties are at least in one regard negative compared to the original. In 87 % of the cases the substitute's EHS properties are considered equal or positive compared to the original

Regarding the costs of the substitutes the expert's opinion is that in 50 % of the cases the substitute is equal in price or cheaper than the original. The other 50 % of the substitutes is deemed costlier. None of the substitutes is mentioned as very negative in this respect (costs of the substitute > 200% of the costs of the original).

Experts' opinion on the substitutability of antimony-containing flame retardants in textiles

The below table shows the average outcome of the experts replies per application/substitute. In case the result was exactly between two columns, the outcome has been rounded to the negative side. The explanation of the scoring system is given at the end of the table.

1	2	3	4	5 Combined substitutes applicability — = very poor - = poor 0 = moderate + = good ++ = very good U = unknown						6 Substitutes environment, health and safety impact — = very negative - = negative 0 = equal + = positive ++ = very positive U = unknown						7 Substitutes costs — = >200 % of original - = 120-200% of original 0 = 80-120% of original + = 50-80% of original ++ = < 50 % of original U = unknown					8
Materials	Major applications	Possible substitutes of antimony-containing flame retardants or replacement of material. S=other Synergist FM=other Flame Retardant AM=Alternative Material	100% substitution or replacement would be feasible within 10 years without compromising required flame retardant quality	—	-	0	+	++	U	—	-	0	+	++	U	—	-	0	+	++	U	Comments -Other applications -Other synergists, FR substitutes or replacing materials
All below mentioned materials	All below mentioned applications	Zinc Stannate (S)	Yes																			
		Zinc Hydro Stannate(S)	0%																			
		Bismuthtrioxide (S)																				
Wool	furniture, clothing, interiors, technical textiles, furniture upholstery	- Phosphorus constituents(FR)	67%																			
		- zirconium constituents(FR)																				
	Backing of carpets	- aluminum trihydroxide(FR)	100%																				In combination with PVC
Cotton	furniture, clothing, interiors, technical textiles	- cellulose reactive methylated phosphonamides (FR)																				
		- ammoniumpolyphosphate																					- ammoniumpolyphosphate is not used in cotton
		- diammoniumphosphate	100%																				- diammoniumphosphate has durability problems
		- polymeric phosphonium salt condensates (FR)																				
	furniture upholstery	- Phosphorus(FR)	100%																				
	Backing of carpets	- aluminum trihydroxide	100%																				In combination with PVC
Polyester fibers	furniture, clothing, interiors, technical textiles	- phosphinic acid derivate co-monomer(FR)																				
		- cyclic phosphonate(FR)	100%																				- bisphenol is not used in EU or USA, if anywhere
		- chlorophosphates(AM)																				
		- bisphenol S (FR)																				
	Furniture upholstery	- phosphorus(FR)	100%																				
	Backing of carpets	- aluminum trihydroxide(FR)	100%																				

Missing materials in textiles with antimony-containing flame retardants

D. Experts' opinion on the substitutability of antimony-containing flame retardants in building and construction

Antimony-containing flame retardants are applied in various plastics that are used in the building and construction sector. The scientific literature provides information on possible substitutes for antimony in these applications. Three main alternatives can be distinguished:

- Antimony trioxide is replaced by another synergist. The halogenated hydrocarbon in the flame retardant is not replaced
- The halogenated flame retardant, including antimony trioxide is replaced
- The base material in which the flame retardant is applied, is replaced by another material

We have asked experts in this field to give their opinion about the various substitutes. It concerns

- the performance of the substitute
- the environment, health and safety impacts of the substitute
- the costs of the substitute

Furthermore we have asked the expert's opinions on the question whether a 100 % substitution or replacement of the antimony-containing flame retardancy systems would be feasible within 10 years without compromising the required flame retardant quality.

The below table provides an overview of the results.

Summarized, the expert's opinion on the substitutability of antimony-containing flame retardants in the building and construction sector is as follows:

In an average of 46 % of the applications the original antimony-containing system can be adequately substituted by a non-antimony-containing system

As for the future the expert's opinion is that in an average of 92% of the applications substitution or replacement would be feasible within 10 years without compromising the required flame retardant quality.

Regarding the EHS (environment, health and safety) aspects of the substitutes, the expert's opinion is that in 5 % of the cases the substitute's EHS properties are at least in one regard negative compared to the original. In 95 % of the cases the substitute's EHS properties are considered equal or positive compared to the original

Regarding the costs of the substitutes the expert's opinion is that in 90 % of the cases the substitute is equal in price or cheaper than the original. The other 10 % of the substitutes is deemed costlier. In no case the substitutes are labeled as very negative in this respect (costs of the substitute > 200% of the costs of the original).

Experts' opinion on the substitution of antimony-containing flame retardants in building and construction

The below table shows the average outcome of the experts replies per application/substitute. In case the result was exactly between two columns, the outcome has been rounded to the negative side. The explanation of the scoring system is given at the end of the table.

1 Materials	2 Major applications	3 Possible substitutes of halogenated flame retardants or replacement of material. S=other Synergist FR=other Flame Retardant AM=Alternative material	4 100% substitution or replacement would be feasible within 10 years without compromising required flame retardancy quality	5 Combined substitutes applicability: — = very poor, - = poor, 0 = moderate, + = positive, ++ = very good, U = unknown	6 Substitutes environment, health and safety impact: — = very negative, - = negative, 0 = equal, + = positive, ++ = very positive, U = unknown	7 Substitutes costs: — = >200 % of original, - = 120-200% of original, 0 = 80-120% of original, + = 50-80% of original, ++ = < 50 % of original, U = unknown	8 Comments -Other applications -Other synergists, FR substitutes or replacing materials
				— - 0 + ++ U	— - 0 + ++ U	— - 0 + ++ U	
All below mentioned materials	All below mentioned applications	Zinc Stannate (S)					
		Zinc Hydroxy Stannate(S)	50%				
		- Bismuthtrioxide (S)					
PE Polyehtylene	pipes, construction sheets	- ammonium-polyphosphate(FR)	100%				
	mounting boxes, wall sockets	- HDPE with magnesium hydroxide(FR)	100%				
	Foils	- ammonium polyphosphate(FR)	100%				
PP Polypropylene	pipes, construction sheets, flooring	- ammonium-polyphosphate(FR)	100%				
	Foils	- ammonium-polyphosphate(FR)	100%				
EPS,XPS Polystyrene, expanded or extruded	insulation panels	- mineral wool(AM)					
		- foam glass(AM)	50%				
PET/PBT Polyethylene Terephtalate/ Polybuthylene terephtalate	lighting, relays, contactors, starters	- porcelain(AM)					
		- bakelite(AM)	100%				
		- halogen free PA(AM)					

1 Materials	2 Major applications	3 Possible substitutes of halogenated flame retardants or replacement of material. S=other Synergist FR=other Flame Retardant AM=Alternative material	4 100% substitution or replacement would be feasible within 10 years without compromising required flame retardancy quality	5 Combined substitutes applicability — = very poor - = poor 0 = moderate + = positive ++= very good U = unknown	6 Substitutes environment, health and safety impact —= very negative - = negative 0 = equal + = positive ++= very positive U = unknown	7 Substitutes costs —= >200 % of original - = 120-200% of original 0 = 80-120% of original + = 50-80% of original ++ = < 50 % of original U = unknown	8 -Comments -Other applications -Other synergists, FR substitutes or replacing materials
PA Polyamide	lighting, relays, contactors, starters	- porcelain(AM)					
		- bakelite(AM)	100%				
PUR Polyurethane	insulation panels	- ammonium-polyphosphates(FR)					
		- red phosphorus(FR)	100%				
		- mineral wool(AM)					
PVC Polyvinylchloride	Pipes, fittings, window profiles	- aluminumtrihydroxide(FR)					
		- magnesiumhydroxide(FR)	100%				
		- zincborate(FR)					
	Foils	- ammoniumpolyphosphate	100%				
Rubber	cables,wires	- aluminum trihydroxide(FR)					
		- zinc borate(FR)	100%				
		- polyethylene vinylacetate with aluminum trihydroxide(AM)					

Missing materials in the building and construction sector with halogenated flame retardants

E.   Experts' opinion on the substitutability of antimony in glass

Antimony has various applications in glass. The scientific literature provides information on possible substitutes for antimony in each of these applications.

We have asked three experts in this field to give their independent opinion about the various substitutes of antimony in glass.

It concerns

-   the performance of the substitute
-   the environment, health and safety impacts of the substitute
-   the costs of the substitute

The interviewed experts have given their opinion as well on the question whether substitution or replacement of the antimony in glass would be feasible within 10 years without compromising the required glass quality.

The annexed table provides an overview of the detailed results.

Summarized, the expert's opinion on the substitutability of antimony in glass is as follows:

In an average of 56 % of the applications antimony can be adequately substituted by a non-antimony compound

The majority of the expert's opinion is that application of antimony compounds in fining and decolorizing of glass cannot within 10 years for 100% be substituted without compromising the required flame retardant quality.

Regarding the EHS (environment, health and safety) aspects of the substitutes, the expert's opinion is that in all cases the substitute's EHS properties are considered equal or positive compared to the antimony compound.

Regarding the costs of the substitutes the expert's opinion is that in 60 % of the cases the substitute is equal in price or cheaper than the original. The other 40 % of the substitutes is deemed costlier. 20% of the substitutes is mentioned as very negative in this respect (costs of the substitute > 200% of the costs of the original).

Experts' opinion on the substitution of antimony in glass

The below table shows the average outcome of the experts replies per application/substitute. In case the result was exactly between two columns, the outcome has been rounded to the negative side. The explanation of the scoring system is given at the end of the table.

1	2	3	4	5 Substitute applicability (—=very poor, -=poor, 0=moderate, +=good, ++=very good, U=unknown)						6 Substitute environment, health and safety impact (—=very negative, -=negative, 0=equal, +=positive, ++=very positive, U=unknown)						7 Substitute costs (—=>200% of original, -=120-200% of original, 0=80-120% of original, +=50-80% of original, ++=<50% of original, U=unknown)						8
Application	Antimony compound	Potential substitutes, processes or other alternatives	100 % substitution or replacement of antimony would be feasible within 10 years without compromising the required product quality	—	-	0	+	++	U	—	-	0	+	++	U	—	-	0	+	++	U	Comments -Other substitutes or alternatives
Fining agent	antimony trioxide	- Sodium sulphate	33%				▓						▓					▓				1)2)5)
Decolorant	antimony trioxide	- Adequate oven design and sand with very low iron content	33%			▓						▓						▓				3)4)
Colorant	antimony sulfide	Many	100%					▓														
Antisolorant	antimony trioxide	- Sand with very low iron content	?																			

Missing applications

1) Sodium sulfate can replace antimony in some types of glass, but gives more foam and may not be as effective. Alternatives generally show lower fining performance. This is very critical for some very high quality glass products

2) Sodium chloride, tin oxides or arsenic oxide may be other substitutes, although some of these may be less recommended due to their environment and health effects

3) Antimony oxides in pentavalent state strongly oxidize glass. There are few alternatives but with drawbacks. They are less effective as decolorant or they lead to solarisation effects of the glass exposed to UV (e.g. CeO2)

4) Costs are function of environmental legislation (furnace investment)

5) Sulfur refining at low iron content will also increase the energy costs. It is the advantage of antimony that it acts as decolorizer and fining agent simultaneously

F.   Antimony applications

Non-metallurgical uses

Antimony in flame retardants

About 50 % of worldwide antimony use is in flame retardants. Antimony-containing flame retardants are mainly applied in plastics. In its application in flame retardants, antimony trioxide (Sb_2O_3) is almost always used in combination with halogen-bearing compounds, usually in a proportion of about 25%-35% (Butterman and Carlin, 2004). The flame retardant content of the products wherein it is contained is substantial. According to Alaee et al (2003), the brominated flame retardant content (including in the order of 30 % antimony trioxide) is about 10 to 15 % in various types of plastics, e.g. high impact polystyrene foam, polyamides, polyurethanes. So this means that these plastics contain 3-5 % of antimony trioxide.

In itself Sb_2O_3 does not have flame retardant properties, but it improves the flame retardant properties of the used halogen hydrocarbons. So it can be described as a synergist in this application.

The plastics with antimony trioxide containing flame retardants are mainly commodity plastics such as flexible PVC, polyethylene, polypropylene, polybutylene, polystyrene, PET, ABS and polyurethanes. In PVC antimony trioxide can be used as such, because PVC is a halogenated compound itself.

There are four main application areas for flame retardants: (1) electric and electronic equipment (such as televisions, computers, refrigerators, etc.), (2) building and construction (such as wiring, insulation materials, paints, etc.), (3) textile and coatings (such as foam upholstery carpets, foam matrasses, curtains, etc.) and (4) transportation (such as seat covers and fillings, insulation panels, carpets, cable wiring, etc.). See below Table. This table makes clear that the majority of the flame retardants (with or without antimony trioxide) are applied in electric and electronic equipment. Of the brominated flame retardants, including antimony trioxide, in Europe more than 50 % are used in electric and electronic equipment as well (EFRA, 2013). According to Camino (2008) in the EU in 2008, 30 % of the plastics in electric and electronic equipment were flame retarded. Of this flame retarded plastics 41 % contain halogenated flame retardants (with antimony). According to Cusack (2007b), of the halogenated flame

Table Proportional use of flame retardants

Application	Proportional use of flame retardants		
	Worldwide (Keyser,2009)	EU-2006 (Cusack, 2007a)	Denmark (Lassen et al. (1999)
Electric and electronic equipment	39%	56%	70%
Building and construction	34%	31%	15%
Textile, adhesives and coatings	15%	7%	1%
Transportation	12%	6%	12%
Total	100%	100%	98%

retardants used in electric and electronic equipment, 59 % is used in casings, 30% in printed circuit boards, 9 % in connectors and relays and 2 % in wires and cables.

According to Flame retardants On Line (2013), total flame retardant consumption was about 2 million tons in 2012 with a global annual growth of about 4-5 %.

Antimony as PET catalyst

Antimony trioxide and antimony triacetate are used as catalyst for the polycondensation of PET. PET is the acronym for polyethylene terephthalate. PET is mainly used for producing synthetic fibres (> 60 %) used in textiles like carpets (mentioned polyester in that application) and plastic bottles (about 30 %) that are mainly used as containers for beverage, food and other liquids (Wikipedia, 2014). The third major application of PET is in plastic films, mainly used for packaging purposes. PET is the third polymer in the world with about 18 % of total polymer production after polyethylene (PE) and polypropylene (PP) (Wikipedia, 2014). PET is produced by the polymerisation reaction between terephthalic acid and ethylene glycol. From the start of the PET production, antimony compounds (such as antimony trioxide, antimony acetate or antimony glycolate) are used as polymerisation catalyst and are still used for > 90 % of global PET manufacturing (Thiele, 2004) despite certain disadvantages. The resulting antimony content in PET is between 150 and 300 ppm (Thiele, 2004).

Antimony as heat stabilizer

Many common plastics are susceptible to degrading effects of heat and ultraviolet light (UV). Heat is relevant both during the production and processing (for instance extrusion) of the plastic and during use. Effects of heat and UV may be oxidation, chain scission, uncontrolled recombination and cross-linking reactions. Protection is done by adding heat stabilizers to the plastic. The majority of the heat and UV stabilizers are used in polyvinylchloride (PVC). According to Butterman and Carlin (2004), in the USA this may be 85-90 %. Markarian (2007) provides comparable figures. PVC is mainly used for construction materials used in residential housing and industrial building, such as window profiles, roofing membranes, wall and floor coverings, sewer and clean water pipes, cable insulation and conduit ducts.

Antimony, in the form of antimony mercaptide, is used as heat stabilizer (mostly) in PVC, although antimony competes with some other stabilizer families. Antimony mercaptides are sensitive for photodecomposition and are therefore mainly applied in underground applications of PVC.

Antimony in ceramics

In ceramics, antimony is applied as pigment:

Antimony trioxide + tin oxide for grey to blue colour

Antimony trioxide + titanium dioxide for yellow colour

Antimony trioxide or sodium antimonite together with titanium dioxide as opacifier

(Butterman and Carlin, 2004)

Antimony in glass

Antimony's most important use in glass (as antimony oxide and sodium antimonite) is that of fining agent / decolorant/antisolorant in high quality transparent glass, for instance in cathode ray tubes and solar glass. As a fining agent, the used antimony compound is added to the high temperature glass melt. This causes big gas bubbles, effectively stirring and cleaning the viscous glass melt to eliminate gas seeds in the final product. The fining agent releases gases that encapsulate smaller seeds in the glass melt. There are several fining agents in use. The type of fining agent depends of the specific glass, the melt temperature and the viscosity of the melt. At present, antimony (III) compounds in combination with a strong oxidising agent, such as sodium or potassium nitrate, are used as fining agent in glass melts for PV modules, in combination with their function as decolourant.

An antisolorant prevents glass from colorizing under the influence of UV light.

Antimony sulphide is used as glass colorant for amber, green or red glass (Butterman and Carlin, 2004).

Antimony in other non-metallic uses

Antimony compounds are used in a big variety of non-metallic applications e.g. as antisolarant (color stabilizer) in pigments (for instance in striping applied to road pavements), for coloring rubber black, in anti-electrostatic plastic coatings of electronic equipment, as additive to some lubricants to increase their chemical stability, in fluorescent lamps, as vulcanization agent for the production of red rubber, as primer for ammunition, as lubricant of friction material in automotive break and clutch linings, in brake pads of cars, in fireworks and matches (Butterman and Carlin, 2004)

<u>Metallurgical uses</u>

Antimony in lead-acid batteries

Antimony is used to strengthen the lead plates in lead-acid batteries. These would be too soft otherwise. However, antimony increases water electrolysis and self-discharge of the battery and, hence, water loss. This phenomenon necessitates venting and periodic addition of water to the electrolyte. Therefore, battery producers have focused to decrease the antimony content of the lead plates as much as possible in combination with higher liquid quantities and a closed system to produce "low maintenance" and "maintenance free" batteries. Maintenance free batteries are antimony free and do not need periodic water refilling. During the last decades, antimony is being replaced by calcium in lead-acid batteries. Calcium-calcium lead-acid batteries have a much lower self-discharge. As a result of these efforts, the antimony content of automotive batteries is falling. However, the required technology for calcium-calcium lead- acid batteries is more complicated and therefore these batteries are still more expensive than the traditional antimony-containing lead-acid batteries. Nevertheless, experts expect that eventually, antimony use in car batteries will be completely eliminated (Roskill Consulting Group, 2011). Despite this development toward antimony free batteries, currently, global antimony use in car batteries is still increasing because of the

strong growth of the number of cars in countries such as China, India and Brazil. According to Roskill Consulting Group Limited (2011), global antimony use in lead-acid batteries increased from 40,000 tons in 2000 to 53,000 tons in 2010. Antimony-containing lead-acid batteries remain still in use for other applications as well, because of their longer life-time compared to calcium lead-acid batteries, e.g. load-leveling batteries, emergency power supply, traction batteries for forklifts, baggage carts. But because of the inherent maintenance necessity of antimony-containing batteries they are also being gradually replaced in those applications by antimony free batteries. Car batteries used to contain up to 7 % antimony, but today the conventional batteries with antimonial lead grids would contain only 1.6 % (Butterman and Carlin, 2004). According to the same source, non-automotive batteries may still contain a substantial amount (up to 11 %) of antimony.

Antimony in alloys

Antimony itself is hard and brittle, but as an alloying agent it hardens and strengthens metals. The use of antimony-containing lead alloys is increasing because of the lead use in construction in fast growing economies in Asia, Latin America and Africa (Roskill Consulting Group (2011). Lead sheets used on roofs and for gutters, contain up to 6 % of antimony in order to harden and strengthen the lead. The weight percent of antimony in a number of alloys is presented in the Table below.

Table Principal antimony alloys (Butterman and Carlin, 2004)

Antimony-containing alloys	Antimony (weight %)
Battery grids	1.6
Bearing metal	6-16
Britannia metal	2-10
Sheets, pipes, pumps, valves for the chemical industry	4-15
Leaded roofing and gutters	6
Sheet and pipe	2-6
Bullets	0.5-1.5
Fragmentation ammunition	12-15
Collapsible tubes	1-4
Electrical cable covering	0.5-1.0
Pewter	1-8
Solder (filler)	2-5
Solder (plumber)	0-2
Specialty castings	11
Type metal	4-23

REFERENCES IN ANNEX I

Alaee, M., Arias, P., Sjödin, A., Bergman, A., 2003, An overview of commercially used brominated fire retardants, their applications, their use patterns in different countries/regions and possible modes of release. Environ. Int. 29, 683-689

Butterman, W.C., Carlin, J.F., 2004, Mineral commodity profiles, Antimony, US Geological Survey

Camino, G., 2008, Introduction to flame retardants in polymers, Elawijt Center, April 25

Cusack, P., 2007a, EU brominated fire retardant consumption (by industry sector), 5th International Conference on Design and Manufacture for Sustainable Development, Loughborough University, 10-11 July

Cusack, P., 2007b, EU flame retardant consumption 2006, Proceedings of the 5th International Conference on Design and Manufacturing for Sustainable Development, Loughborough University, 10-11, July

EFRA website www.flameretardants.eu, 23-10-2013

Flame retardants on line http://www.flameretardants-online.com/web/en/106/

Keyser, C., 2009, Fire retardant global industry overview, December 14, Personal email communication with Mike Kiser, placed on internet.

Lassen, C., Lokke, S., Andersen, L.I., 1999, Brominated flame retardants – Substance flow analysis and assessment of alternatives, Danish Environmental Protection Agency, Environmental project no 494

Markarian, J., 2007, PVC additives, What lies ahead? Plastic additives and compounding November/December

Roskill Consulting Group Limited, 2011, Study of the antimony market, October

Thiele, U.K., 2004, Quo vadis polyester catalyst? Chemical Fibers International, 54, 162-163

Wikipedia http://nl.wikipedia.org/wiki/Polyethyleentereftalaat, 6-1-2014

Annex II

Supplementary information to Chapter 5 (zinc)

No substitution, no material efficiency measures, no dissipation reduction measures, no further build-up of anthropogenic stock

Application	Zinc consumption in 2010 (units)	reduction of zinc consumption by substitution (%)	remaining zinc consumption after substitution (units)	dissipation (%)	remaining after dissipation (units)	current zinc recycling (30% zinc recycling from galvanized steel) (%)	remaining secondary zinc after current recycling (units)	50% zinc recycling from galvanized steel, brass and bronze (%)	remaining secondary zinc (units)	80% zinc recycling from galvanized steel, brass and bronze (%)	remaining zinc (units)
Galvanizing	54	0%	54	8%	50	30%	15	50%	25	80%	40
Die casts	13	0%	13	0%	13	90%	12	90%	12	90%	12
Brass and Bronze	10	0%	10	0%	10	0%	0	50%	5	80%	8
Rolled zinc	8	0%	8	0%	8	90%	7	90%	7	90%	7
Chemicals	15	0%	15	25%	11	0%	0	0%	0	0%	0
Total	100	0%	100	8%	92	37%	34	53%	49	72%	67
Remaining primary zinc extraction					83				64		42
Primary zinc extraction reduction					**19%**				**37%**		**59%**

Low substitution scenario (20%), no material efficiency measures, no dissipation reduction measures, no further build-up of anthropogenic stock

Application	Zinc consumption in 2010 (units)	reduction of zinc consumption by substitution (%)	remaining Zinc consumption after substitution (units)	dissipation (%)	remaining after dissipation (units)	current zinc recycling (30% zinc recycling from galvanized steel) (%)	remaining secondary zinc (units)	50% zinc recycling from galvanized steel, brass and bronze (%)	remaining secondary zinc (units)	80% zinc recycling from galvanized steel, brass and bronze (%)	secondary zinc (units)
Galvanizing	54	15%	46	8%	42	30%	13	50%	21	80%	34
Die casts	13	15%	11	0%	11	90%	10	90%	10	90%	10
Brass and Bronze	10	30%	7	0%	7	0%	0	50%	4	80%	6
Rolled zinc	8	90%	1	0%	1	90%	1	90%	1	90%	1
Chemicals	15	0%	15	25%	11	0%	0	0%	0	0%	0
Total	100	20%	80	9%	72	32%	23	49%	35	69%	50
Remaining primary zinc extraction					71				56		37
Primary zinc extraction reduction					**31%**				**46%**		**64%**

Low substitution scenario (20%), material efficiency measures (10%), dissipation reduction measures, no further build-up of anthropogenic stock

Application	Zinc consumption in 2010 (units)	reduction of zinc consumption by substitution (%)	remaining zinc consumption after substitution (units)	material efficiency measures (%)	remaining zinc after material efficiency measures (units)	dissipation after anti-dissipation measures (%)	remaining zinc after anti-dissipation measures (units)	current zinc recycling (30% zinc recycling from galvanized steel) (%)	remaining secondary zinc after current recycling (units)	50% zinc recycling from galvanized steel, brass and bronze (%)	remaining secondary zinc (units)	80% zinc recycling from galvanized steel, brass and bronze (%)	remaining zinc (units)
Galvanizing	54	15%	46	10%	41	1%	41	30%	12	50%	20	80%	33
Die casts	13	15%	11	10%	10	0%	10	90%	9	90%	9	90%	9
Brass and Bronze	10	30%	7	10%	6	0%	6	0%	0	50%	3	80%	5
Rolled zinc	8	90%	1	10%	1	0%	1	90%	1	90%	1	90%	1
Chemicals	15	0%	15	10%	14	25%	10	0%	0	0%	0	0%	0
Total	100	20%	80	10%	72	5%	68	32%	22	49%	33	70%	47
Remaining primary zinc extraction							63				48		31
Primary zinc extraction reduction							**39%**				**53%**		**70%**

Medium substitution scenario (50 %), no material efficiency measures, no dissipation reduction measures, no further build-up of anthropogenic stock

Application	Zinc consumption in 2010	reduction of zinc consumption by substitution	remaining zinc consumption after substitution	material efficiency measures	remaining zinc after material efficiency measures	dissipation	remaining zinc after dissipation measures	current zinc recycling (30 % zinc recycling from galvanized steel)	remaining secondary zinc after current recycling	50 % zinc recycling from galvanized steel, brass and bronze	remaining secondary zinc	80 % zinc recycling from galvanized steel, brass and bronze	remaining zinc
	units	(%)	units	%	units	%	units	%	units	%	units	%	units
Galvanizing	54	50%	27	0%	27	8%	25	30%	7	50%	12	80%	20
Die casts	13	50%	7	0%	7	0%	7	90%	6	90%	6	90%	6
Brass and Bronze	10	60%	4	0%	4	0%	4	0%	0	50%	2	80%	3
Rolled zinc	8	90%	1	0%	1	0%	1	90%	1	90%	1	90%	1
Chemicals	15	25%	11	0%	11	25%	8	0%	0	0%	0	0%	0
Total	100	50%	50	0%	50	10%	45	31%	14	47%	21	66%	30
Remaining primary zinc extraction									45		36		25
Primary zinc extraction reduction									57%		65%		76%

Medium substitution scenario (50 %), material efficiency measures (10 %), dissipation reduction measures (10 %), no further build-up of anthropogenic stock

Application	Zinc consumption in 2010	reduction of zinc consumption by substitution	remaining zinc consumption after substitution	material efficiency measures	remaining zinc after material efficiency measures	dissipation	remaining zinc after anti-dissipation measures	current zinc recycling (30 % zinc recycling from galvanized steel)	remaining secondary zinc after current recycling	50 % zinc recycling from galvanized steel, brass and bronze	remaining secondary zinc	80 % zinc recycling from galvanized steel, brass and bronze	remaining zinc
	units	(%)	units	%	units	%	units	%	units	%	units	%	units
Galvanizing	54	50%	27	10%	24	1%	24	30%	7	50%	12	80%	19
Die casts	13	50%	7	10%	6	0%	6	90%	5	90%	5	90%	5
Brass and Bronze	10	60%	4	10%	4	0%	4	0%	0	50%	2	80%	3
Rolled zinc	8	90%	1	10%	1	0%	1	90%	1	90%	1	90%	1
Chemicals	15	25%	11	10%	10	25%	8	0%	0	0%	0	0%	0
Total	100	50%	50	10%	45	6%	42	31%	13	47%	20	67%	28
Remaining primary zinc extraction									40		31		21
Primary zinc extraction reduction									62%		70%		80%

High substitution scenario (70 %), no material efficiency measures, no dissipation reduction measures, no further build-up of anthropogenic stock

Application	Zinc consumption in 2010	reduction of zinc consumption by substitution	remaining zinc consumption after substitution	material efficiency measures	remaining zinc after material efficiency measures	dissipation	remaining zinc after dissipation measures	current zinc recycling (30 % zinc recycling from galvanized steel)	remaining secondary zinc after current recycling	50 % zinc recycling from galvanized steel, brass and bronze	remaining secondary zinc	80 % zinc recycling from galvanized steel, brass and bronze	remaining zinc
	units	(%)	units	%	units	%	units	%	units	%	units	%	units
Galvanizing	54	70%	16	0%	16	8%	15	30%	4	50%	7	80%	12
Die casts	13	70%	4	0%	4	0%	4	90%	4	90%	4	90%	4
Brass and Bronze	10	90%	1	0%	1	0%	1	0%	0	50%	1	80%	1
Rolled zinc	8	90%	1	0%	1	0%	1	90%	1	90%	1	90%	1
Chemicals	15	45%	8	0%	8	25%	6	0%	0	0%	0	0%	0
Total	100	70%	30	0%	30	11%	27	32%	9	45%	12	63%	17
Remaining primary zinc extraction									27		23		17
Primary zinc extraction reduction									74%		78%		84%

High substitution scenario (70 %), material efficiency measures (10 %), dissipation reduction measures (10 %), no further build-up of anthropogenic stock

Application	Zinc consumption in 2010	reduction of zinc consumption by substitution	remaining zinc consumption after substitution	material efficiency measures	remaining zinc after material efficiency measures	dissipation	remaining zinc after anti-dissipation measures	current zinc recycling (30 % zinc recycling from galvanized steel)	remaining secondary zinc after current recycling	50 % zinc recycling from galvanized steel, brass and bronze	remaining secondary zinc	80 % zinc recycling from galvanized steel, brass and bronze	remaining zinc
	units	(%)	units	%	units	%	units	%	units	%	units	%	units
Galvanizing	54	70%	16	10%	15	1%	14	30%	4	50%	7	80%	12
Die casts	13	70%	4	10%	4	0%	4	90%	3	90%	3	90%	3
Brass and Bronze	10	90%	1	10%	1	0%	1	0%	0	50%	0	80%	0
Rolled zinc	8	90%	1	10%	1	0%	1	90%	1	90%	1	90%	1
Chemicals	15	45%	8	10%	7	25%	6	0%	0	0%	0	0%	0
Total	100	70%	30	10%	27	7%	25	32%	8	46%	11	64%	16
Remaining primary zinc extraction									24		20		14
Primary zinc extraction reduction									77%		81%		87%

Annex III

Supplementary information to Chapter 7 (geological scarcity and market)

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A.   The impact of substitutability, of improvement of material efficiency, and of recycling on long-term trends in mineral resource prices

An adequate substitute for a raw material will lead to attractively priced alternative services or products and will in this way limit the price of a commodity to the price of the substitute, if that substitute is at least of equivalent quality. For different applications of primary resources there are different substitutes, which may differ in price. As long as the price of a commodity is lower than the price of an adequate substitute, replacement will not automatically take place. Conversely, the price of an adequate substitute will cap the price of the original to the price level of the substitute. The price of a resource will remain constant once a "backstop" technology is available (Heal 1976). For instance, the price of fossil fuels will be limited to the price of renewable energy sources such as wind and sunlight. The application of boron in glass wool will be limited by the cost price of its substitute rock wool.

The availability of a suitable substitute can also lead to accelerated exploitation and consumption of the original in order to still generate maximum returns. An example is the mass marketing of natural gas by the Dutch government in the years 1960 and 1970, in an attempt to maximize profit before the anticipated introduction of nuclear energy would make this gas superfluous (de Pous, 1962). Neumayer (2000) argues that despite the technological progress and possibilities of substitution there is no guarantee that the price mechanism of the free market system will prevent resources from being exhausted

In the case of non-substitutability (for example, using a resource such as phosphorus as a plant nutrient) or in the case of complex recyclability (such as, for example, molybdenum from stainless steel), the price of a commodity may increase further, because alternatives are lacking or are not readily available.

The conclusion is that there is mutual interaction between primary resource prices on the one hand and, on the other hand, increased application of substitutes, material efficiency and recycling:
higher prices for primary resources stimulate substitution, material efficiency, and recycling, the availability of substitutes, better material efficiency methods, and recycling techniques will cap the price of primary materials.

B. The impact of the anthropogenic stocks of minerals on long-term trends in mineral resource prices

A part of mineral resources will be inevitably dissipated in the environment through their usage, e.g. minerals in washing powder, pharmaceuticals, fertilizer, or fuels. However, another part of mineral resources accumulates during various periods in the usage phase: e.g. various metals in infrastructure, buildings, cars, or electronic equipment. Sooner or later, however, all these systems and products will arrive in a waste stage. This may take years, decades, or – for some products – even centuries. They will break down or be destroyed. It will be technically possible to recycle almost 100 % of a mineral resource from end-of-life products and systems, but this will not happen if recycling is more expensive than the costs of the primary raw material. Recycling costs depend on the chemical characteristics of the mineral and on the composition of the alloys and products in which it is used.

For the time being, the quantity of minerals contained in the so-called anthropogenic stocks is still increasing, due to the growing economies of developing countries such as China and India. For instance, China currently consumes more than half of the world's steel production. But at a certain moment in the future, further accumulation of minerals in the anthropogenic stocks will end and the global flow of minerals into the usage phase will be in equilibrium with the flows of minerals out of the usage phase (in end-of-life products or through dissipation). This means that eventually the primary use (extraction) of geologically scarce mineral resources is at least equal to the quantity that is inevitably dissipated in the environment through usage. In such cases the rest of the resource needed must be generated through recycling from end-of-life products.

Henckens et al. (2015a, 2015b and 2015c) have investigated to what extent the scarce elements antimony, boron, molybdenum, and zinc need to be recycled from end-of-life products after these elements have been maximally substituted, material efficiency has been approved, and dissipation has been reduced as far as technologically possible. The results are presented in the below Table.

Table Recycling rates needed to reduce the use of primary antimony, boron, molybdenum, and zinc to a sustainable level as compared to current recycling rates. (Data derived from Henckens et al., 2015a, 2015b and 2015c)

	Necessary reduction of the use of primary material to achieve sustainability	Assumed substitution	Necessary future recycling rate from end-of life products remaining after maximum substitution	Current recycling rate from end-of-life products
Antimony	96%	92%	42%	7%
Boron	55%	43%	12%	0%
Molybdenum	81%	0%	88%	33%
Zinc	82%	54%	78%	55%

The conclusion is that for three of the four elements investigated (antimony, molybdenum, and zinc), recycled material will need to be an important resource for the future supply of these minerals. For these three minerals, if extraction of the primary resource is limited to a sustainable level, the costs of recycling from end-of-life products will become a dominant factor for the resource price. For boron, recycling costs may be a less dominant factor for the price of the resource if the production of primary boron is reduced to a sustainable level, because this level can in principle be achieved by substitution alone.

C. **Price trends of geologically scarce commodities in the United States of America (from USGS, Historical statistics for Mineral and Material Commodities in the United States, 2015) per metric ton (Sb,Mo,Zn,Re,Au)**

Year	Antimony		Molybdenum		Zinc		Rhenium		Gold	
	1998$*100	index (1970=1)	1998 $*100	index (1970=1)	1998$ *100	index (1970=1)	1998$	index (1970=1)	1998$	index (1970=1)
1900	41	0.31			19	1.34			11,900,000	2.42
1901	36	0.27			18	1.27			11,900,000	2.42
1902	25	0.19			20	1.41			11,400,000	2.32
1903	24	0.18			22	1.55			11,000,000	2.24
1904	25	0.19			20	1.41			11,000,000	2.24
1905	41	0.31			24	1.69			11,000,000	2.24
1906	87	0.65			25	1.76			11,000,000	2.24
1907	57	0.43			22	1.55			10,600,000	2.16
1908	32	0.24			18	1.27			11,000,000	2.24
1909	30	0.23			22	1.55			11,000,000	2.24
1910	29	0.22			21	1.48			10,600,000	2.16
1911	29	0.22			22	1.55			10,600,000	2.16
1912	29	0.22	76	0.46	26	1.83			10,300,000	2.10
1913	27.3	0.21	110	0.67	20.3	1.43			1,000,000	2.04
1914	31.3	0.24	364	2.22	18.3	1.29			994,000	2.02
1915	107	0.80	360	2.20	50.5	3.56			994,000	2.02
1916	83.6	0.63	334	2.04	44.8	3.15			932,000	1.90
1917	58	0.44	402	2.45	25	1.76			801,000	1.63
1918	30.1	0.23	354	2.16	19	1.34			685,000	1.40
1919	17	0.13	243	1.48	14.5	1.02			604,000	1.23
1920	15.2	0.11	91.1	0.56	14	0.99			538,000	1.10
1921	9.9	0.07	143	0.87	9.5	0.67			605,000	1.23
1922	11.7	0.09	47.6	0.29	12.2	0.86			649,000	1.32
1923	16.6	0.12	162	0.99	14.1	0.99			635,000	1.29
1924	22.7	0.17	192	1.17	13.2	0.93			633,000	1.29
1925	35.7	0.27	83.3	0.51	15.8	1.11			617,000	1.26
1926	32.2	0.24	144	0.88	15	1.06			611,000	1.24
1927	25.3	0.19	159	0.97	12.9	0.91			624,000	1.27
1928	21.6	0.16	213	1.30	12.7	0.89			632,000	1.29
1929	18.8	0.14	107	0.65	13.6	0.96			6,300,000	1.28
1930	16.6	0.12	121	0.74	9.9	0.70			646,000	1.32
1931	15.8	0.12	101	0.62	8.6	0.61			775,000	1.58
1932	14.8	0.11	134	0.82	7.6	0.54			794,000	1.62
1933	18.1	0.14	211	1.29	11.2	0.79			10,700,000	2.18
1934	24	0.18	191	1.16	11.2	0.79			13,600,000	2.77
1935	36.3	0.27	186	1.13	11.4	0.80			13,300,000	2.71
1936	31.9	0.24	174	1.06	12.7	0.89			13,200,000	2.69

Year	Antimony		Molybdenum		Zinc		Rhenium		Gold	
	1998$*100	index (1970=1)	1998 $*100	index (1970=1)	1998$ *100	index (1970=1)	1998$	index (1970=1)	1998$	index (1970=1)
1937	38.6	0.29	173	1.05	16.3	1.15			12,700,000	2.59
1938	31.6	0.24	182	1.11	11.8	0.83			13,000,000	2.65
1939	32	0.24	178	1.09	13.2	0.93			13,000,000	2.65
1940	35.9	0.27	180	1.10	16.3	1.15			12,700,000	2.59
1941	34.2	0.26	168	1.02	18.3	1.29			12,100,000	2.46
1942	34.4	0.26	159	0.97	18.2	1.28			10,900,000	2.22
1943	33.1	0.25	155	0.95	17.2	1.21			10,300,000	2.10
1944	32.2	0.24	161	0.98	16.9	1.19			10,100,000	2.06
1945	31.6	0.24	156	0.95	16.5	1.16			10,100,000	2.06
1946	31.8	0.24	150	0.91	16	1.13			935,000	1.90
1947	53.9	0.41	133	0.81	16.9	1.19			818,000	1.67
1948	54.7	0.41	126	0.77	20.2	1.42			759,000	1.55
1949	58.4	0.44	144	0.88	18.4	1.30			698,000	1.42
1950	43.8	0.33	145	0.88	20.7	1.46			757,000	1.54
1951	61.3	0.46	145	0.88	24.8	1.75			703,000	1.43
1952	56.8	0.43	144	0.88	21.9	1.54			681,000	1.39
1953	48.2	0.36	148	0.90	14.6	1.03			682,000	1.39
1954	40.7	0.31	154	0.94	14.3	1.01			686,000	1.40
1955	43.3	0.33	157	0.96	16.5	1.16			687,000	1.40
1956	46.2	0.35	163	0.99	17.8	1.25			677,000	1.38
1957	44.7	0.34	165	1.01	14.6	1.03			649,000	1.32
1958	39.6	0.30	166	1.01	12.8	0.90			638,000	1.30
1959	38.5	0.29	169	1.03	14.1	0.99			632,000	1.29
1960	37.9	0.28	167	1.02	15.7	1.11			623,000	1.27
1961	40.6	0.31	176	1.07	13.9	0.98			616,000	1.25
1962	41.2	0.31	178	1.09	13.8	0.97			609,000	1.24
1963	40.8	0.31	176	1.07	14.1	0.99			601,000	1.22
1964	48.9	0.37	185	1.13	15.7	1.11	533,000	0.67	593,000	1.21
1965	52.1	0.39	189	1.15	16.6	1.17	519,000	0.65	584,000	1.19
1966	50.8	0.38	182	1.11	16.1	1.13	493,000	0.62	567,000	1.15
1967	49.3	0.37	182	1.11	14.9	1.05	476,000	0.60	552,000	1.12
1968	47.4	0.36	180	1.10	14	0.99	354,000	0.45	604,000	1.23
1969	56.5	0.42	177	1.08	14.3	1.01	352,000	0.04	591,000	1.20
1970	133	1.00	164	1.00	14.2	1.00	793,000	1.00	491,000	1.00
1971	63.2	0.48	162	0.99	14.3	1.01	977,000	1.23	536,000	1.09
1972	50.7	0.38	153	0.93	15.2	1.07	872,000	1.10	733,000	1.49
1973	55.4	0.42	142	0.87	16.7	1.18	776,000	0.98	11,500,000	2.34
1974	133	1.00	155	0.95	26.2	1.85	401,000	0.51	17,000,000	3.46
1975	118	0.89	189	1.15	26	1.83	306,000	0.39	15,700,000	3.20
1976	104	0.78	205	1.25	23.4	1.65	221,000	0.28	11,500,000	2.34
1977	105	0.79	288	1.76	20.4	1.44	159,000	0.20	12,800,000	2.61

Year	Antimony		Molybdenum		Zinc		Rhenium		Gold	
	1998$*100	index (1970=1)	1998 $*100	index (1970=1)	1998$ *100	index (1970=1)	1998$	index (1970=1)	1998$	index (1970=1)
1978	63.5	0.48	506	3.09	17.1	1.20	113,000	0.14	15,500,000	3.16
1979	69.9	0.53	1140	6.95	18.5	1.30	207,000	0.26	22,200,000	4.52
1980	65.9	0.50	409	2.49	16.3	1.15	678,000	0.85	39,000,000	7.94
1981	53.8	0.40	253	1.54	17.6	1.24	137,000	0.17	26,500,000	5.40
1982	39.9	0.30	152	0.93	14.3	1.01	618,000	0.08	20,400,000	4.15
1983	32.9	0.25	132	0.80	14.9	1.05	72,000	0.09	22,300,000	4.54
1984	52.3	0.39	123	0.75	16.8	1.18	773,000	0.10	18,200,000	3.71
1985	43.	0.33	108	0.66	13.5	0.95	765,000	0.10	15,500,000	3.16
1986	40	0.30	94	0.57	12.5	0.88	893,000	0.11	17,500,000	3.56
1987	35.1	0.26	91.8	0.56	13.3	0.94	916,000	0.12	22,100,000	4.50
1988	31.6	0.24	105	0.64	18.3	1.29	162,000	0.20	19,400,000	3.95
1989	27.4	0.21	97.5	0.59	23.8	1.68	143,000	0.18	16,200,000	3.30
1990	22.5	0.17	78.4	0.48	20.5	1.44	141,000	0.18	15,500,000	3.16
1991	21.7	0.16	62.8	0.38	13.9	0.98	145,000	0.18	14,000,000	2.85
1992	20.2	0.15	56.5	0.34	15	1.06	157,000	0.20	12,900,000	2.63
1993	19.2	0.14	58.2	0.35	11.5	0.81	113,000	0.14	13,100,000	2.67
1994	43.1	0.32	115	0.70	12	0.85	101,000	0.13	13,600,000	2.77
1995	53.8	0.40	186	1.13	13.2	0.93	749,000	0.09	13,300,000	2.71
1996	33.7	0.25	86.6	0.53	11.7	0.82	758,000	0.10	13,000,000	2.65
1997	15.1	0.11	96.2	0.59	14.4	1.01	731,000	0.09	10,900,000	2.22
1998	15.8	0.12	75	0.46	11.3	0.80	817,000	0.10	949,000	1.93
1999	13.5	0.10	57.2	0.35	11.5	0.81	101,000	0.13	881,000	1.79
2,000	13.6	0.10	53.3	0.33	11.6	0.82	825,000	0.10	853,000	1.74
2001	13.2	0.10	47.8	0.29	8.9	0.63	906,000	0.11	806,000	1.64
2002	17.7	0.13	75	0.46	7.7	0.54	976,000	0.12	906,000	1.85
2003	20.9	0.16	104	0.63	7.9	0.56	98,000	0.12	10,400,000	2.12
2004	25.5	0.19	317	1.93	10	0.70	923,000	0.12	11,400,000	2.32
2005	29.5	0.22	585	3.57	12.4	0.87	868,000	0.11	11,900,000	2.42
2006	42.5	0.32	442	2.70	28.3	1.99	101,000	0.13	15,800,000	3.22
2007	44.5	0.33	525	3.20	26.7	1.88	188,000	0.24	17,700,000	3.60
2008	46.7	0.35	477	2.91	14.8	1.04	787,000	0.99	21,300,000	4.34
2009	39.5	0.30	196	1.20	13.1	0.92	5700000	0.72	23,800,000	4.85
2010	66.1	0.50	261	1.59	16.8	1.18	353,000	0.45	29,500,000	6.01
2011	104	0.78	249	1.52	17	1.20	338,000	0.43	36,700,000	7.47
2012	88.4	0.66	199	1.21	15	1.06	287,000	0.36	38,200,000	7.78
2013	71.4	0.54	160	0.98	14.8	1.04	221,000	0.28	31,800,000	6.48

D. **Price trends of geologically moderately scarce commodities in the United States of America (from USGS, Historical statistics for Mineral and Material Commodities in the United States, 2014) per metric ton. Price index: 1970 =1 (Sn, Cr, Cu, Pb, B, As, Fe, Ni, Ag, Cd, W, Bi)**

Year	tin Unit value 1998$	Price index	Chromium Unit value 1998$	Price index	Copper Unit value 1998$	Price index	Lead Unit value 1998$	Price index	boron (as B2O3) Unit value 1998$	Price index	As Unit value 1998$	Price index	Iron(tons of gross weight) Unit value 1998$	Price index	Nickel Unit value 1998$	Price index	Silver Unit value 1998$	Price index	Cadmium Unit value 1998$	Price index	Tungsten Unit value 1998$	Price index	Bismuth Unit value 1998$	Price index
1900	12,900	0.80	1,090	2.03	7,000	1.30	2,000	1.38	2,170	3.07	2,600	3.27	47.45	1.05	22,000	1.85	390,000	1.63	28,000	0.85	11,000	0.46	97,000	1.75
1901	7,220	0.45	1,160	2.16	7,000	1.30	1,900	1.31	2,390	3.38	2,200	2.77	33.53	0.74	24,000	2.02	380,000	1.59	29,000	0.88	7,000	0.30	78,000	1.41
1902	11,200	0.70	882	1.64	4,800	0.89	1,700	1.17	6,140	8.68	1,800	2.26	34.07	0.75	19,000	1.60	320,000	1.34	22,000	0.66	8,000	0.34	62,000	1.12
1903	11,300	0.70	765	1.42	5,300	0.99	1,700	1.17	1,020	1.44	1,700	2.14	34.36	0.76	16,000	1.34	320,000	1.34	21,000	0.63	6,300	0.27	60,000	1.08
1904	11,200	0.70	836	1.55	5,100	0.95	1,700	1.17	815	1.15	1,800	2.26	25.57	0.56	16,000	1.34	340,000	1.42	24,000	0.73	10,000	0.42	60,000	1.08
1905	12,600	0.78	769	1.43	6,300	1.17	1,800	1.24	1,140	1.61	1,900	2.39	32.18	0.71	16,000	1.34	360,000	1.51	26,000	0.79	14,000	0.59	51,000	0.92
1906	15,900	0.99	738	1.37	7,700	1.43	2,300	1.59	1,070	1.51	3,400	4.27	38.36	0.85	16,000	1.34	390,000	1.63	31,000	0.94	16,000	0.68	50,000	0.90
1907	14,800	0.92	652	1.21	7,700	1.43	2,100	1.45	1,100	1.56	2,400	3.02	43.97	0.97	17,000	1.43	370,000	1.55	32,000	0.97	22,000	0.93	48,000	0.86
1908	11,800	0.73	731	1.36	5,300	0.99	1,700	1.17	2,010	2.84	2,300	2.89	41.27	0.91	18,000	1.51	310,000	1.30	30,000	0.91	14,000	0.59	70,000	1.26
1909	11,900	0.74	685	1.27	5,300	0.99	1,700	1.17	1,880	2.66	2,000	2.51	39.09	0.86	16,000	1.34	30,0000	1.26	21,000	0.63	16,000	0.68	70,000	1.26
1910	13,200	0.82	608	1.13	5,000	0.93	1,700	1.17	1,390	1.97	1,400	1.76	43.33	0.95	15,000	1.26	30,0000	1.26	21,000	0.63	18,700	0.79	75,000	1.35
1911	16,400	1.02	603	1.12	4,900	0.91	1,700	1.17	1,450	2.05	1,500	1.89	37.02	0.82	15,000	1.26	30,0000	1.26	26,000	0.79	15,000	0.63	82,000	1.48
1912	17,200	1.07	498	0.93	6,200	1.15	1,700	1.17	1,270	1.80	1,700	2.14	31.86	0.70	15,000	1.26	340,000	1.42	28,000	0.85	14,800	0.62	76,000	1.37
1913	16,100	1.00	501	0.93	5,630	1.05	1,600	1.10	1,190	1.68	2,100	2.64	35.9	0.79	15,300	1.29	323,000	1.35	28,000	0.85	16,600	0.70	72,700	1.31
1914	12,300	0.76	449	0.83	4,760	0.88	1,400	0.97	698	0.99	1,780	2.24	29.67	0.65	14,700	1.24	294,000	1.23	32,000	0.97	16,600	0.70	104,000	1.87
1915	13,700	0.85	526	0.98	6,180	1.15	1,680	1.16	752	1.06	1,880	2.36	29.52	0.65	14,600	1.23	264,000	1.11	42,300	1.28	65,800	2.78	102,000	1.84
1916	14,300	0.89	660	1.23	9,360	1.74	2,270	1.57	727	1.03	2,640	3.32	34.93	0.77	13,800	1.16	322,000	1.35	51,400	1.55	70,700	2.98	120,000	2.16
1917	17,400	1.08	750	1.39	8,190	1.52	2,420	1.67	888	1.26	5,190	6.53	39.87	0.88	11,800	0.99	344,000	1.44	41,300	1.25	32,600	1.38	96,300	1.74
1918	21,100	1.31	1,280	2.38	5,890	1.09	1,700	1.17	560	0.79	3,770	4.74	36.45	0.80	9,760	0.82	340,000	1.42	35,200	1.06	34,900	1.47	81,600	1.47
1919	13,200	0.82	680	1.26	3,780	0.70	1,210	0.83	358	0.51	2,750	3.46	33.02	0.73	8,320	0.70	340,000	1.42	25,400	0.77	23,600	1.00	64,000	1.15
1920	8,660	0.54	333	0.62	3,140	0.58	1,470	1.01	299	0.42	3,350	4.21	33.41	0.74	7,530	0.63	267,000	1.12	21,000	0.63	8910	0.38	45,800	0.83
1921	5,990	0.37	232	0.43	2,540	0.47	945	0.65	818	1.16	2,020	2.54	30.64	0.68	8,420	0.71	184,000	0.77	19,700	0.60	11,000	0.46	39,200	0.71

Year	tin Unit value 1998$	tin Price index	Chromium Unit value 1998$	Chromium Price index	Copper Unit value 1998$	Copper Price index	Lead Unit value 1998$	Lead Price index	boron (as B2O3) Unit value 1998$	boron (as B2O3) Price index	As Unit value 1998$	As Price index	Iron (tons of gross weight) Unit value 1998$	Iron (tons of gross weight) Price index	Nickel Unit value 1998$	Nickel Price index	Silver Unit value 1998$	Silver Price index	Cadmium Unit value 1998$	Cadmium Price index	Tungsten Unit value 1998$	Tungsten Price index	Bismuth Unit value 1998$	Bismuth Price index
1922	6,980	0.43	255	0.47	2,900	0.54	1,220	0.84	859	1.21	3,040	3.82	30.29	0.67	8,140	0.68	212,000	0.89	23,300	0.70	12,700	0.54	42,400	0.76
1923	8,960	0.56	265	0.49	3,100	0.58	1,550	1.07	776	1.10	3,400	4.27	32.86	0.72	7,560	0.64	199,000	0.83	18,500	0.56	13,300	0.56	52,500	0.95
1924	10,500	0.65	280	0.52	2,790	0.52	1,740	1.20	726	1.03	2,780	3.50	27.71	0.61	6,300	0.53	205,000	0.86	12,600	0.38	11,200	0.47	42,700	0.77
1925	11,900	0.74	239	0.44	2,920	0.54	1,880	1.30	701	0.99	1,330	1.67	23.33	0.51	6,800	0.57	207,000	0.87	12,300	0.37	13,700	0.58	41,100	0.74
1926	13,200	0.82	232	0.43	2,840	0.53	1,710	1.18	689	0.97	858.2	1.08	23.03	0.51	7,280	0.61	183,000	0.77	12,200	0.37	14,200	0.60	61,500	1.11
1927	13,300	0.83	235	0.44	2,690	0.50	1,400	0.97	785	1.11	1,020	1.28	23.3	0.51	7,220	0.61	171,000	0.72	12,400	0.37	13,500	0.57	47,500	0.86
1928	10,600	0.66	240	0.45	3,110	0.58	1,320	0.91	726	1.03	1,110	1.40	23.43	0.52	7,770	0.65	178,000	0.75	12,600	0.38	13,700	0.58	41,700	0.75
1929	9,490	0.59	255	0.47	3,850	0.72	1,440	0.99	636	0.90	1,110	1.40	24.86	0.55	7,350	0.62	162,000	0.68	12,600	0.38	17,300	0.73	35,700	0.64
1930	6,850	0.43	334	0.62	2,860	0.53	1,200	0.83	733	1.04	1,140	1.43	27.84	0.61	7,570	0.64	120,000	0.50	12,900	0.39	16,400	0.69	29,100	0.52
1931	5,790	0.36	498	0.93	1,980	0.37	1,010	0.70	774	1.09	1,250	1.57	29.14	0.64	8,270	0.69	99,900	0.42	13,000	0.39	16,400	0.69	29,600	0.53
1932	5,770	0.36	635	1.18	1,520	0.28	833	0.57	517	0.73	1,390	1.75	28.81	0.63	9,190	0.77	107,000	0.45	14,400	0.44	15,300	0.65	22,300	0.40
1933	10,800	0.67	503	0.93	2,020	0.38	1,070	0.74	599	0.85	1,460	1.84	32.78	0.72	9,670	0.81	141,000	0.59	15,200	0.46	16,800	0.71	29,800	0.54
1934	14,000	0.87	480	0.89	2,330	0.43	1,030	0.71	632	0.89	1,330	1.67	31.46	0.69	9,390	0.79	188,000	0.79	14,700	0.44	24,700	1.04	32,200	0.58
1935	13,200	0.82	530	0.99	2,330	0.43	1,070	0.74	613	0.87	1,210	1.52	29.52	0.65	9,190	0.77	245,000	1.03	18,300	0.55	22,100	0.93	27,500	0.50
1936	12,000	0.75	529	0.98	2,520	0.47	1,220	0.84	601	0.85	1,190	1.50	30.12	0.66	9050	0.76	170,000	0.71	25,300	0.76	24,200	1.02	25,800	0.46
1937	13,600	0.84	482	0.90	3,350	0.62	1490	1.03	596	0.84	1,070	1.35	29.09	0.64	8,740	0.73	164,000	0.69	30,500	0.92	30,700	1.30	24,900	0.45
1938	10,800	0.67	494	0.92	2,610	0.49	1,200	0.83	664	0.94	1,010	1.27	33.37	0.74	8,930	0.75	160,000	0.67	25,000	0.76	27,800	1.17	26,700	0.48
1939	13,000	0.81	477	0.89	2,900	0.54	1,300	0.90	899	1.27	1,020	1.28	34	0.75	9,050	0.76	147,000	0.62	16,500	0.50	27,900	1.18	28,500	0.51
1940	12,800	0.80	486	0.90	2,960	0.55	1,330	0.92	895	1.27	1,190	1.50	29.19	0.64	8,990	0.76	131,000	0.55	21,100	0.64	33,400	1.41	32,100	0.58
1941	12,700	0.79	455	0.85	2,930	0.54	1,420	0.98	871	1.23	1,290	1.62	26.67	0.59	8,560	0.72	125,000	0.52	22,000	0.66	36,000	1.52	30,600	0.55
1942	11,500	0.71	562	1.04	2,650	0.49	1,430	0.99	815	1.15	1,160	1.46	23.5	0.52	7,050	0.59	122,000	0.51	17,400	0.53	33,500	1.41	27,600	0.50
1943	10,800	0.67	617	1.15	2,500	0.46	1,350	0.93	759	1.07	1,100	1.38	25.47	0.56	6,650	0.56	136,000	0.57	16,400	0.50	32,900	1.39	26,000	0.47

Year	tin Unit value 1998$	tin Price index	Chromium Unit value 1998$	Chromium Price index	Copper Unit value 1998$	Copper Price index	Lead Unit value 1998$	Lead Price index	boron (as B2O3) Unit value 1998$	boron Price index	As Unit value 1998$	As Price index	Iron(tons of gross weight) Unit value 1998$	Iron Price index	Nickel Unit value 1998$	Nickel Price index	Silver Unit value 1998$	Silver Price index	Cadmium Unit value 1998$	Cadmium Price index	Tungsten Unit value 1998$	Tungsten Price index	Bismuth Unit value 1998$	Bismuth Price index
1944	10,600	0.66	651	1.21	2,450	0.46	1,320	0.91	732	1.04	1,080	1.36	25	0.55	6,530	0.55	134,000	0.56	15,300	0.46	30,100	1.27	25,600	0.46
1945	10,400	0.65	634	1.18	2,410	0.45	1,300	0.90	729	1.03	1,060	1.33	25.18	0.55	6,410	0.54	152,000	0.64	15,400	0.47	29,200	1.23	25,000	0.45
1946	10,000	0.62	434	0.81	2,580	0.48	1,490	1.03	680	0.96	1,220	1.53	25.58	0.56	6,430	0.54	214,000	0.90	18,200	0.55	23,400	0.99	26,500	0.48
1947	12,500	0.78	466	0.87	3,420	0.64	2,360	1.63	655	0.93	1,280	1.61	25.11	0.55	5,640	0.47	169,000	0.71	25,300	0.76	23,800	1.00	31,900	0.57
1948	14,800	0.92	513	0.95	3,320	0.62	2,690	1.86	617	0.87	1,210	1.52	26.42	0.58	5,370	0.45	161,000	0.67	24,700	0.75	24,800	1.05	29,800	0.54
1949	15,000	0.93	522	0.97	2,940	0.55	2,320	1.60	624	0.88	1,100	1.38	30.82	0.68	6,040	0.51	159,000	0.67	30,200	0.91	25,100	1.06	30,200	0.54
1950	14,200	0.88	503	0.93	3,210	0.60	1,980	1.37	617	0.87	1,130	1.42	33.72	0.74	6,700	0.56	161,000	0.67	32,300	0.98	26,600	1.12	30,700	0.55
1951	17,500	1.09	501	0.93	3,400	0.63	2,410	1.66	574	0.81	1,190	1.50	34.34	0.76	7,440	0.63	179,000	0.75	35,200	1.06	53,300	2.25	31,100	0.56
1952	16,300	1.01	580	1.08	3,310	0.62	2,230	1.54	566	0.80	1,070	1.35	37.36	0.82	7,730	0.65	168,000	0.70	30,300	0.92	54,100	2.28	30,500	0.55
1953	12,900	0.80	669	1.24	3,910	0.73	1810	1.25	557	0.79	978.3	1.23	41.22	0.91	8,050	0.68	167,000	0.70	26,900	0.81	52,900	2.23	30,300	0.55
1954	12,300	0.76	516	0.96	4,000	0.74	1880	1.30	774	1.09	971.2	1.22	41.88	0.92	8,180	0.69	166,000	0.69	22,700	0.69	52,800	2.23	30,100	0.54
1955	12,700	0.79	523	0.97	5,040	0.94	2040	1.41	837	1.18	974.7	1.23	43.35	0.96	8,900	0.75	174,000	0.73	22,800	0.73	52,300	2.21	30,200	0.54
1956	13,400	0.83	577	1.07	5,540	1.03	2110	1.46	807	1.14	960,1	1.21	44.73	0.99	8,560	0.72	175,000	0.73	22,500	0.68	48,300	2.04	29,700	0.54
1957	12,300	0.76	652	1.21	3,840	0.71	1880	1.30	899	1.27	929.5	1.17	48.31	1.06	9,480	0.80	170,000	0.71	21,800	0.66	19,900	0.84	28,800	0.52
1958	11,800	0.73	631	1.17	3,280	0.61	1510	1.04	902	1.28	903.8	1.14	48.64	1.07	9,210	0.77	162,000	0.68	18,900	0.57	13,800	0.58	28,000	0.50
1959	12,600	0.78	756	1.41	3,820	0.71	1,500	1.03	911	1.29	734.2	0.92	48.55	1.07	9,110	0.77	163,000	0.68	16,700	0.50	16,000	0.68	27,800	0.50
1960	12,300	0.76	476	0.88	3,920	0.73	1,450	1.00	897	1.27	721,7	0.91	48.23	1.06	8,960	0.75	161,000	0.67	18,400	0.56	17,100	0.72	27,300	0.49
1961	13,700	0.85	379	0.70	3,630	0.67	1,310	0.90	901	1.27	635.2	0.80	49.13	1.08	9,400	0.79	162,000	0.68	20,200	0.61	16,200	0.68	27,000	0.49
1962	13,700	0.85	673	1.25	3,670	0.68	1,150	0.79	862	1.22	628.7	0.79	47.53	1.05	9,510	0.80	189,000	0.79	20,500	0.62	17,300	0.73	26,800	0.48
1963	13,700	0.85	619	1.15	3,640	0.68	1,310	0.90	875	1.24	791.1	0.99	49.04	1.08	9,260	0.78	219,000	0.92	26,500	0.80	15,700	0.66	26,400	0.48
1964	18,300	1.14	652	1.21	3,750	0.70	1,580	1.09	830	1.17	803.6	1.01	50.11	1.10	9,160	0.77	218,000	0.91	34,800	1.05	14,800	0.62	26,700	0.48
1965	20,400	1.27	670	1.25	4,020	0.75	1,830	1.26	858	1.21	859	1.08	49.38	1.09	9,020	0.76	215,000	0.90	29,400	0.89	19,600	0.83	39,100	0.70

Year	tin		Chromium		Copper		Lead		boron (as B2O3)		As		Iron (tons of gross weight)		Nickel		Silver		Cadmium		Tungsten		Bismuth	
	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index
1966	18,200	1.13	609	1.13	3,990	0.74	1,670	1.15	824	1.17	736.9	0.93	47.69	1.05	8,740	0.73	208,000	0.87	26,900	0.81	23,200	0.98	44,400	0.80
1967	16,500	1.02	644	1.20	4,100	0.76	1,510	1.04	781	1.10	810.4	1.02	48.39	1.07	9,460	0.79	243,000	1.02	28,400	0.86	20,000	0.84	43,000	0.77
1968	15,300	0.95	645	1.20	4,260	0.79	1,370	0.94	754	1.07	835.9	1.05	47.93	1.06	9,810	0.82	323,000	1.35	27,400	0.83	23,200	0.98	41,300	0.74
1969	16,100	1.00	614	1.14	4,650	0.86	1,460	1.01	714	1.01	840.6	1.06	45.96	1.01	10,300	0.87	255,900	1.07	32,000	0.97	23,300	0.98	45,300	0.82
1970	16,100	1.00	538	1.00	5,380	1.00	1,450	1.00	707	1.00	795.4	1.00	45.38	1.00	11,900	1.00	238,900	1.00	33,100	1.00	23,700	1.00	55,500	1.00
1971	14,800	0.92	755	1.40	4,620	0.86	1,230	0.85	,700	0.99	761.8	0.96	46.57	1.03	11,800	0.99	200,600	0.84	17,000	0.51	26,300	1.11	46,700	0.84
1972	15,300	0.95	767	1.43	4,420	0.82	1,290	0.89	674	0.95	738.3	0.93	47.66	1.05	12,100	1.02	210,500	0.88	22,000	0.66	22,100	0.93	31,200	0.56
1973	18,400	1.14	774	1.44	4,810	0.89	1,320	0.91	688	0.97	694.9	0.87	47.03	1.04	12,400	1.04	301,900	1.26	29,400	0.89	22,000	0.93	42,600	0.77
1974	28,900	1.80	1,060	1.97	5,630	1.05	1,640	1.13	750	1.06	1,250	1.57	53.93	1.19	12,700	1.07	500,600	2.10	29,800	0.90	34,800	1.47	67,400	1.21
1975	22,700	1.41	1,780	3.31	4,290	0.80	1,440	0.99	870	1.23	1,160	1.46	64.88	1.43	13,800	1.16	430,500	1.80	22,400	0.68	35,400	1.49	55,100	0.99
1976	24,000	1.49	1,440	2.68	4,390	0.82	1,460	1.01	917	1.30	1,090	1.37	69.57	1.53	14,200	1.19	400,500	1.68	16,800	0.51	40,100	1.69	47,300	0.85
1977	31,700	1.97	1,340	2.49	3,960	0.74	1,820	1.26	954	1.35	1,030	1.29	70.75	1.56	13,400	1.13	399,600	1.67	17,600	0.53	54,200	2.29	35,800	0.65
1978	34,700	2.16	1,150	2.14	3,630	0.67	1860	1.28	991	1.40	1,690	2.12	72.15	1.59	11,300	0.95	433,800	1.82	13,500	0.41	45,300	1.91	18,600	0.34
1979	36,400	2.26	1,310	2.43	4,570	0.85	2,600	1.79	960	1.36	1,590	2.00	73.35	1.62	13,200	1.11	800,900	3.35	13,700	0.41	41,600	1.76	14,900	0.27
1980	36,900	2.29	1,260	2.34	4,420	0.82	1,850	1.28	1,010	1.43	1,830	2.30	72.4	1.60	12,300	1.03	1,312,000	5.49	12,400	0.37	36,600	1.54	11,500	0.21
1981	29,000	1.80	1,270	2.36	3,330	0.62	1,440	0.99	1,120	1.58	2,090	2.63	72.38	1.59	10,700	0.90	606,200	2.54	7,620	0.23	31,500	1.33	9,970	0.18
1982	24,400	1.52	1,150	2.14	2,710	0.50	949	0.65	1,170	1.65	1,970	2.48	70.47	1.55	8,130	0.68	431,700	1.81	4,140	0.13	23,700	1.00	6,000	0.11
1983	23,600	1.47	1,060	1.97	2,760	0.51	782	0.54	1,240	1.75	1,570	1.97	71.37	1.57	7,650	0.64	601,900	2.52	4,080	0.12	17,000	0.72	6,200	0.11
1984	21,600	1.34	1,140	2.12	2,310	0.43	885	0.61	1,170	1.65	1,510	1.90	69.23	1.53	7,490	0.63	410,800	1.72	5,850	0.18	17,900	0.76	14,800	0.27
1985	19,900	1.24	1,160	2.16	2,240	0.42	638	0.44	1,170	1.65	1,460	1.84	63.68	1.40	7,540	0.63	299,200	1.25	4,040	0.12	14,100	0.59	17,300	0.31
1986	12,600	0.78	1,010	1.88	2,170	0.40	721	0.50	1,170	1.65	1,430	1.80	52.94	1.17	5,770	0.48	261,500	1.09	4,100	0.12	10,500	0.44	10,700	0.19
1987	13,200	0.82	944	1.75	2,610	0.49	1,140	0.79	1,120	1.58	1,500	1.89	45.74	1.01	6,940	0.58	323,300	1.35	6,280	0.19	9,110	0.38	11,600	0.21

Year	tin		Chromium		Copper		Lead		boron (as B2O3)		As		Iron(tons of gross weight)		Nickel		Silver		Cadmium		Tungsten		Bismuth	
	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index
1988	13,400	0.83	1,440	2.68	3,660	0.68	1,130	0.78	1,030	1.46	1,320	1.66	41.4	0.91	19,000	1.60	289,300	1.21	20,900	0.63	10,300	0.43	17,500	0.32
1989	15,100	0.94	1,630	3.03	3,800	0.71	1,140	0.79	996	1.41	1,030	1.29	43.78	0.96	17,500	1.47	232,500	0.97	18,100	0.55	13,900	0.59	16,700	0.30
1990	10,600	0.66	1,110	2.06	3,380	0.63	1,260	0.87	898	1.27	835.5	1.05	38.08	0.84	11,100	0.93	193,300	0.81	9,290	0.28	10,600	0.45	9,790	0.18
1991	9,600	0.60	1,080	2.01	2,890	0.54	884	0.61	852	1.21	871.4	1.10	35.32	0.78	9,760	0.82	155,400	0.65	5,300	0.16	11,800	0.50	7,910	0.14
1992	10,300	0.64	1,020	1.90	2,750	0.51	899	0.62	765	1.08	981.2	1.23	36.21	0.80	8,130	0.68	147,200	0.62	2,320	0.07	10,800	0.46	6,810	0.12
1993	8,700	0.54	777	1.44	2,280	0.42	788	0.54	801	1.13	854.2	1.07	27.65	0.61	5,970	0.50	156,000	0.65	1,120	0.03	7,690	0.32	6,220	0.11
1994	8,950	0.56	764	1.42	2,690	0.50	902	0.62	857	1.21	1,030	1.29	26.84	0.59	6,970	0.59	187,000	0.78	2,740	0.08	10,400	0.44	7,890	0.14
1995	9,800	0.61	1,300	2.42	3,260	0.61	998	0.69	797	1.13	1,030	1.29	30.27	0.67	8,800	0.74	177,100	0.74	4,330	0.13	13,200	0.56	9,080	0.16
1996	9,450	0.59	970	1.80	2,500	0.46	1,120	0.77	869	1.23	1,000	1.26	29.63	0.65	7,790	0.65	173,400	0.73	2,840	0.09	10,800	0.46	8,360	0.15
1997	8,540	0.53	1,040	1.93	2,400	0.45	1,050	0.72	888	1.26	916.8	1.15	30.56	0.67	7,040	0.59	159,700	0.67	1,150	0.03	9,810	0.41	7,840	0.14
1998	8,230	0.51	909	1.69	1,730	0.32	999	0.69	775	1.10	932	1.17	31.14	0.69	4,630	0.39	178,000	0.75	626	0.02	8,300	0.35	7,940	0.14
1999	7,900	0.49	694	1.29	1,640	0.30	942	0.65	907	1.28	826.3	1.04	25.9	0.57	5,880	0.49	165,000	0.69	382	0.01	6,920	0.29	8,310	0.15
2,000	7,730	0.48	721	1.34	1,840	0.34	910	0.63	891	1.26	882.2	1.11	24.21	0.53	8,180	0.69	152,000	0.64	343	0.01	7,840	0.33	7,720	0.14
2,001	6,390	0.40	786	1.46	1,560	0.29	886	0.61	809	1.14	750.5	0.94	21.98	0.48	5,470	0.46	130,000	0.54	460	0.01	11,500	0.49	7,590	0.14
2,002	5,830	0.36	721	1.34	1,510	0.28	871	0.60	748	1.06	870.7	1.09	23.61	0.52	6,130	0.52	135,000	0.57	583	0.02	8,230	0.35	6,270	0.11
2,003	6,640	0.41	790	1.47	1,670	0.31	855	0.59	827	1.17	877	1.10	23.79	0.52	8,530	0.72	140,000	0.59	1,160	0.04	7,720	0.33	5,610	0.10
2,004	10,400	0.65	1,190	2.21	2,550	0.47	1,050	0.72	806	1.14	804	1.01	32.72	0.72	11,900	1.00	186,000	0.78	1,040	0.03	10,000	0.42	6,370	0.11
2,005	8,850	0.55	1,260	2.34	3,190	0.59	1,130	0.78	780	1.10	398	0.50	37.15	0.82	12,300	1.03	197,000	0.82	2,750	0.08	24,900	1.05	7,190	0.13
2,006	10,100	0.63	1,140	2.12	5,610	1.04	1,380	0.95	756	1.07	373	0.47	43.59	0.96	19,600	1.65	302,000	1.26	2,410	0.07	29,900	1.26	8,980	0.16
2,007	15,600	0.97	1,580	2.94	5,690	1.06	2,150	1.48	735	1.04	399	0.50	46.89	1.03	29,300	2.46	339,000	1.42	5,980	0.18	28,200	1.19	24,400	0.44
2,008	18,900	1.17	2,640	4.91	5,330	0.99	2,010	1.39	707	1.00	419	0.53	53.32	1.17	16,000	1.34	365,000	1.53	4,480	0.14	26,600	1.12	21,200	0.38
2,009	14,100	0.88	1,540	2.86	4,040	0.75	1,460	1.01	667	0.94	442	0.56	70.49	1.55	11,100	0.93	359,000	1.50	2,180	0.07	19,500	0.82	13,100	0.24

Year	tin		Chromium		Copper		Lead		boron (as B2O3)		As		Iron (tons of gross weight)		Nickel		Silver		Cadmium		Tungsten		Bismuth	
	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index
2010	20,400	1.27	1,980	3.68	5,740	1.07	1,790	1.23	508	0.72	435	0.55	73.83	1.63	16,300	1.37	485,000	2.03	2,920	0.09	20,200	0.85	14,400	0.26
2011	25,100	1.56	1,940	3.61	6,490	1.21	1,950	1.34	631	0.89	464	0.58	72.07	1.59	16,600	1.39	819,000	3.43	2,000	0.06	33,900	1.43	18,300	0.33
2012	20,100	1.25	1,800	3.35	5,750	1.07	1,790	1.23	557	0.79	496	0.62	69.67	1.54	12,400	1.04	713,000	2.98	1,440	0.04	40,200	1.70	15,800	0.28
2013	16,000	0.99	1,650	3.07	5,240	0.97	1,770	1.22	486	0.69	550	0.69	73.41	1.62	10,500	0.88	592,000	2.48	1,340	0.04	32,600	1.38	13,400	0.24

E.   Price trends of geologically non-scarce commodities in the United States of America (from USGS, Historical statistics for Mineral and Material Commodities in the United States, 2014) per metric ton. Price index: 1970 =1 (Al, Mg, Be, Ti, V, Li, Mn, Co, Ga, Ge)

Year	aluminum		magnesium (as MgO)		beryllium		Titanium dioxide (as TiO2)		vanadium		Lithium		Manganese		Cobalt		Gallium		Germanium	
	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index
1,900	14,000	5.26	380	0.75									450	1.59	97,000	4.73				
1901	14,000	5.26	140	0.28									510	1.80	110,000	5.37				
1902	14,000	5.26	120	0.24									,500	1.76	106,000	5.17				
1903	13,000	4.89	120	0.24									790	2.78	110,000	5.37				
1904	14,000	5.26	130	0.26									430	1.52	113,000	5.51				
1905	14,000	5.26	160	0.31									520	1.83	110,000	5.37				
1906	14,000	5.26	120	0.24									870	3.07	108,000	5.27				
1907	17,000	6.39	120	0.24									810	2.85	82,000	4.00				
1908	12,000	4.51	130	0.26									480	1.69	4,300	0.21				
1909	8,800	3.31	170	0.33									520	1.83	53,000	2.59				
1910	8,600	3.23	240	0.47					46,000	2.22			530	1.87	22,000	1.07				
1911	7,800	2.93	320	0.63					17,000	0.82			510	1.80	5,200	0.25				
1912	8,200	3.08	310	0.61					19,000	0.92			420	1.48	5,400	0.26				
1913	8,550	3.21	303	0.60					28,800	1.39			460	1.62	22,800	1.11				
1914	6,660	2.50	413	0.81					29,400	1.42			445	1.57	40,300	1.97				
1915	12,000	4.51	334	0.66					29,800	1.44			471	1.66	51,300	2.50				
1916	20,000	7.52	309	0.61					25,300	1.22			742	2.62	48,200	2.35				
1917	14,500	5.45	269	0.53					30,600	1.48			594	2.09	49,500	2.41				
1918	8,000	3.01	194	0.38					26,300	1.27			794	2.80	42,100	2.05				
1919	6,680	2.51	174	0.34					23,400	1.13			759	2.68	44,900	2.19				
1920	5,860	2.20	170	0.33					21,800	1.05			465	1.64	50,100	2.44				
1921	4,430	1.67	224	0.44					26,200	1.27			169	0.60	58,900	2.87				

Year	aluminum		magnesium (as MgO)		beryllium		Titanium dioxide (as TiO2)		vanadium		Lithium		Manganese		Cobalt		Gallium		Germanium	
	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index
1922	4,000	1.50	383	0.75					29,900	1.44			318	1.12	64,100	3.13				
1923	5,330	2.00	274	0.54					31,200	1.51			403	1.42	56,900	2.78				
1924	5,670	2.13	356	0.70					29,100	1.41			341	1.20	55,300	2.70				
1925	5,510	2.07	385	0.76					26,400	1.28			375	1.32	50,600	2.47				
1926	5,460	2.05	404	0.80					37,200	1.80			359	1.27	48,400	2.36				
1927	5,230	1.97	275	0.54					34,100	1.65			327	1.15	48,100	2.35				
1928	5,100	1.92	274	0.54					36,400	1.76			353	1.25	48,800	2.38				
1929	5,100	1.92	227	0.45					38,100	1.84			366	1.29	46,900	2.29				
1930	5,150	1.94	217	0.43					39,700	1.92			322	1.13	48,700	2.38				
1931	5,500	2.07	251	0.49					48,100	2.32			280	0.99	38,800	1.89				
1932	6,130	2.30	296	0.58					58,600	2.83			420	1.48	35,900	1.75				
1933	6,470	2.43	273	0.54					61,700	2.98			485	1.71	32,200	1.57				
1934	6,290	2.36	549	1.08					58,200	2.81			353	1.24	28,600	1.40				
1935	5,240	1.97	363	0.71	2960,000	5.32			56,800	2.74			368	1.30	30,000	1.46				
1936	5,320	2.00	256	0.50	2920,000	5.25			55,700	2.69	32,900		320	1.13	32,700	1.60				
1937	4,980	1.87	256	0.50	2500,000	4.50			53,700	2.59			311	1.10	35,500	1.73				
1938	5,100	1.92	265	0.52	2550,000	4.59			54,600	2.64			410	1.44	35,000	1.71				
1939	5,180	1.95	270	0.53	2590,000	4.66	2090	1.48	55,200	2.67			415	1.46	36,300	1.77				
1940	4,790	1.80	271	0.53	1160,000	2.09	2240	1.59	54,600	2.64			367	1.29	30,500	1.49				
1941	4,030	1.52	322	0.63	1100,000	1.98	2,510	1.78	48,000	2.32			380	1.34	28,700	1.40				
1942	3,310	1.24	671	1.32	1040,000	1.87	2,120	1.50	43,300	2.09			346	1.22	22,100	1.08				
1943	3,120	1.17	784	1.54	935,000	1.68	1,950	1.38	46,400	2.24			336	1.19	27,500	1.34	28,300,000	7.93		

Year	aluminum		magnesium (as MgO)		beryllium		Titanium dioxide (as TiO2)		vanadium		Lithium		Manganese		Cobalt		Gallium		Germanium	
	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index
1944	3,060	1.15	757	1.49	919,000	1.65	1,730	1.23	43,700	2.11			405	1.43	38,900	1.90	27,800,000	7.79		
1945	3,010	1.13	492	0.97	898,000	1.62	1,800	1.28	42,900	2.07			446	1.57	33,100	1.61	27,300,000	7.65	3,990,000	3.38
1946	2,760	1.04	435	0.86	829,000	1.49	1,750	1.24	37,800	1.83			410	1.45	28,400	1.39	25,000,000	7.00	3,310,000	2.81
1947	2,420	0.91	414	0.81	1530,000	2.75	1,970	1.40	33,100	1.60			375	1.32	21,400	1.04	21,900,000	6.13	2,900,000	2.46
1948	2,340	0.88	466	0.92	1420,000	2.55	1,980	1.40	31,900	1.54			362	1.27	20,600	1.00	16,900,000	4.73	3,430,000	2.91
1949	2,570	0.97	505	0.99	1430,000	2.57	2,070	1.47	31,000	1.50			398	1.40	24,300	1.19	17,100,000	4.79	4,970,000	4.21
1950	2,640	0.99	507	1.00	1420,000	2.55	2,010	1.43	27,400	1.32			478	1.69	24,800	1.21	20,300,000	5.69	2,690,000	2.28
1951	2,640	0.99	427	0.84	1310,000	2.36	2,340	1.66	28,800	1.39			461	1.62	27,700	1.35	18,800,000	5.27	2,490,000	2.11
1952	2,630	0.99	425	0.84	1290,000	2.32	2,030	1.44	30,200	1.46	14,600	3.02	519	1.83	30,700	1.50	18,400,000	5.15	2,970,000	2.52
1953	2,810	1.06	426	0.84	962,000	1.73	1,980	1.40	29,900	1.44	11,400	2.36	589	2.08	30,800	1.50	18,300,000	5.13	4,390,000	3.72
1954	2,920	1.10	545	1.07	955,000	1.72	2,440	1.73	30,000	1.45	13,300	2.75	539	1.90	33,200	1.62	18,200,000	5.10	3,940,000	3.34
1955	3,180	1.20	481	0.95	959,000	1.72	2,260	1.60	30,000	1.45	13,000	2.69	499	1.76	33,200	1.62	18,300,000	5.13	3,960,000	3.36
1956	3,170	1.19	484	0.95	945,000	1.70	2560	1.82	29,500	1.43	12,800	2.65	574	2.02	33,400	1.63	18,000,000	5.04	3,210,000	2.72
1957	3,240	1.22	587	1.16	914,000	1.64	2380	1.69	30,400	1.47	9,940	2.06	703	2.48	25,500	1.24	17,400,000	4.87	2,580,000	2.19
1958	3,090	1.16	451	0.89	889,000	1.60	1910	1.35	27,800	1.34	9,100	1.88	612	2.16	24,600	1.20	16,900,000	4.73	2,510,000	2.13
1959	3,040	1.14	424	0.83	883,000	1.59	1,800	1.28	30,300	1.46	8,990	1.86	571	2.01	22,000	1.07	16,800,000	4.71	1,960,000	1.66
1960	3,150	1.18	424	0.83	850,000	1.53	1,800	1.28	29,800	1.44	8,960	1.86	523	1.84	18,700	0.91	14,300,000	4.01	1,650,000	1.40
1961	3,050	1.15	408	0.80	649,000	1.17	1,780	1.26	29,700	1.43	8,040	1.66	563	1.98	17,900	0.87	12,300,000	3.45	1,630,000	1.38
1962	2,830	1.06	459	0.90	643,000	1.16	1,770	1.26	27,200	1.31	6,400	1.33	474	1.67	17,300	0.84	9,460,000	2.65	1,620,000	1.37
1963	2,650	1.00	431	0.85	634,000	1.14	1,770	1.26	26,800	1.29	6,220	1.29	400	1.41	16,900	0.82	6,380,000	1.79	1,440,000	1.22
1964	2,750	1.03	482	0.95	626,000	1.13	1,640	1.16	23,800	1.15	6,160	1.28	415	1.46	16,700	0.81	6,320,000	1.77	1,420,000	1.20
1965	2,780	1.05	483	0.95	616,000	1.11	1,540	1.09	23,500	1.14	5,110	1.06	398	1.40	18,000	0.88	6,220,000	1.74	1,400,000	1.19
1966	2,710	1.02	449	0.88	599,000	1.08	1,570	1.11	24,700	1.19	5,330	1.10	405	1.43	17,200	0.84	6,030,000	1.69	879,000	0.74
1967	2,690	1.01	484	0.95	581,000	1.04	1,490	1.06	24,000	1.16	4,730	0.98	387	1.36	21,400	1.04	5,850,000	1.64	854,000	0.72

Year	aluminum		magnesium (as MgO)		beryllium		Titanium dioxide (as TiO2)		vanadium		Lithium		Manganese		Cobalt		Gallium		Germanium	
	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index
1968	2,650	1.00	484	0.95	558,000	1.00	1,410	1.00	21,300	1.03	4,660	0.96	334	1.18	21,100	1.03	5,630,000	1.58	820,000	0.69
1969	2,670	1.00	466	0.92	587,000	1.06	1,500	1.06	26,400	1.28	4,490	0.93	287	1.01	18,100	0.88	3,770,000	1.06	823,000	0.70
1970	2,660	1.00	508	1.00	556,000	1.00	1,410	1.00	20,700	1.00	4,830	1.00	284	1.00	20,500	1.00	3,570,000	1.00	1,180,000	1.00
1971	2,570	0.97	523	1.03	532,000	0.96	1,550	1.10	45,100	2.18	4,510	0.93	294	1.03	19,400	0.95	3,420,000	0.96	1,180,000	1.00
1972	2,150	0.81	417	0.82	516,000	0.93	2,030	1.44	28,400	1.37	4,520	0.94	339	1.19	20,400	1.00	2,930,000	0.82	1,140,000	0.97
1973	2,130	0.80	422	0.83	397,000	0.71	2,730	1.94	26,700	1.29	4,480	0.93	357	1.26	23,800	1.16	2,750,000	0.77	1,070,000	0.91
1974	3,140	1.18	426	0.84	436,000	0.78	2,950	2.09	27,100	1.31	5,750	1.19	528	1.86	24,900	1.21	2,560,000	0.72	969,000	0.82
1975	2,320	0.87	509	1.00	397,000	0.71	2,560	1.82	25,500	1.23	5,210	1.08	640	2.26	28,100	1.37	2,350,000	0.66	888,000	0.75
1976	2,600	0.98	507	1.00	376,000	0.68	2,490	1.77	38,100	1.84	5,240	1.08	705	2.49	27,000	1.32	2,220,000	0.62	839,000	0.71
1977	2820	1.06	492	0.97	569,000	1.02	2,290	1.62	36,800	1.78	5,220	1.08	722	2.55	32,100	1.57	1,480,000	0.41	845,000	0.72
1978	2,800	1.05	463	0.91	568,000	1.02	2,400	1.70	34,300	1.66	5,270	1.09	719	2.54	54,900	2.68	1,380,000	0.39	797,000	0.68
1979	3,500	1.32	422	0.83	510,000	0.92	2,350	1.67	31,400	1.52	5,080	1.05	715	2.52	120,000	5.85	1,150,000	0.32	894,000	0.76
1980	3,320	1.25	489	0.96	523,000	0.94	2,370	1.68	23,900	1.15	5,260	1.09	,700	2.47	102,000	4.98	1,250,000	0.35	1,290,000	1.09
1981	2,370	0.89	484	0.95	585,000	1.05	2,410	1.71	22,200	1.07	5,570	1.15	647	2.28	66,100	3.22	1,130,000	0.32	1,630,000	1.38
1982	1,740	0.65	481	0.95	618,000	1.11	2,440	1.73	18,200	0.88	5,250	1.09	750	2.64	42,600	2.08	794,000	0.22	1,790,000	1.52
1983	2,470	0.93	452	0.89	642,000	1.15	2,110	1.50	22,600	1.09	5,340	1.11	594	2.10	24,300	1.19	769,000	0.22	1,730,000	1.47
1984	2,120	0.80	414	0.81	616,000	1.11	2,110	1.50	21,700	1.05	5,340	1.11	633	2.23	29,800	1.45	698,000	0.20	1,660,000	1.41
1985	1,640	0.62	554	1.09	655,000	1.18	2,240	1.59	20,900	1.01	5,020	1.04	597	2.10	36,100	1.76	720,000	0.20	1,610,000	1.36
1986	1,830	0.69	544	1.07	669,000	1.20	2,310	1.64	20,500	0.99	4,920	1.02	557	1.96	24,000	1.17	706,000	0.20	1,580,000	1.34
1987	2,280	0.86	451	0.89	724,000	1.30	2,340	1.66	19,800	0.96	4,910	1.02	565	1.99	21,100	1.03	682,000	0.19	1,520,000	1.29
1988	3,350	1.26	416	0.82	741,000	1.33	2,450	1.74	18,500	0.89	4,950	1.02	671	2.36	22,300	1.09	654,000	0.18	1,460,000	1.24
1989	2,550	0.96	408	0.80	756,000	1.36	2,740	1.94	31,900	1.54	5,010	1.04	798	2.81	22,700	1.11	624,000	0.17	1,390,000	1.18

Year	aluminum Unit value 1998$	aluminum Price index	magnesium (as MgO) Unit value 1998$	magnesium (as MgO) Price index	beryllium Unit value 1998$	beryllium Price index	Titanium dioxide (as TiO2) Unit value 1998$	Titanium dioxide (as TiO2) Price index	vanadium Unit value 1998$	vanadium Price index	Lithium Unit value 1998$	Lithium Price index	Manganese Unit value 1998$	Manganese Price index	Cobalt Unit value 1998$	Cobalt Price index	Gallium Unit value 1998$	Gallium Price index	Germanium Unit value 1998$	Germanium Price index
1990	2,030	0.76	373	0.73	740,000	1.33	2,690	1.91	20,700	1.00	5,030	1.04	858	3.02	22,700	1.11	592,000	0.17	1,320,000	1.12
1991	1,570	0.59	411	0.81	739,000	1.33	2,540	1.80	13,400	0.65	5,040	1.04	966	3.40	30,100	1.47	568,000	0.16	1,270,000	1.08
1992	1,480	0.56	372	0.73	717,000	1.29	2,330	1.65	10,400	0.50	5,020	1.04	760	2.68	55,100	2.69	552,000	0.15	1,230,000	1.04
1993	1,330	0.50	373	0.73	734,000	1.32	2,170	1.54	6,440	0.31	4,750	0.98	683	2.41	35,300	1.72	372,000	0.10	1,200,000	1.02
1994	1,730	0.65	374	0.74	715,000	1.29	2,040	1.45	12,800	0.62	4,850	1.00	662	2.33	46,400	2.26	357,000	0.10	1,170,000	0.99
1995	2,020	0.76	435	0.86	908,000	1.63	2,040	1.45	11,800	0.57	4,640	0.96	640	2.26	62,400	3.04	417,000	0.12	1,470,000	1.25
1996	1,630	0.61	428	0.84	882,000	1.59	1,970	1.40	13,100	0.63	4,510	0.93	676	2.38	58,600	2.86	405,000	0.11	2,080,000	1.76
1997	1,730	0.65	439	0.86	862,000	1.55	1,790	1.27	15,500	0.75	4,550	0.94	645	2.27	47,000	2.29	559,000	0.16	1,500,000	1.27
1998	1,440	0.54	391	0.77	849,000	1.53	1,840	1.30	21,500	1.04	4,480	0.93	591	2.08	44,200	2.16	595,000	0.17	1,700,000	1.44
1999	1,420	0.53	372	0.73	830,000	1.49	1,850	1.31	7,660	0.37	4,360	0.90	523	1.84	33,000	1.61	626,000	0.18	1,370,000	1.16
2,000	1550	0.58	384	0.76	878,000	1.58	1,780	1.26	6,780	0.33	4,230	0.88	551	1.94	28,100	1.37	606,000	0.17	1,180,000	1.00
2001	1,400	0.53	391	0.77	152,000	0.27	1,740	1.23	4,960	0.24	1,370	0.28	487	1.72	21,500	1.05	589,000	0.16	819,000	0.69
2002	1,300	0.49	398	0.78	246,000	0.44	1,630	1.16	4,780	0.23	1,440	0.30	426	1.50	15,500	0.76	480,000	0.13	562,000	0.48
2003	1,330	0.50	453	0.89	221,000	0.40	1,620	1.15	7,710	0.37	1,370	0.28	530	1.87	18,200	0.89	364,000	0.10	337,000	0.29
2004	1,600	0.60	513	1.01	237,000	0.43	1,530	1.09	20,300	0.98	1,480	0.31	944	3.33	37,400	1.82	474,000	0.13	518,000	0.44
2005	1,670	0.63	496	0.98	182,000	0.33	1,820	1.29	53,500	2.58	1,220	0.25	594	2.09	28,100	1.37	449,000	0.13	551,000	0.47
2006	2,160	0.81	487	0.96	228,000	0.41	1,740	1.23	25,000	1.21	1,880	0.39	646	2.28	24,800	1.21	358,000	0.10	768,000	0.65
2007	2,120	0.80	417	0.82	249,000	0.45	1,470	1.04	22,900	1.11	2,770	0.57	935	3.30	42,900	2.09	417,000	0.12	975,000	0.83
2008	2,010	0.76	391	0.77	265,000	0.48	1,670	1.18	38,500	1.86	3,360	0.70	1,800	6.34	51,800	2.53	438,000	0.12	1,130,000	0.96
2009	1,330	0.50	442	0.87	259,000	0.47	1,680	1.19	16,200	0.78	3,440	0.71	1,040	3.67	26,000	1.27	341,000	0.10	714,000	0.61
2010	1,720	0.65	449	0.88	375,000	0.67	1,740	1.23	19,000	0.92	3,250	0.67	1,120	3.95	29,700	1.45	449,000	0.13	897,000	0.76
2011	1,860	0.70	456	0.90	325,000	0.58	2,410	1.71	19,300	0.93	2,800	0.58	1,060	3.74	26,200	1.28	499,000	0.14	1,050,000	0.89

Year	aluminum		magnesium (as MgO)		beryllium		Titanium dioxide (as TiO2)		vanadium		Lithium		Manganese		Cobalt		Gallium		Germanium	
	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index
2012	1,580	0.59	356	0.70	320,000	0.58	2,580	1.83	18,100	0.87	3,000	0.62	997	3.51	21,600	1.05	376,000	0.11	1,160,000	0.98
2013	1,450	0.55	357	0.70	321,000	0.58	2,160	1.53	16,600	0.80	3,070	0.64	1,140	4.02	19,500	0.95	351,000	0.10	1,330,000	1.13

F. **Price trends of geologically non-scarce commodities in the United States of America (from USGS, Historical statistics for Mineral and Material Commodities in the United States, 2014) per metric ton. Price index: 1970 =1 (Se, Sr, Zr, Nb, In, Ba, REE, Ta, PGM, Hg, Tl)**

Year	Selenium Unit value 1998$	Selenium Price index	Strontium Unit value 1998$	Strontium Price index	Zirconium (tons gross weight) Unit value 1998$	Zirconium Price index	Niobium Unit value 1998$	Niobium Price index	Indium Unit value 1998$	Indium Price index	Barium (tons gross weight) Unit value 1998$	Barium Price index	REE total (tons rare earth oxides) Unit value 1998$	REE Price index	Tantalum Unit value 1998$	Tantalum Price index	PGM Unit value 1998$	PGM Price index	Mercury Unit value 1998$	Mercury Price index	Thallium Unit value 1998$	Thallium Price index
1,900											65	1.21					390,0000	0.39	29,000	0.58		
1901											78	1.45					12,000,000	1.20	27,000	0.54		
1902											100	1.86					14,000,000	1.40	26,000	0.52		
1903											71	1.32					13,000,000	1.30	22,000	0.44		
1904											63	1.17					12,000,000	1.20	22,000	0.44		
1905											75	1.39					14,000,000	1.40	21,000	0.42		
1906											70	1.30					16,000,000	1.60	22,000	0.44		
1907											74	1.38					2,0000,000	2.00	21,000	0.42		
1908											72	1.34					14,000,000	1.40	24,000	0.48		
1909	140,000	1.68									69	1.28					15,000,000	1.50	25,000	0.50		
1910	130,000	1.56									57	1.06					17,000,000	1.70	24,000	0.48		
1911	120,000	1.44									57	1.06					22,000,000	2.20	24,000	0.48		
1912	93,000	1.12									71	1.32					22,000,000	2.20	21,000	0.42		
1913	60,900	0.73									129	2.40					22600,000	2.26	19,100	0.38		
1914	54,000	0.65									171	3.18					20400,000	2.04	23,100	0.46		
1915	50,400	0.61									117	2.17					20800,000	2.08	41,100	0.83		
1916	44,600	0.54									106	1.97					28,000,000	2.80	55,100	1.11		
1917	60,400	0.73	437	1.87							82.4	1.53					33,900,000	3.39	39,800	0.80		
1918	71,400	0.86	24.5	0.10	470	1.79					81	1.51					31,600,000	3.16	39,300	0.79		
1919	49,500	0.59	373	1.59	565	2.16					91.7	1.70					30,100,000	3.01	25,600	0.52		
1920	35,900	0.43	282	1.21	480	1.83					92.3	1.72					27,600,000	2.76	19,400	0.39		
1921	42,800	0.51	123	0.53	530	2.02					140	2.60					20,200,000	2.02	12,100	0.24		

Year	Selenium Unit value 1998$	Selenium Price index	Strontium Unit value 1998$	Strontium Price index	Zirconium (tons gross weight) Unit value 1998$	Zirconium Price index	Niobium Unit value 1998$	Niobium Price index	Indium Unit value 1998$	Indium Price index	Barium (tons gross weight) Unit value 1998$	Barium Price index	REE total (tons rare earth oxides) Unit value 1998$	REE Price index	Tantalum Unit value 1998$	Tantalum Price index	PGM Unit value 1998$	PGM Price index	Mercury Unit value 1998$	Mercury Price index	Thallium Unit value 1998$	Thallium Price index
1922	41,900	0.50	109	0.47	550	2.10					124	2.30	23,800	13.76			25,500,000	2.55	16,800	0.34		
1923	39,100	0.47	1,210	5.17	530	2.02					112	2.08	3,280	1.90			30,100,000	3.01	18,600	0.37		
1924	39,100	0.47	1,400	5.98	520	1.98					105	1.95	2,090	1.21			30,300,000	3.03	19,500	0.39		
1925	34,900	0.42	1,610	6.88	500	1.91					89.6	1.67	10,000	5.78			31,600,000	3.16	22,600	0.45		
1926	39,600	0.48	1,590	6.79	490	1.87					87.5	1.63	2,850	1.65			29,400,000	2.94	24,800	0.50		
1927	40,300	0.48	1,620	6.92	490	1.87					76.6	1.42	2,210	1.28			25,000,000	2.50	32,000	0.64		
1928	44,800	0.54	1,650	7.05	490	1.87					79.6	1.48	4,300	2.49			21,100,000	2.11	34,100	0.69		
1929	34,700	0.42	1,650	7.05	480	1.83					72.9	1.36	3,920	2.27			18,000,000	1.80	33,700	0.68		
1930	40,900	0.49	2,480	10.60	480	1.83					76.2	1.42	5,890	3.40			13,200,000	1.32	32,700	0.66		
1931	44,900	0.54	2,700	11.54	510	1.95					68.6	1.28	3,930	2.27			9,390,000	0.94	27,100	0.55		
1932	49,900	0.60	2,740	11.71	557	2.13					70.4	1.31	70,600	40.81			9,680,000	0.97	20,100	0.40		
1933	52,500	0.63	709	3.03	586	2.24					80.7	1.50	145,000	83.82			9,800,000	0.98	21,600	0.43		
1934	51,000	0.61	591	2.53	737	2.81					71	1.32	142,000	82.08			9,330,000	0.93	26,100	0.53		
1935	52,500	0.63	605	2.59	557	2.13					74	1.38	139,000	80.35			9,860,000	0.99	24,800	0.50		
1936	48,500	0.58	774	3.31	549	2.10			1,130,0000	33.43	77	1.43	137,000	79.19			10700,000	1.07	27,300	0.55		
1937	46,900	0.56	597	2.55	574	2.19			1,090,0000	32.25	77.7	1.44	41	0.02			13,000,000	1.30	29,700	0.60		
1938	45,900	0.55	2,030	8.68	701	2.68			1,120,0000	33.14	89	1.65	38	0.02			10,100,000	1.01	25,300	0.51		
1939	46,600	0.56	557	2.38	710	2.71			1,130,0000	33.43	70.3	1.31	29	0.02			12,200,000	1.22	35,400	0.71		
1940	44,900	0.54	305	1.30	899	3.43			860,0000	25.44	48.2	0.90	98,700	57.05			11,000,000	1.10	59,700	1.20		
1941	42,800	0.51	430	1.84	794	3.03			4460,000	13.20	26.5	0.49	124,000	71.68			8,220,000	0.82	59,400	1.20		
1942	38,600	0.46	351	1.50	716	2.73			7230,000	21.39	25.5	0.47	99,300	57.40			11,500,000	1.15	57,000	1.15	220,000	3.17
1943	36,400	0.44	350	1.50	728	2.78			3,790,000	11.21	29.5	0.55	68,300	39.48			9,160,000	0.92	53,400	1.07	208,000	3.00

Year	Selenium Unit value 1998$	Selenium Price index	Strontium Unit value 1998$	Strontium Price index	Zirconium (tons gross weight) Unit value 1998$	Zirconium (tons gross weight) Price index	Niobium Unit value 1998$	Niobium Price index	Indium Unit value 1998$	Indium Price index	Barium (tons gross weight) Unit value 1998$	Barium (tons gross weight) Price index	REE total (tons rare earth oxides) Unit value 1998$	REE total Price index	Tantalum Unit value 1998$	Tantalum Price index	PGM Unit value 1998$	PGM Price index	Mercury Unit value 1998$	Mercury Price index	Thallium Unit value 1998$	Thallium Price index
1944	35,700	0.43	347	1.48	715	2.73			2,60,0000	7.69	54.5	1.01	80,400	46.47			8,930,000	0.89	31,800	0.64	225,000	3.25
1945	35,000	0.42	313	1.34	676	2.58			1,430,000	4.23	63	1.17	87,500	50.58			8,830,000	0.88	35,600	0.72	251,000	3.62
1946	32,300	0.39	309	1.32	473	1.81			603,000	1.78	55.8	1.04	92,500	53.47			9,500,000	0.95	23,700	0.48	258,000	3.72
1947	30,300	0.36	316	1.35	346	1.32			528,000	1.56	43.6	0.81	105,000	60.69			8,980,000	0.90	17,700	0.36	290,000	4.18
1948	29,800	0.36	436	1.86	343	1.31			489,000	1.45	37	0.69	99,300	57.40			12,000,000	1.20	15,000	0.30	224,000	3.23
1949	30,200	0.36	324	1.38	351	1.34			495,000	1.46	40.3	0.75	61,000	35.26			12,000,000	1.20	15,800	0.32	212,000	3.06
1950	41,000	0.49	280	1.20	348	1.33			489,000	1.45	55.4	1.03	23,900	13.82			11,800,000	1.18	15,900	0.32	186,000	2.68
1951	45,000	0.54	342	1.46	362	1.38			452,000	1.34	41.1	0.76	10,400	6.01			12,100,000	1.21	38,300	0.77	173,000	2.50
1952	44,100	0.53	303	1.29	293	1.12			444,000	1.31	52.9	0.98	24,000	13.87			11,100,000	1.11	35,400	0.71	169,000	2.44
1953	48,800	0.59	275	1.18	255	0.97			441,000	1.30	60.2	1.12	43,200	24.97			12,200,000	1.22	34,100	0.69	168,000	2.42
1954	61,800	0.74	247	1.06	305	1.16			438,000	1.30	58	1.08	52,300	30.23			11,300,000	1.13	46,500	0.94	167,000	2.41
1955	100,000	1.20	320	1.37	331	1.26			441,000	1.30	58.6	1.09	41,000	23.70			9,330,000	0.93	51,400	1.03	168,000	2.42
1956	149,000	1.79	307	1.31	325	1.24			433,000	1.28	59.4	1.10	30,400	17.57			10,800,000	1.08	45,100	0.91	165,000	2.38
1957	125,000	1.50	292	1.25	352	1.34			420,000	1.24	60.6	1.13	11,200	6.47			9,830,000	0.98	41,400	0.83	160,000	2.31
1958	90,200	1.08	301	1.29	255	0.97			408,000	1.21	61.8	1.15	28,800	16.65			6,780,000	0.68	37,500	0.75	93,200	1.34
1959	86,300	1.04	390	1.67	291	1.11			404,000	1.20	60.7	1.13	28,200	16.30			6,650,000	0.67	36,900	0.74	92,200	1.33
1960	82,100	0.99	335	1.43	286	1.09			397,000	1.17	61	1.13	19,500	11.27			8,850,000	0.89	33,600	0.68	90,700	1.31
1961	76,900	0.92	337	1.44	285	1.09			395,000	1.17	64	1.19	446	0.26			7,320,000	0.73	31,200	0.63	90,200	1.30
1962	71,200	0.86	342	1.46	282	1.08			391,000	1.16	59.4	1.10	1,840	1.06			7,890,000	0.79	29,800	0.60	89,200	1.29
1963	60,200	0.72	307	1.31	277	1.06			385,000	1.14	58.8	1.09	1,700	0.98			8,560,000	0.86	29,200	0.59	87,800	1.27
1964	52,200	0.63	310	1.32	274	1.05	14,100	0.95	406,000	1.20	59.4	1.10	2,030	1.17	92,100	1.14	9,680,000	0.97	48,100	0.97	86,800	1.25
1965	51,300	0.62	295	1.26	270	1.03	13,900	0.94	458,000	1.36	57.6	1.07	2,510	1.45	108,000	1.34	9,840,000	0.98	85,300	1.72	85,500	1.23

Year	Selenium Unit value 1998$	Price index	Strontium Unit value 1998$	Price index	Zirconium (tons gross weight) Unit value 1998$	Price index	Niobium Unit value 1998$	Price index	Indium Unit value 1998$	Price index	Barium (tons gross weight) Unit value 1998$	Price index	REE total (tons rare earth oxides) Unit value 1998$	Price index	Tantalum Unit value 1998$	Price index	PGM Unit value 1998$	Price index	Mercury Unit value 1998$	Price index	Thallium Unit value 1998$	Price index
1966	49,900	0.60	293	1.25	262	1.00	17,600	1.19	444,000	1.31	56.2	1.04	1,430	0.83	176,000	2.18	9,950,000	1.00	64,400	1.30	82,900	1.20
1967	48,400	0.58	270	1.15	254	0.97	14,900	1.01	431,000	1.28	58.6	1.09	2,740	1.58	135,000	1.67	10,900,000	1.09	69,200	1.39	80,500	1.16
1968	46,500	0.56	279	1.19	292	1.11	13,600	0.92	377,000	1.12	63.5	1.18	1,880	1.09	82,200	1.02	10,700,000	1.07	72,900	1.47	77,500	1.12
1969	68,400	0.82	239	1.02	277	1.06	14,700	0.99	357,000	1.06	62.6	1.16	1,870	1.08	85,300	1.06	10,900,000	1.09	65,100	1.31	73,300	1.06
1970	83,200	1.00	234	1.00	262	1.00	14,800	1.00	338,000	1.00	53.8	1.00	1,730	1.00	80,700	1.00	10,000,000	1.00	49,700	1.00	69,300	1.00
1971	79,700	0.96	258	1.10	242	0.92	13,200	0.89	324,000	0.96	60.1	1.12	4,190	2.42	70,400	0.87	9,300,000	0.93	34,200	0.69	66,400	0.96
1972	77,200	0.93	331	1.41	234	0.89	15,900	1.07	314,000	0.93	57.9	1.08	14,400	8.32	59,300	0.73	9,830,000	0.98	24,700	0.50	64,400	0.93
1973	74,900	0.90	635	2.71	243	0.93	16,400	1.11	209,000	0.62	52.8	0.98	7,890	4.56	78,900	0.98	12,700,000	1.27	30,500	0.61	60,600	0.87
1974	120,000	1.44	707	3.02	912	3.48	17,100	1.16	469,000	1.39	50.1	0.93	10,100	5.84	125,000	1.55	16,500,000	1.65	27,000	0.54	54,500	0.79
1975	120,000	1.44	624	2.67	524	2.00	16,300	1.10	551,000	1.63	51.3	0.95	6,210	3.59	131,000	1.62	14,600,000	1.46	13,900	0.28	50,000	0.72
1976	114,000	1.37	647	2.76	473	1.81	24,300	1.64	739,000	2.19	68	1.26	12,500	7.23	136,000	1.69	10,100,000	1.01	10,100	0.20	47,300	0.68
1977	101,000	1.21	438	1.87	444	1.69	23,400	1.58	845,000	2.50	68.1	1.27	6,990	4.04	178,000	2.21	9,410,000	0.94	10,600	0.21	44,400	0.64
1978	82,800	1.00	545	2.33	413	1.58	23,900	1.61	688,000	2.04	70.4	1.31	6,250	3.61	265,000	3.28	12,400,000	1.24	11,100	0.22	41,300	0.60
1979	67,600	0.81	584	2.50	370	1.41	48,100	3.25	972,000	2.88	80.5	1.50	10,300	5.95	559,000	6.93	17,400,000	1.74	18,300	0.37	37,000	0.53
1980	47,700	0.57	512	2.19	360	1.37	40,600	2.74	1,080,000	3.20	86.7	1.61	3,880	2.24	562,000	6.96	21,400,000	2.14	22,400	0.45	32,600	0.47
1981	17,300	0.21	565	2.41	326	1.24	34,600	2.34	434,000	1.28	86.1	1.60	3,350	1.94	181,000	2.24	16,200,000	1.62	21,500	0.43	158,000	2.28
1982	13,100	0.16	468	2.00	307	1.17	24,700	1.67	226,000	0.67	83.8	1.56	3,990	2.31	102,000	1.26	12,100,000	1.21	18,200	0.37	149,000	2.15
1983	14,000	0.17	390	1.67	298	1.14	23,900	1.61	169,000	0.50	83.5	1.55	4,620	2.67	130,000	1.61	12,300,000	1.23	15,300	0.31	144,000	2.08
1984	31,200	0.38	554	2.37	286	1.09	18,500	1.25	151,000	0.45	71.8	1.33	3,730	2.16	135,000	1.67	12,600,000	1.26	14,300	0.29	121,000	1.75
1985	24,800	0.30	738	3.15	292	1.11	17,900	1.21	128,000	0.38	64.1	1.19	3,320	1.92	92,700	1.15	12,500,000	1.25	13,700	0.28	134,000	1.93
1986	18,700	0.22	785	3.35	311	1.19	12,900	0.87	125,000	0.37	71.4	1.33	5,710	3.30	87,000	1.08	14,400,000	1.44	10,000	0.20	131,000	1.89

Year	Selenium		Strontium		Zirconium (tons gross weight)		Niobium		Indium		Barium (tons gross weight)		REE total (tons rare earth oxides)		Tantalum		PGM		Mercury		Thallium	
	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index
1987	20,700	0.25	717	3.06	320	1.22	11,000	0.74	337,000	1.00	65.4	1.22	5,700	3.29	10,0000	1.24	15,100,000	1.51	12,300	0.25	189,000	2.73
1988	29,900	0.36	681	2.91	368	1.40	10,600	0.72	440,000	1.30	61.4	1.14	3,070	1.77	186,000	2.30	14,900,000	1.49	13,400	0.27	242,000	3.49
1989	22,100	0.27	760	3.25	464	1.77	13,500	0.91	362,000	1.07	63.6	1.18	8,910	5.15	95,600	1.18	16,000,000	1.60	11,000	0.22	724,000	10.45
1990	16,000	0.19	646	2.76	506	1.93	12,800	0.86	287,000	0.85	58.2	1.08	11,200	6.47	111,000	1.38	19,000,000	1.90	9,020	0.18	728,000	10.51
1991	14,200	0.17	664	2.84	437	1.67	10,700	0.72	261,000	0.77	61.8	1.15	11,300	6.53	91,000	1.13	16,600,000	1.66	4,250	0.09	738,000	10.65
1992	13,100	0.16	602	2.57	339	1.29	10,400	0.70	261,000	0.77	60.1	1.12	11,700	6.76	90,700	1.12	13,000,000	1.30	6,790	0.14	871,000	12.57
1993	12,200	0.15	743	3.18	329	1.26	9,250	0.63	234,000	0.69	51.6	0.96	10,200	5.90	79,000	0.98	9,660,000	0.97	6,110	0.12	896,000	12.93
1994	11,900	0.14	609	2.60	337	1.29	9,020	0.61	157,000	0.46	42.7	0.79	8,780	5.08	77,800	0.96	9,160,000	0.92	6,200	0.12	1,040,000	15.01
1995	11,600	0.14	749	3.20	376	1.44	10,100	0.68	415,000	1.23	45.9	0.85	8,780	5.08	79,900	0.99	7,700,000	0.77	7,680	0.15	1,180,000	17.03
1996	9,160	0.11	743	3.18	480	1.83	9,830	0.66	396,000	1.17	44.4	0.83	7,430	4.29	77,600	0.96	8,720,000	0.87	7,890	0.16	1,250,000	18.04
1997	6,580	0.08	794	3.39	469	1.79	9,610	0.65	324,000	0.96	46.9	0.87	8,670	5.01	90,200	1.12	8,590,000	0.86	4,700	0.09	1,300,000	18.76
1998	5,490	0.07	836	3.57	353	1.35	9,460	0.64	306,000	0.91	57.1	1.06	8,900	5.14	91,400	1.13	10,200,000	1.02	4,060	0.08	1,280,000	18.47
1999	5,390	0.06	789	3.37	324	1.24	9,260	0.63	296,000	0.88	51.4	0.96	6260	3.62	89,400	1.11	10,300,000	1.03	3,970	0.08	1,270,000	18.33
2000	8,020	0.10	830	3.55	355	1.35	18,700	1.26	178,000	0.53	43.8	0.81	6110	3.53	559,000	6.93	17,000,000	1.70	4,260	0.09	1,230,000	17.75
2001	7,710	0.09	822	3.51	345	1.32			110,000	0.33	41.8	0.78	5330	3.08	91,600	1.14	18,200,000	1.82	4,140	0.08	1,190,000	17.17
2002	8,530	0.10	891	3.81	350	1.34			87,900	0.26	42.2	0.78	6,800	3.93	82,000	1.02	8,710,000	0.87	4,080	0.08	1,130,000	16.31
2003	11,070	0.13	784	3.35	361	1.38			151,000	0.45	40.4	0.75	5,450	3.15	71,100	0.88	11,500,000	1.15	4,370	0.09	1,150,000	16.59
2004	47,400	0.57	535	2.29	433	1.65			555,000	1.64	42.6	0.79	7,410	4.28	66,400	0.82	12,500,000	1.25	8,800	0.18	1,380,000	19.91
2005	94,300	1.13	662	2.83	476	1.82			790,000	2.34	45.9	0.85	5,500	3.18	75,800	0.94	11,800,000	1.18	13,400	0.27	1,590,000	22.94
2006	43,800	0.53	788	3.37	635	2.42			742,000	2.20	45.3	0.84	3,150	1.82	70,700	0.88	17,100,000	1.71	15,700	0.32	3,760,000	54.26
2007	57,300	0.69	983	4.20	600	2.29			625,000	0.00	56.5	1.05	4,160	2.40	78,700	0.98	17,700,000	1.77	12,100	0.24	3,580,000	51.66
2008	53,900	0.65	939	4.01	597	2.28			519,000	1.54	57.8	1.07	10,300	5.95	89,200	1.11	17,300,000	1.73	13,200	0.27	3,710,000	53.54

Year	Selenium		Strontium		Zirconium (tons gross weight)		Niobium		Indium		Barium (tons gross weight)		REE total (tons rare earth oxides)		Tantalum		PGM	Mercury			Thallium	
	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index	Unit value 1998$	Price index
2009	38,700	0.47	567	2.42	631	2.41			380,000	1.12	64.7	1.20	7,100	4.10	82,200	1.02	8,810,000	0.88	13,400	0.27	4,330,000	62.48
2010	62,300	0.75	964	4.12	643	2.45			422,000	1.25	64.4	1.20	14,500	8.38	109,000	1.35	13,800,000	1.38	23,300	0.47	4,430,000	63.92
2011	106,000	1.27	841	3.59	1,920	7.33			522,000	1.54	71.4	1.33	42,100	24.34	244,000	3.02	18,100,000	1.81	38,900	0.78	4,350,000	62.77
2012	85,200	1.02	738	3.15	1,880	7.18			461,000	1.36	95.7	1.78	36,300	20.98	207,000	2.57	13,800,000	1.38	38,100	0.77	4,830,000	69.70
2013	55,800	0.67	367	1.57	734	2.80			430,000	1.27	95.9	1.78	13,400	7.75	222,000	2.75	15,700,000	1.57	37,600	0.76	5,040,000	72.73

## G. Linear regression analysis of the price trends of individual mineral resources
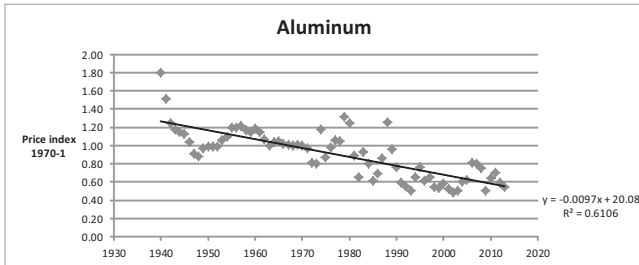
SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.7814069
R Square	0.6105967
Adjusted R Square	0.6051884
Standard error	0.1677511
Observations	74

ANOVA

	df	SS	MS	F	Significance F
Regression	1	3.177005179	3.177005	112.8983	2.136E-16
Residual	72	2.026110057	0.02814		
Total	73	5.203115236			

	Coefficient	Standard error	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	20.079859	1.8045551	11.12732	2.66E-17	16.4825444	23.6771741	16.48254441	23.6771741
X	-0.0097	0.000912952	-10.6254	2.14E-16	-0.01152038	-0.0078805	-0.011520382	-0.007880508
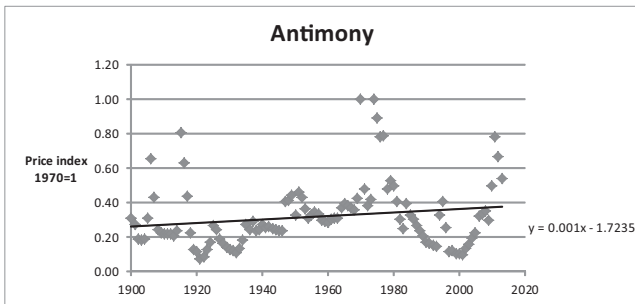
SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.184249
R Square	0.033948
Adjusted R Square	0.025322
Standard error	0.184897
Observations	114

ANOVA

	df	SS	MS	F	Significance F
Regression	1	0.13455	0.13455	3.935734	0.049716908
Residual	112	3.828923	0.034187		
Total	113	3.963473			

	Coefficient	andard err	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	-1.72346	1.029723	-1.67371	0.096978	-3.76372496	0.31680516	-3.763724963	0.316805164
X	0.001044	0.000526	1.983869	0.049717	1.31386E-06	0.00208665	1.31386E-06	0.002086646
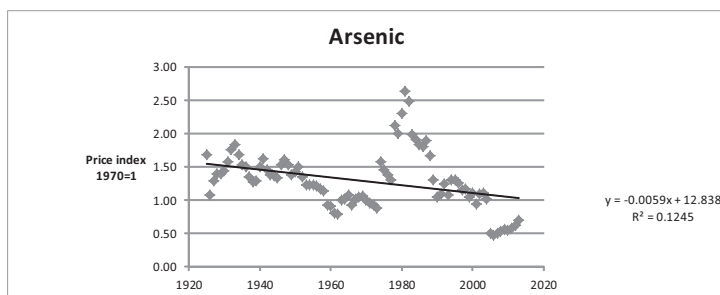
Arsenic

y = -0.0059x + 12.838
R² = 0.1245

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.3528679
R Square	0.1245157
Adjusted R Square	0.1144527
Standard error	0.4044185
Observations	89

ANOVA

	df	SS	MS	F	Significance F
Regression	1	2.023751196	2.023751	12.37357	0.00069464
Residual	87	14.22922485	0.163554		
Total	88	16.25297604			

	Coefficient	Standard error	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	12.837739	3.2858422	3.906986	0.000184	6.306771599	19.3687059	6.306771599	19.36870594
X	-0.00587	0.001668645	-3.51761	0.000695	-0.00918625	-0.002553	-0.009186255	-0.002553028
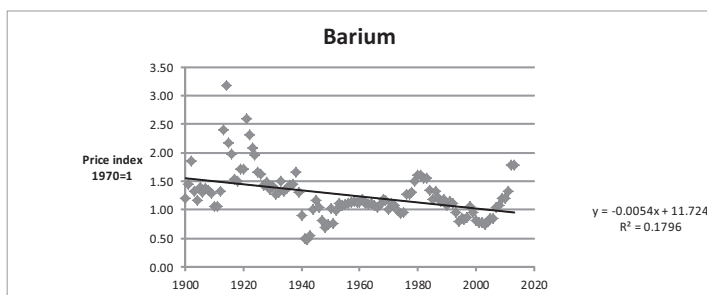
Barium

y = -0.0054x + 11.724
R² = 0.1796

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.42377253
R Square	0.17958316
Adjusted R Square	0.17225801
Standard error	0.37965398
Observations	114

ANOVA

	df	SS	MS	F	Significance F
Regression	1	3.533661768	3.533662	24.51597	2.62549E-06
Residual	112	16.14336017	0.144137		
Total	113	19.67702194			

	Coefficient	Standard error	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	11.7241711	2.114361719	5.545017	1.98E-07	7.534834401	15.9135078	7.534834401	15.91350783
X	-0.0053501	0.001080533	-4.95136	2.63E-06	-0.007491045	-0.0032092	-0.00749105	-0.00320917
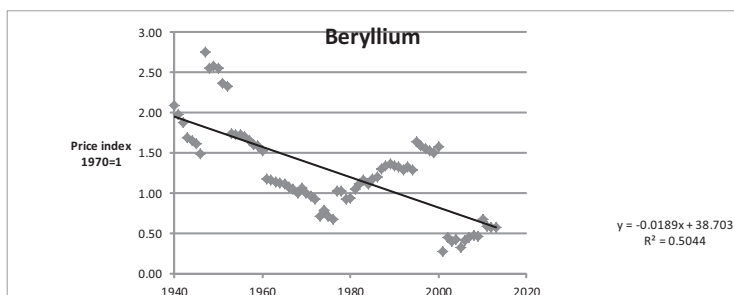
$$y = -0.0189x + 38.703$$
$$R^2 = 0.5044$$

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.7102406
R Square	0.5044417
Adjusted R Square	0.4975589
Standard error	0.4066188
Observations	74

ANOVA

	df	SS	MS	F	Significance F
Regression	1	12.11779469	12.11779	73.29066	1.37462E-12
Residual	72	11.90439799	0.165339		
Total	73	24.02219267			

	Coefficient	Standard error	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	38.702585	4.374136686	8.848051	4.01E-13	29.98290248	47.42226672	29.98290248	47.42226672
X	-0.018945	0.002212943	-8.561	1.37E-12	-0.023356416	-0.01453357	-0.02335642	-0.014533574
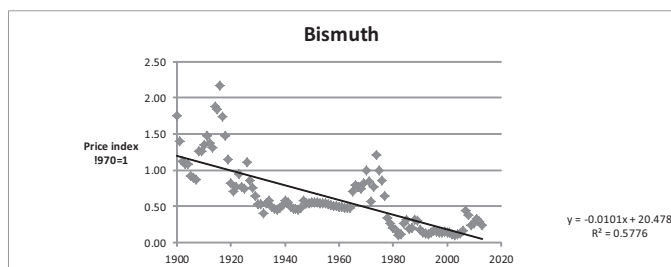
$$y = -0.0101x + 20.478$$
$$R^2 = 0.5776$$

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.75997673
R Square	0.57756463
Adjusted R Square	0.57379289
Standard error	0.28808939
Observations	114

ANOVA

	df	SS	MS	F	Significance F
Regression	1	12.70904357	12.70904	153.1293	1.08491E-22
Residual	112	9.295495506	0.082995		
Total	113	22.00453908			

	Coefficient	Standard error	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	20.4776624	1.604421938	12.76327	1.41E-23	17.29870601	23.6566188	17.298706	23.65661882
X	-0.0101463	0.000819931	-12.3745	1.08E-22	-0.01177086	-0.00852168	-0.01177086	-0.008521684
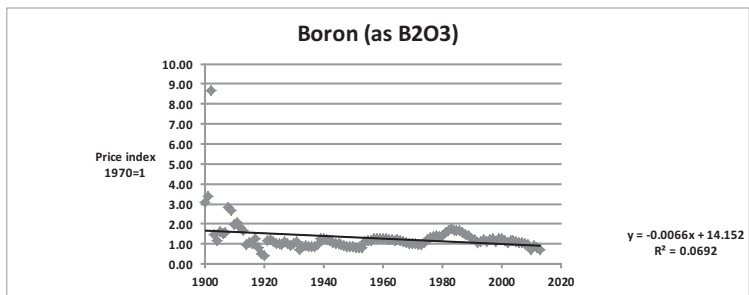
Boron (as B2O3)

$y = -0.0066x + 14.152$
$R^2 = 0.0692$

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.2630191
R Square	0.069179
Adjusted R Square	0.0608681
Standard error	0.8009369
Observations	114

ANOVA

	df	SS	MS	F	Significance F
Regression	1	5.339774263	5.339774	8.32389	0.004694448
Residual	112	71.84798269	0.6415		
Total	113	77.18775695			

	Coefficient	Standard error	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	14.151592	4.460562288	3.172603	0.00195	5.313559827	22.98962462	5.313559827	22.98962462
X	-0.006577	0.002279546	-2.88512	0.004694	-0.01109338	-0.00206012	-0.011093381	-0.002060125
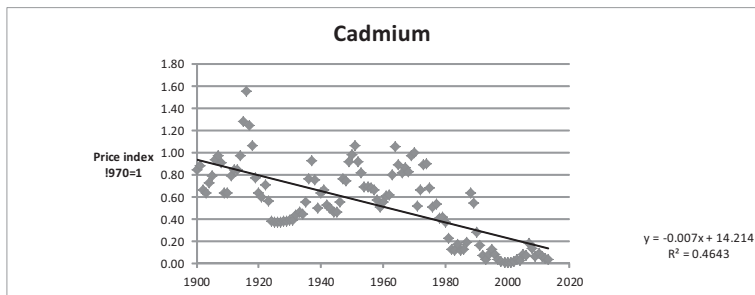
Cadmium

$y = -0.007x + 14.214$
$R^2 = 0.4643$

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.68138656
R Square	0.46428765
Adjusted R Square	0.4595045
Standard error	0.24932722
Observations	114

ANOVA

	df	SS	MS	F	Significance F
Regression	1	6.034105353	6.034105	97.06742	7.22519E-17
Residual	112	6.962375205	0.062164		
Total	113	12.99648056			

	Coefficient	Standard error	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	14.2138108	1.388548427	10.23645	9.31E-18	11.46258007	16.9650415	11.46258007	16.9650415
X	-0.00699128	0.00070961	-9.85228	7.23E-17	-0.008397278	-0.0055853	-0.008397278	-0.00558528
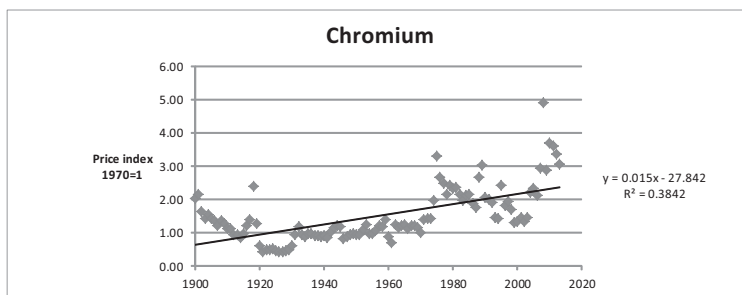
Chromium

$y = 0.015x - 27.842$
$R^2 = 0.3842$

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.6198229
R Square	0.3841804
Adjusted R Square	0.378682
Standard error	0.6303891
Observations	114

ANOVA

	df	SS	MS	F	Significance F
Regression	1	27.76623683	27.76624	69.87144	1.93902E-13
Residual	112	44.50772277	0.39739		
Total	113	72.27395961			

	Coefficient	Standard error	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	-27.84188	3.510750821	-7.93046	1.79E-12	-34.79798274	-20.8857773	-34.7979827	-20.88577729
X	0.0149971	0.00179415	8.358914	1.94E-13	0.011442266	0.01855202	0.011442266	0.018552022
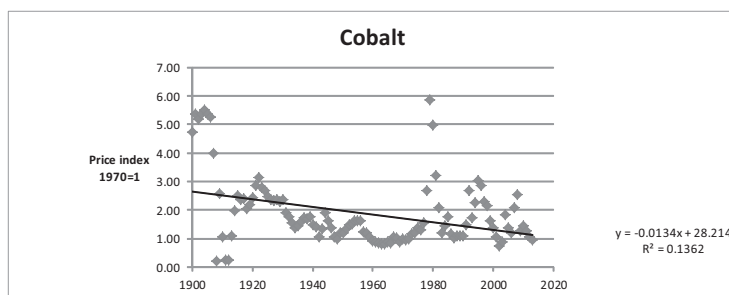
Cobalt

$y = -0.0134x + 28.214$
$R^2 = 0.1362$

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.3689963
R Square	0.1361582
Adjusted R Square	0.1284454
Standard error	1.1247233
Observations	114

ANOVA

	df	SS	MS	F	Significance F
Regression	1	22.33156609	22.33157	17.65338	5.34729E-05
Residual	112	141.6802884	1.265003		
Total	113	164.0118545			

	Coefficient	Standard error	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	28.213902	6.263787777	4.504288	1.64E-05	15.80300992	40.624795	15.80300992	40.62479503
X	-0.0134496	0.003201074	-4.20159	5.35E-05	-0.01979213	-0.00710709	-0.01979213	-0.00710709
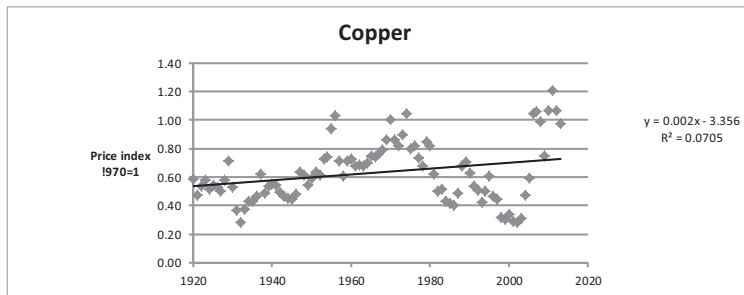
Copper

Price index !970=1

y = 0.002x - 3.356
R² = 0.0705

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.26552425
R Square	0.07050313
Adjusted R Square	0.0603999
Standard error	0.20188528
Observations	94

ANOVA

	df	SS	MS	F	Significance F
Regression	1	0.284418327	0.284418	6.978278	0.009695218
Residual	92	3.749705203	0.040758		
Total	93	4.03412353			

	Coefficient	Standard error	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	-3.3559938	1.50925755	-2.22361	0.028623	-6.353509523	-0.35847798	-6.35350952	-0.358477985
X	0.00202723	0.000767411	2.641643	0.009695	0.000503082	0.003551371	0.000503082	0.003551371
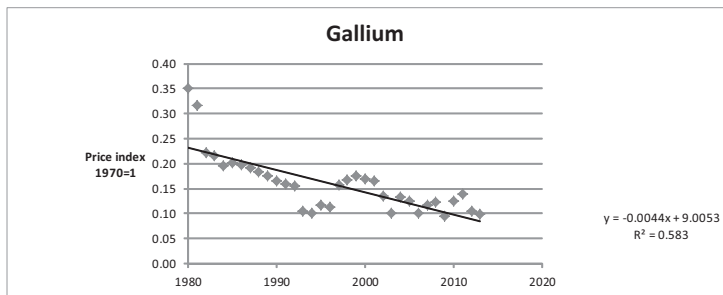
Gallium

Price index 1970=1

y = -0.0044x + 9.0053
R² = 0.583

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.76352784
R Square	0.58297476
Adjusted R Square	0.56994273
Standard error	0.03789924
Observations	34

ANOVA

	df	SS	MS	F	Significance F
Regression	1	0.064253723	0.064254	44.73397	1.50321E-07
Residual	32	0.045963266	0.001436		
Total	33	0.110216989			

	Coefficient	Standard error	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	9.00532919	1.322711655	6.808233	1.07E-07	6.311053718	11.6996047	6.311053718	11.69960466
X	-0.0044311	0.000662507	-6.68835	1.5E-07	-0.00578056	-0.00308159	-0.00578056	-0.003081594
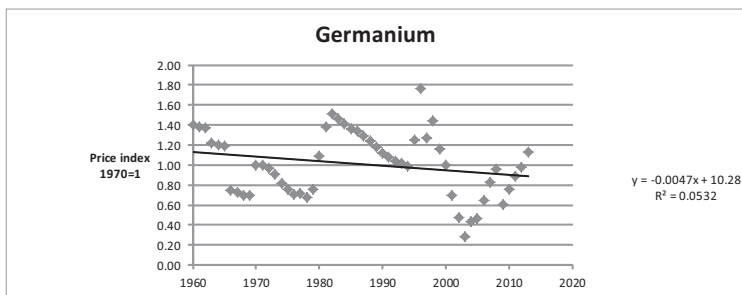
Germanium

$y = -0.0047x + 10.28$
$R^2 = 0.0532$

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.23056526
R Square	0.05316034
Adjusted R Square	0.03495189
Standard error	0.31282239
Observations	54

ANOVA

	df	SS	MS	F	Significance F
Regression	1	0.285700057	0.2857	2.919542	0.093475935
Residual	52	5.088608211	0.097858		
Total	53	5.374308269			

	Coefficient	Standard error	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	10.2799076	5.425930604	1.894589	0.063714	-0.608018664	21.16783396	-0.608018664	21.16783396
X	-0.0046669	0.002731318	-1.70867	0.093476	-0.010147703	0.000813879	-0.010147703	0.000813879
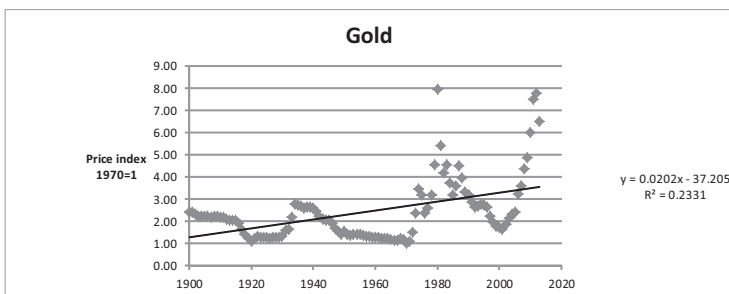
Gold

$y = 0.0202x - 37.205$
$R^2 = 0.2331$

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.48278576
R Square	0.23308209
Adjusted R Square	0.22623461
Standard error	1.21901156
Observations	114

ANOVA

	df	SS	MS	F	Significance F
Regression	1	50.58173107	50.58173	34.0391	5.33081E-08
Residual	112	166.4307881	1.485989		
Total	113	217.0125191			

	Coefficient	Standard error	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	-37.205229	6.788895969	-5.48031	2.65E-07	-50.65655657	-23.7539023	-50.6565566	-23.75390232
X	0.0202417	0.003469428	5.834304	5.33E-08	0.013367469	0.027115923	0.013367469	0.027115923
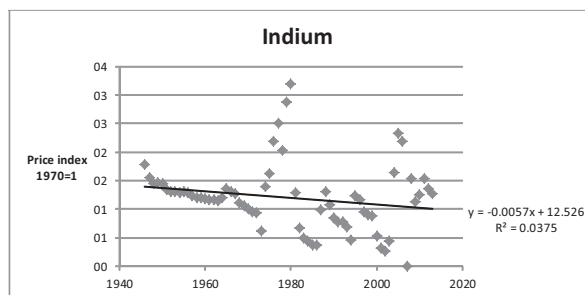
Indium

y = -0.0057x + 12.526
R² = 0.0375

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.19354516
R Square	0.03745973
Adjusted R Square	0.02287578
Standard error	0.57751813
Observations	68

ANOVA

	df	SS	MS	F	Significance F
Regression	1	0.856684461	0.856684	2.56856	0.113782523
Residual	66	22.01279438	0.333527		
Total	67	22.86947884			

	Coefficient	Standard error	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	12.5255409	7.06344707	1.77329	0.080794	-1.577086186	26.628168	-1.577086186	26.628168
X	-0.0057185	0.003568123	-1.60267	0.113783	-0.012842521	0.001405454	-0.012842521	0.001405454
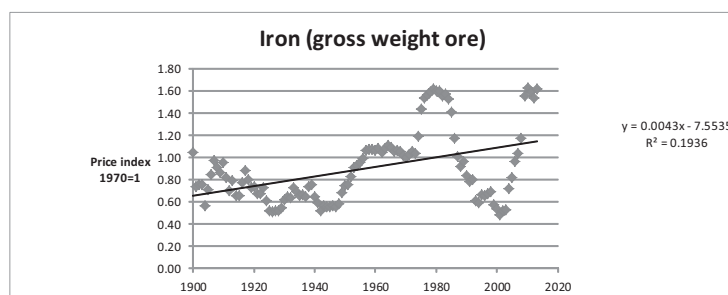
Iron (gross weight ore)

y = 0.0043x - 7.5535
R² = 0.1936

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.4399687
R Square	0.1935725
Adjusted R Square	0.1863722
Standard error	0.2926951
Observations	114

ANOVA

	df	SS	MS	F	Significance F
Regression	1	2.303175444	2.303175	26.88415	9.68164E-07
Residual	112	9.595084581	0.08567		
Total	113	11.89826002			

	Coefficient	Standard error	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	-7.553451	1.630071756	-4.63382	9.76E-06	-10.7832292	-4.32367278	-10.78322925	-4.32367278
X	0.0043193	0.000833039	5.184992	9.68E-07	0.002668742	0.00596986	0.002668742	0.005969862
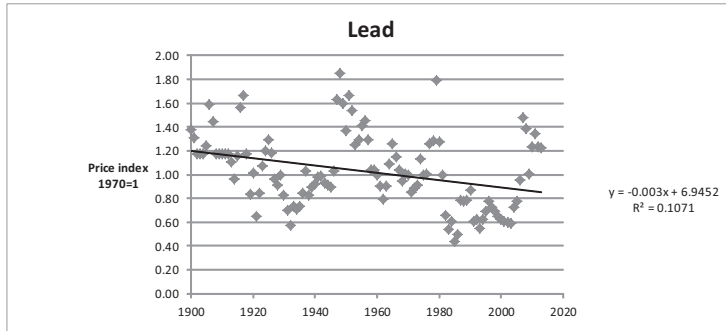
Lead

y = -0.003x + 6.9452
R² = 0.1071

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.3273104
R Square	0.1071321
Adjusted R Square	0.09916
Standard error	0.2899422
Observations	114

ANOVA

	df	SS	MS	F	Significance F
Regression	1	1.12972583	1.129726	13.43848	0.000378498
Residual	112	9.415444043	0.084066		
Total	113	10.54516987			

	Coefficient	Standard error	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	6.9452258	1.614740441	4.301141	3.65E-05	3.745824629	10.14462702	3.745824629	10.14462702
X	-0.0030251	0.000825204	-3.66585	0.000378	-0.00466011	-0.00139004	-0.004660114	-0.001390042
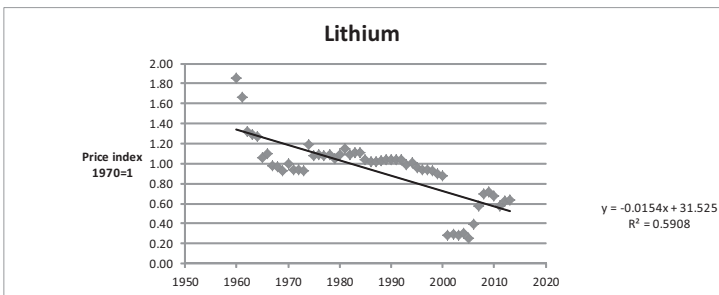
Lithium

y = -0.0154x + 31.525
R² = 0.5908

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.7686385
R Square	0.5908051
Adjusted R Square	0.5829359
Standard error	0.2035492
Observations	54

ANOVA

	df	SS	MS	F	Significance F
Regression	1	3.11068559	3.110686	75.0788	1.15055E-11
Residual	52	2.154478363	0.041432		
Total	53	5.265163953			

	Coefficient	Standard error	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	31.525141	3.530577882	8.929173	4.47E-12	24.44051779	38.6097634	24.44051779	38.60976345
X	-0.0153994	0.001777231	-8.6648	1.15E-11	-0.018965629	-0.01183308	-0.018965629	-0.01183308
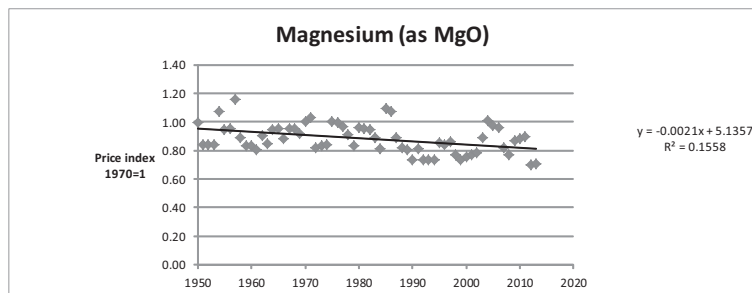
Magnesium (as MgO)

$y = -0.0021x + 5.1357$
$R^2 = 0.1558$

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.39469078
R Square	0.15578081
Adjusted R Square	0.14216437
Standard error	0.09379921
Observations	64

ANOVA

	df	SS	MS	F	Significance F
Regression	1	0.100658107	0.100658	11.44064	0.001249187
Residual	62	0.545494047	0.008798		
Total	63	0.646152154			

	Coefficient	Standard error	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	5.1356836	1.257725293	4.083311	0.000129	2.621526558	7.64984063	2.621526558	7.649840633
X	-0.00214683	0.000634706	-3.3824	0.001249	-0.00341559	-0.00087807	-0.003415592	-0.00087807
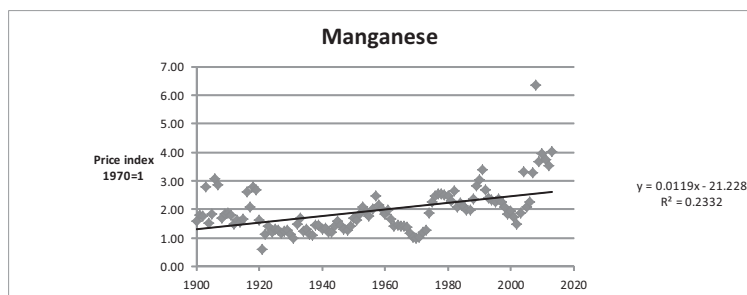
Manganese

$y = 0.0119x - 21.228$
$R^2 = 0.2332$

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correllation coefficient	0.4828851
R Square	0.233178
Adjusted R Square	0.2263314
Standard error	0.7135727
Observations	114

ANOVA

	df	SS	MS	F	Significance F
Regression	1	17.34153749	17.34154	34.05737	5.29257E-08
Residual	112	57.02883256	0.509186		
Total	113	74.37037006			

	Coefficient	Standard error	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	-21.228007	3.974015526	-5.3417	4.89E-07	-29.102009	-13.3540043	-29.102009	-13.3540043
X	0.0118521	0.002030899	5.835869	5.29E-08	0.007828095	0.015876026	0.007828095	0.015876026
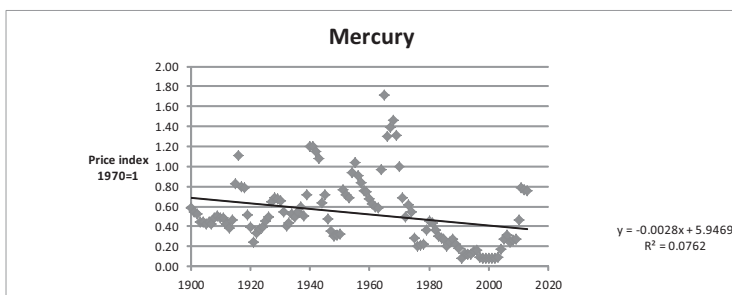
Mercury

Price index 1970=1

y = -0.0028x + 5.9469
R² = 0.0762

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.27611309
R Square	0.07623844
Adjusted R Square	0.06799057
Standard error	0.31989888
Observations	114

ANOVA

	df	SS	MS	F	Significance F
Regression	1	0.945926906	0.945927	9.243408	0.002943046
Residual	112	11.46155311	0.102335		
Total	113	12.40748002			

	Coefficient	Standard error	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	5.94690646	1.781574773	3.338006	0.001146	2.416944417	9.476868501	2.416944417	9.47686850
X	-0.0027681	0.000910464	-3.0403	0.002943	-0.00457205	-0.000964114	-0.004572049	-0.00096411
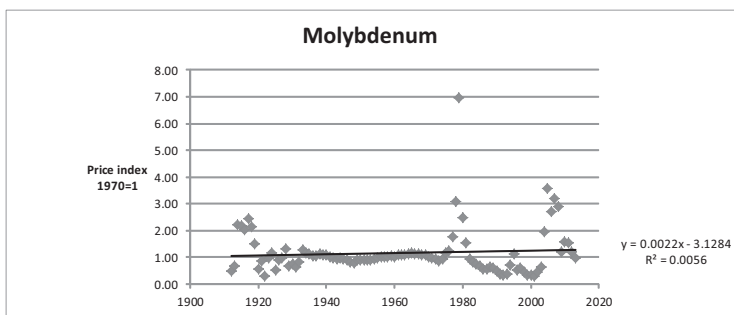
Molybdenum

Price index 1970=1

y = 0.0022x - 3.1284
R² = 0.0056

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.074992
R Square	0.005624
Adjusted R Square	-0.00432
Standard error	0.86337
Observations	102

ANOVA

	df	SS	MS	F	Significance F
Regression	1	0.421568066	0.421568	0.565553	0.453797864
Residual	100	74.54084115	0.745408		
Total	101	74.96240921			

	Coefficient	Standard error	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	-3.1284	5.698583553	-0.54898	0.584244	-14.4342247	8.17743025	-14.4342247	8.177430252
X	0.002183	0.00290341	0.752033	0.453798	-0.00357682	0.00794374	-0.00357682	0.007943742
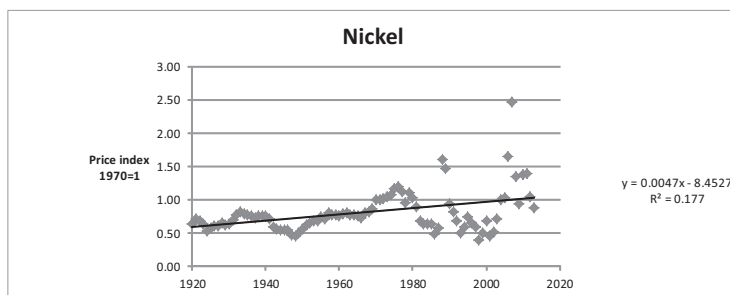
Nickel

y = 0.0047x - 8.4527
R² = 0.177

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.4206826
R Square	0.1769738
Adjusted R Square	0.1680279
Standard error	0.2783873
Observations	94

ANOVA

	df	SS	MS	F	Significance F
Regression	1	1.533140924	1.533141	19.7826	2.42428E-05
Residual	92	7.129952386	0.077499		
Total	93	8.66309331			

	Coefficient	Standard error	T-stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	-8.4526511	2.081172647	-4.06148	0.000102	-12.58603958	-4.31926255	-12.58603958	-4.31926255
X	0.0047067	0.001058212	4.447763	2.42E-05	0.002604977	0.006808379	0.002604977	0.006808379
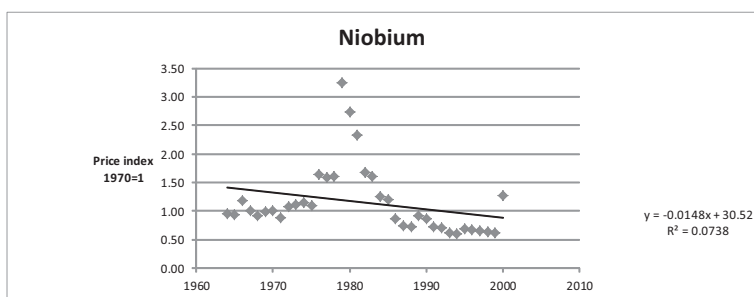
Niobium

y = -0.0148x + 30.52
R² = 0.0738

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.27157996
R Square	0.07375568
Adjusted R Square	0.04729155
Standard error	0.57648224
Observations	37

ANOVA

	df	SS	MS	F	Significance F
Regression	1	0.92621071	0.926211	2.787006	0.103953556
Residual	35	11.6316121	0.332332		
Total	36	12.55782281			

	Coefficient	Standard error	T-stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	30.5197054	17.59310915	1.734753	0.091584	-5.196204918	66.23561581	-5.196204918	66.23561581
X	-0.0148184	0.008876314	-1.66943	0.103954	-0.032838285	0.003201465	-0.032838285	0.003201465
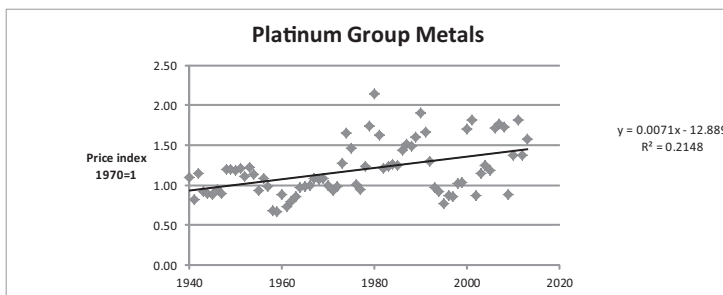
Platinum Group Metals

y = 0.0071x - 12.889
R² = 0.2148

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.4634994
R Square	0.2148317
Adjusted R Square	0.20392658
Standard error	0.29491764
Observations	74

ANOVA

	df	SS	MS	F	Significance F
Regression	1	1.713442752	1.713443	19.70008	3.19919E-05
Residual	72	6.26230191	0.086976		
Total	73	7.975744662			

	Coefficient	Standard error	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	-12.889446	3.172529228	-4.06283	0.000122	-19.21376718	-6.56512431	-19.2137672	-6.565124315
X	0.00712389	0.001605031	4.438478	3.2E-05	0.003924324	0.010323466	0.003924324	0.010323466
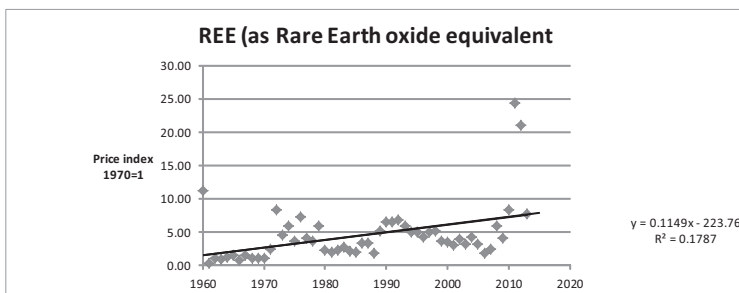
REE (as Rare Earth oxide equivalent

y = 0.1149x - 223.76
R² = 0.1787

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.42274696
R Square	0.178715
Adjusted R Square	0.16292105
Standard error	3.9129658
Observations	54

ANOVA

	df	SS	MS	F	Significance F
Regression	1	173.2537137	173.2537	11.31541	0.001449545
Residual	52	796.1876717	15.3113		
Total	53	969.4413854			

	Coefficient	Standard error	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	-223.76463	67.87071932	-3.29692	0.001766	-359.9571876	-87.572063	-359.957188	-87.57206339
X	0.11492532	0.034164928	3.363839	0.00145	0.04636838	0.18348227	0.04636838	0.183482269
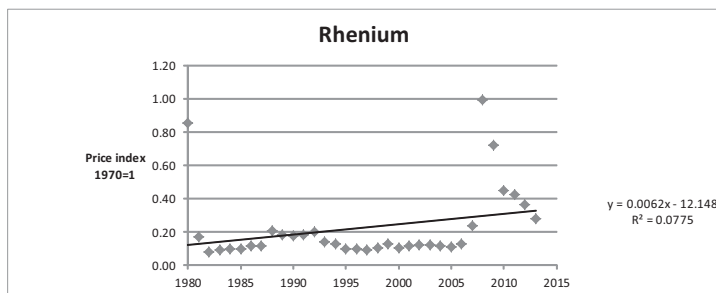
Rhenium

y = 0.0062x - 12.148
R² = 0.0775

SUMMARY OUTPUT of regression analysis

Regression statistics	
Multiple correlation coefficient	0.2783747
R Square	0.0774925
Adjusted R Square	0.0486641
Standard error	0.2162216
Observations	34

ANOVA

	df	SS	MS	F	Significance F
Regression	1	0.125671814	0.125672	2.688065	0.11089828
Residual	32	1.49605702	0.046752		
Total	33	1.621728834			

	Coefficient	Standard error	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	-12.14805	7.54629562	-1.6098	0.117263	-27.51934678	3.22325556	-27.5193468	3.223255558
X	0.006197	0.003779717	1.639532	0.110898	-0.001502065	0.013896	-0.00150207	0.013895997
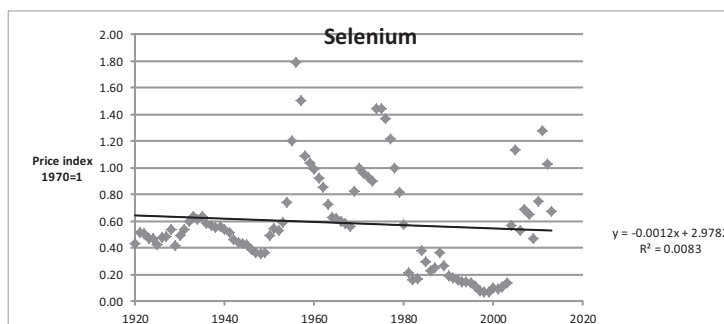
Selenium

y = -0.0012x + 2.9782
R² = 0.0083

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.0910738
R Square	0.0082944
Adjusted R Square	-0.002485
Standard error	0.3650225
Observations	94

ANOVA

	df	SS	MS	F	Significance F
Regression	1	0.10252532	0.102525	0.76947	0.382665924
Residual	92	12.25821359	0.133241		
Total	93	12.36073891			

	Coefficient	Standard error	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	2.9781625	2.728841974	1.091365	0.277962	-2.44155319	8.397878223	-2.44155319	8.397878223
X	-0.001217	0.001387532	-0.87719	0.382666	-0.00397289	0.001538623	-0.00397289	0.001538623
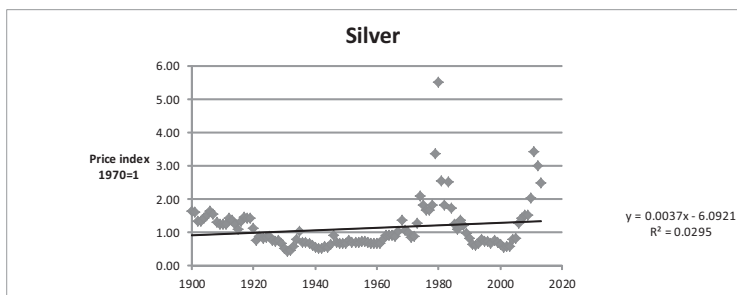
Silver

$y = 0.0037x - 6.0921$
$R^2 = 0.0295$

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.17170707
R Square	0.02948332
Adjusted R Square	0.02081799
Standard error	0.70333386
Observations	114

ANOVA

	df	SS	MS	F	Significance F
Regression	1	1.683117356	1.683117	3.402447	0.067742276
Residual	112	55.40399347	0.494679		
Total	113	57.08711083			

	Coefficient	Standard error	T-stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	-6.0920996	3.916993525	-1.5553	0.122696	-13.85312014	1.668920997	-13.85312014	1.668920997
X	0.00369239	0.002001758	1.844572	0.067742	-0.00027384	0.007658614	-0.00027384	0.007658614
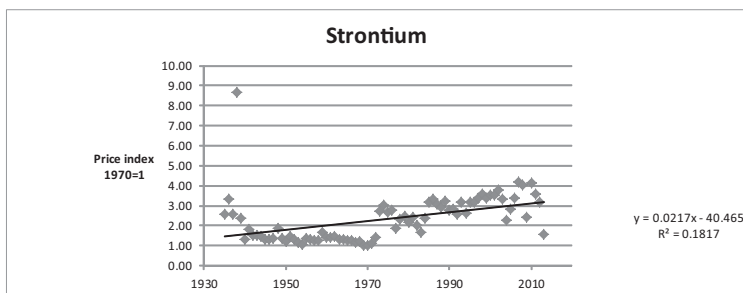
Strontium

$y = 0.0217x - 40.465$
$R^2 = 0.1817$

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.42625053
R Square	0.18168951
Adjusted R Square	0.17106211
Standard error	1.06282884
Observations	79

ANOVA

	df	SS	MS	F	Significance F
Regression	1	19.31208373	19.31208	17.09631	8.97341E-05
Residual	77	86.97959599	1.129605		
Total	78	106.2916797			

	Coefficient	Standard error	T-stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	-40.465151	10.35199937	-3.90892	0.000198	-61.07861481	-19.8516863	-61.07861481	-19.8516863
X	0.021682	0.005243824	4.134769	8.97E-05	0.011240213	0.032123788	0.011240213	0.032123788
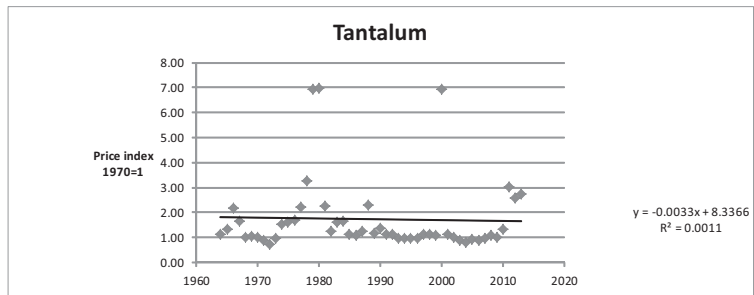
Tantalum

$$y = -0.0033x + 8.3366$$
$$R^2 = 0.0011$$

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.03330768
R Square	0.0011094
Adjusted R Square	-0.0197008
Standard error	1.46947292
Observations	50

ANOVA

	df	SS	MS	F	Significance F
Regression	1	0.115115864	0.115116	0.05331	0.818381237
Residual	48	103.6488315	2.159351		
Total	49	103.7639474			

	Coefficient	Standard error	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	8.33662089	28.63657742	0.291118	0.772215	-49.241077	65.91431878	-49.241077	65.91431878
X	-0.003325	0.014400716	-0.23089	0.818381	-0.032279568	0.025629592	-0.032279568	0.025629592
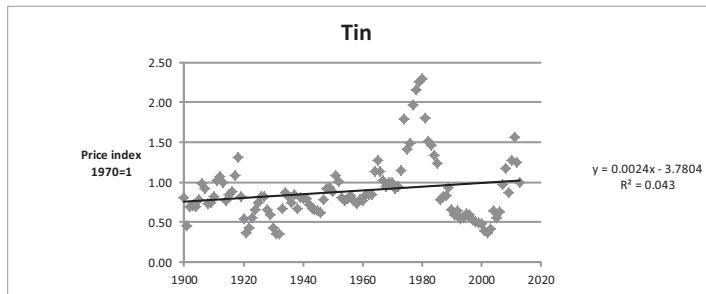
Tin

$$y = 0.0024x - 3.7804$$
$$R^2 = 0.043$$

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.2072576
R Square	0.0429557
Adjusted R Square	0.0344107
Standard error	0.3738131
Observations	114

ANOVA

	df	SS	MS	F	Significance F
Regression	1	0.702450539	0.702451	5.026976	0.02692515
Residual	112	15.65045422	0.139736		
Total	113	16.35290476			

	Coefficient	Standard error	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	-3.78037	2.081832539	-1.81589	0.072063	-7.9052545	0.34451413	-7.9052545	0.344514127
X	0.0023854	0.001063909	2.242092	0.026925	0.000277382	0.00449338	0.000277382	0.004493381
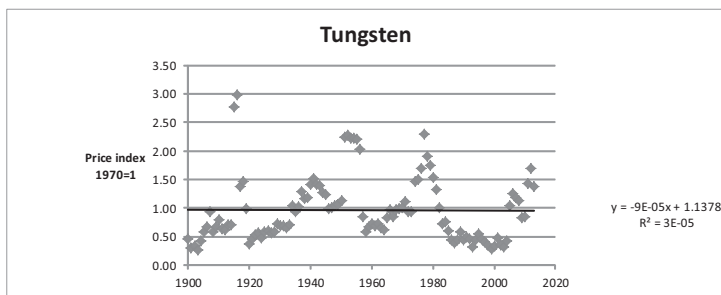
Tungsten

$y = -9E-05x + 1.1378$
$R^2 = 3E-05$

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.00537851
R Square	2.8928E-05
Adjusted R Square	-0.00889938
Standard error	0.56568878
Observations	114

ANOVA

	df	SS	MS	F	Significance F
Regression	1	0.001036837	0.001037	0.00324	0.95470902
Residual	112	35.84042558	0.320004		
Total	113	35.84146242			

	Coefficient	Standard error	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	1.13782224	3.150423207	0.361165	0.718657	-5.10433751	7.37998199	-5.104337505	7.379981989
X	-9.1644E-05	0.001610006	-0.05692	0.954709	-0.00328167	0.00309838	-0.003281666	0.003098377
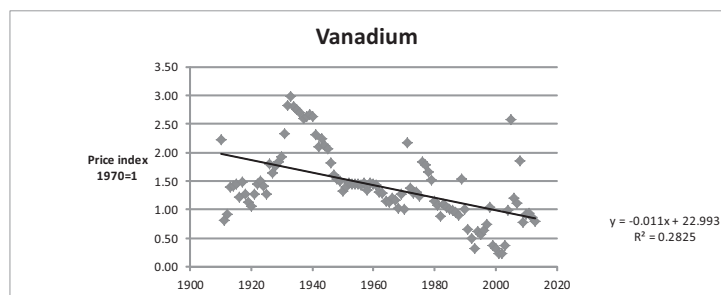
Vanadium

$y = -0.011x + 22.993$
$R^2 = 0.2825$

SUMMARY OUTPUT of linear regression analysis

Regression statistics	
Multiple correlation coefficient	0.5314673
R Square	0.2824575
Adjusted R Square	0.2754228
Standard error	0.5316489
Observations	104

ANOVA

	df	SS	MS	F	Significance F
Regression	1	11.34894519	11.34895	40.15186	6.446E-09
Residual	102	28.83035672	0.282651		
Total	103	40.17930191			

	Coefficient	Standard error	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	22.992945	3.40662858	6.749472	9.22E-10	16.2359129	29.74997621	16.23591294	29.74997621
X	-0.011004	0.001736543	-6.33655	6.45E-09	-0.0144481	-0.00755927	-0.014448118	-0.007559267
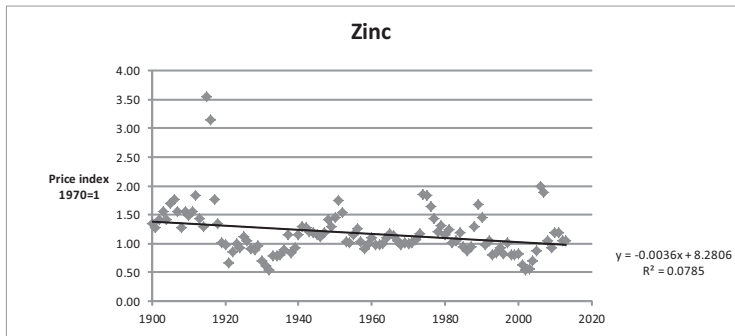
Zinc

$y = -0.0036x + 8.2806$
$R^2 = 0.0785$

SUMMARY OUTPUT of regression analysis

Regression statistics	
Multiple correlation coefficient	0.2801936
R Square	0.0785084
Adjusted R Square	0.0702808
Standard error	0.412895
Observations	114

ANOVA

	df	SS	MS	F	Significance F
Regression	1	1.626755725	1.626756	9.54208	0.002532731
Residual	112	19.09401683	0.170482		
Total	113	20.72077256			

	Coefficient	Standard error	T- stat	P-value	Lowest 95%	Highest 95%	Lowest 95,0%	Highest 95,0%
Intercept	8.2806358	2.299487057	3.60108	0.000474	3.724496948	12.8367746	3.724496948	12.83677464
X	-0.00363	0.00117514	-3.08903	0.002533	-0.00595843	-0.00130165	-0.00595843	-0.001301649

REFERENCES IN ANNEX III

De Pous, J.W., 1962, Nota inzake het aardgas, Slotbeschouwing, 2de kamer zitting 1961-1962, 11 juli

Heal, G., 1976, The relationship between price and extraction cost for a resource with a backstop technology, The Bell Journal of Economics, 7 (2) 371-378

Henckens, M.L.C.M., Driessen, P.P.J., Worrell, E., 2015b, How can we adapt to geological scarcity of antimony. Investigation of antimony's substitutability and of other measures to achieve a sustainable use, unpublished results

Henckens, M.L.C.M., Driessen, P.P.J., Worrell, E., 2015c, The sustainable use of zinc and molybdenum. Investigation of measures to reduce primary zinc and molybdenum use to a sustainable level, unpublished results

Henckens, M.L.C.M., Driessen, P.P.J., Worrell, E., 2015a, Towards a sustainable use of primary boron. Approach to a sustainable use of primary resources, Resour. Conserv. Recycl. 103, 9-18

Neumayer, E., 2000, Scarce or abundant? The economics of natural resource availability. Journal of Economic Surveys 14(3) 307-335

United States Geological Survey, 2015, Historical statistics for Mineral and Material Commodities in the United States

Annex IV

Supplementary information to chapter 8
(normative principles)

Table of contents

A.   List of multilateral environmental agreements signed from 1960 onwards with a (semi-)global scope and included result oriented normative principles

The list is derived from the International Environmental Agreements Database of the University of Oregon (Mitchell, 2016). The selection does only include multilateral agreements with a global or semi-global scope. The list does not include agreements with a regional scope, except agreements on oceans and on the Antarctic and Arctic regions. We have not selected multilateral agreements on (nuclear) energy, radioactive material, weaponry and other military issues, creation of institutions, financing, patents, occupational health, training, confidentiality of data, communication, information management and public participation, disasters and emergence situations, sustainable housing, research and monitoring, meteorology, liability, industrial safety, human health related to tobacco, compliance and enforcement, cultural heritage and transport. The remaining selection consists of the 29 international environmental agreements in the table.

1. Principle of Conservation and/or sustainable use of resources
2. Principle of protection of wild flora and fauna, environment and nature
3. Precautionary principle
4. Inter-generational principle
5. Sustainable development principle

No	Year	Agreement	Number of ratifying countries	Number of signatories	Ratifying countries in 2016 These are only mentioned in case the number of signatories is less than 30	1	2	3	4	5
									Normative principles included in the considered international environmental agreements	
1	1971	Convention On Wetlands Of International Importance Especially As Waterfowl Habitat	161				X			
2	1972	Convention For The Conservation Of Antarctic Seals	17	17	Argentina, Australia, Belgium, Brasilia, Canada, Chile, France, Germany, Italy, Japan, New Zealand, Norway, Pakistan, Poland, Russian Federation, South Africa, United Kingdom, United States	X				
3	1972	Convention For The Prevention Of Marine Pollution By Dumping From Ships And Aircraft	13	13	Belgium, Denmark, Finland, France, Germany, Iceland, Ireland, Netherlands, Norway, Portugal, Spain, Sweden, United Kingdom		X			
4	1972	Convention On The Prevention Of Marine Pollution By Dumping Of Wastes And Other Matter	85				X			
5	1972	Convention for the Protection of the World Cultural and Natural Heritage	189						X	
6	1973	Agreement On Conservation Of Polar Bears	5	5	Canada, Denmark, Norway, Russian Federation, United States		X			
7	1973	Convention on international trade in endangered species of wild fauna and flora	181					X		
8	1973	International Convention For The Prevention Of Pollution From Ships	32				X			
9	1974	Convention On The Prevention Of Marine Pollution From Land-Based Sources	13	13	Belgium, Denmark, European Union, France, Germany, Iceland, Ireland, Netherlands, Norway, Portugal, Spain, Sweden, United Kingdom		X			

No	Year	Agreement	Number of ratifying countries	Number of signatories	Ratifying countries in 2016 These are only mentioned in case the number of signatories is less than 30	Normative principles included in the considered international environmental agreements				
						1	2	3	4	5
10	1976	Convention On Conservation Of Nature In The South Pacific	5	5	Australia, Cook Islands, Fuji, France, Papua New Guinea, Samoa		X		X	X
11	1979	Convention On Long-Range Transboundary Air Pollution	59				X			
12	1979	Convention On The Conservation Of Migratory Species Of Wild Animals	119				X		X	
13	1980	Convention On The Conservation Of Antarctic Marine Living Resources	34				X			
14	1982	United Nations Convention On The Law Of The Sea	165			X	X	X		
15	1985	Convention for the Protection of the Ozone Layer (Vienna Convention)	197					X		
16	1985	Convention On The Control Of Transboundary Movements Of Hazardous Wastes And Their Disposal	175				X			
17	1992	Convention on biological diversity	193			X				
18	1992	United Nations Framework Convention on Climate Change	195			X		X	X	X
19	1994	Implementation Of Part XI Of The United Nations Convention On The Law Of The Sea Agreement Relating To The	1	38			X			
20	1994	WTO agreement on the Application of Sanitary and Phytosanitary Measures	159					X		

No	Year	Agreement	Number of ratifying countries	Number of signatories	Ratifying countries in 2016 These are only mentioned in case the number of signatories is less than 30	Normative principles included in the considered international environmental agreements				
						1	2	3	4	5
21	1995	Agreement for the implementation of the Law of the Sea Convention relating to the conservation and management of straddling fish stocks and highly migratory fish stocks	0	94		X				X
22	2000	Convention on the Conservation and Management of the Highly Migratory Fish Stocks of the Western and Central Pacific Ocean	25			X	X	X	X	
23	2001	International Convention On The Control Of Harmful Anti-Fouling Systems On Ships	69				X	X		
24	2001	International Treaty On Plant Genetic Resources For Food And Agriculture	127			X			X	
25	2001	Convention on Persistent Organic Pollutants	178				X	X		
26	2004	International Convention For The Control And Management Of Ships' Ballast Water And Sediments	43				X	X		
27	2006	International Tropical Timber Agreement	63			X				X
28	2009	Agreement on Port State Measures to prevent deter and illuminate illegal, unreported and unregulated fishing	11	27	Ratified by Chile, EU, Gabon, Mozambique, Myanmar, New Zealand, Norway, Oman, Seychelles, Sri Lanka, Uruguay					X
29	2013	Minamata Convention on Mercury	12	129			X			

B.   **Elements in the pre-ambles of 29 international environmental agreements for assessing the gravity of a resource scarcity problem in view of the potential justification of a global agreement.**

Elements of gravity of a resource scarcity problem	Sub-elements	
*Potential **size** of the problem*	- The number of countries affected (spatial dimension)	a
	- The proportion of the resource that is endangered (volume dimension)	b
	- The extent that future generations are affected (temporal dimension)	c
*Potential **seriousness** of the problem*	The potential extent of	
	- (Ir)reversibility	d
	- The impact on human life, directly or indirectly	e
	- The impact on health, safety and survival of the living environment (animals, plants, natural cycles and equilibria, eco-systems, natural tipping points, food chains, biodiversity, habitats)	f
	- The impact on the uniqueness of the endangered resource	g
	- The impact on economy and welfare	h
*Potential **urgency** of the problem*	- Available time span to redress the developments in order to prevent the problem from becoming too grave to be adequately solved	

International Environmental Agreements	Element of gravity — Size	Sub-elements a	b	c	Element of gravity — Seriousness	Sub-elements d	e	f	g	h	Element of gravity — Urgency
1971 Convention On Wetlands Of International Importance Especially As Waterfowl Habitat	Recognizing that waterfowl in their seasonal migrations may transcend frontiers and so should be regarded as an international resource.	X	X		Considering the fundamental ecological functions of wetlands as regulators of water regimes and as habitats supporting a characteristic flora and fauna, especially waterfowl.		X	X			N/A
					Being convinced that wetlands constitute a resource of great economic, cultural, scientific and recreational value, the loss of which would be irreparable.	X			X		
1972 Convention For The Conservation Of Antarctic Seals	N/A				Recognizing that the stocks of Antarctic seals are an important living resource in the marine environment which requires an international agreement for its effective conservation.		X	X			N/A
					Recognizing that this resource should not be depleted by over-exploitation, and hence that any harvesting should be regulated so as not to exceed the levels of the optimum sustainable yield.	X					

International Environmental Agreements	Element of gravity	Sub-elements			Element of gravity	Sub-elements					Element of gravity
	Size	a	b	c	Seriousness	d	e	f	g	h	Urgency
1972 Convention For The Prevention Of Marine Pollution By Dumping From Ships And Aircraft	Noting that this Pollution has many sources, including dumping from ships and aircraft and discharges through rivers, estuaries, outfalls and pipelines within national jurisdiction, that it is important that states use the best practicable means to prevent such pollution, and that products and processes which will minimize the amount of harmful waste requiring disposal should be developed.	X			Mindful that the ecological equilibrium and the legitimate uses of the sea are increasingly threatened by pollution.		X				Being convinced that international action to control the pollution of the sea by the dumping of harmful substances from ships and aircraft can and should be taken without delay, but that this action should not preclude discussion of measures to control other sources of marine pollution as soon as possible.
	Considering that the states bordering the North-East Atlantic have a peculiar responsibility to protect that waters of this region.	X									

International Environmental Agreements	Element of gravity — Size	Sub-elements a	b	c	Element of gravity — Seriousness	Sub-elements d	e	f	g	h	Element of gravity — Urgency
1972 Convention On The Prevention Of Marine Pollution By Dumping Of Wastes And Other Matter	Recalling resolution 2749(XXV) of the General Assembly of the United Nations on the principles governing the sea-bed and the ocean floor and the subsoil thereof, beyond the limits of national jurisdiction.	X	X	X	Recognizing that the marine environment and the living organisms which it supports are of vital importance to humanity, and all people have an interest in assuring that it is so managed that its quality and resources are not impaired.			X	X		Being convinced that international action to control the pollution of the sea by dumping can and must be taken without delay but that this action should not preclude discussion of measures to control other sources of marine pollution as soon as possible.
					Recognizing that the capacity of the sea to assimilate wastes and render them harmless, and its ability to regenerate natural resources, is not unlimited.	X					
1972 World Heritage Convention	Considering that deterioration or disappearance of any item of the cultural or natural heritage constitutes a harmful impoverishment of the heritage of all the nations of the world.	X		X	Noting that the cultural heritage and the natural heritage are increasingly threatened with destruction not only by the traditional causes of decay, but also by changing social and economic conditions which aggravate the situation with even more formidable	X	X	X			N/A
	Considering that parts of the cultural or natural heritage are of outstanding interest and therefore need to be preserved as part of the world heritage of mankind as a whole.	X		X	phenomena of damage or destruction.						

International Environmental Agreements	Element of gravity: Size	Sub-elements			Element of gravity: Seriousness	Sub-elements					Element of gravity: Urgency
		a	b	c		d	e	f	g	h	
1973 Agreement On Conservation Of Polar Bears	N/A				Recognizing that the polar bear is a significant resource of the Arctic Region which requires additional protection.				X	X	Desiring to take immediate action to bring further conservation and management measures into effect.
1973 Convention on international trade in endangered species of wild fauna and flora	Recognizing, in addition, that international co-operation is essential for the protection of certain species of wild fauna and flora against over-exploitation through international trade.		X		Recognizing that wild fauna and flora in their many beautiful and varied forms are an irreplaceable part of the natural systems of the earth which must be protected for this and the generations to come.	X	X	X			Convinced of the urgency of taking appropriate measures to this end.
	Recognizing that wild fauna and flora in their many beautiful and varied forms are an irreplaceable part of the natural systems of the earth which must be protected for this and the generations to come.	X			Conscious of the ever-growing value of wild fauna and flora from aesthetic, scientific, cultural, recreational and economic points of view.				X		
1973 International Convention For The Prevention Of Pollution From Ships	N/A				Recognizing that deliberate, negligent or accidental release of oil and other harmful substances from ships constitutes a serious source of pollution.		X				N/A

International Environmental Agreements	Element of gravity	Sub-elements			Element of gravity	Sub-elements					Element of gravity
	Size	a	b	c	Seriousness	d	e	f	g	h	Urgency
1974 Convention On The Prevention Of Marine Pollution From Land-Based Sources	Recognizing that the marine environment and the fauna and flora which it supports are of vital importance to all nations.	X			Mindful that the ecological equilibrium and the legitimate uses of the sea are increasingly threatened by pollution.	X					Convinced that international action to control the pollution of the sea from land-based sources can and should be taken without delay, as part of progressive and coherent measures to protect the marine environment from pollution, whatever its origin, including current efforts to combat the pollution of international waterway.

International Environmental Agreements	Element of gravity — Size	Sub-elements a	Sub-elements b	Sub-elements c	Element of gravity — Seriousness	Sub-elements d	Sub-elements e	Sub-elements f	Sub-elements g	Sub-elements h	Element of gravity — Urgency
1976 Convention On Conservation Of Nature In The South Pacific	N/A				Convinced of the urgency for action inspired by these Principles, especially in relation to the maintenance of the capacity of the earth to produce essential renewable natural resources, the safeguarding of representative samples of natural ecosystems, and the safeguarding of the heritage of wildlife and its habitat.	X	X	X	X		Convinced of the urgency for action inspired by these Principles, especially in relation to the maintenance of the capacity of the earth to produce essential renewable natural resources, the safeguarding of representative samples of natural ecosystems, and the safeguarding of the heritage of wildlife and its habitat.
					Conscious of the importance of natural resources from a nutritional, scientific, educational, cultural and aesthetic point of view.				X		
					Conscious also of the dangers threatening these irreplaceable resources.	X					
1979 Convention On Long-Range Transboundary Air Pollution	Recognizing the existence of possible adverse effects, in the short and long term, of air pollution including transboundary air pollution.	X			Recognizing the existence of possible adverse effects, in the short and long term, of air pollution including transboundary air pollution.	X					N/A

International Environmental Agreements	Element of gravity — Size	Sub-elements a	b	c	Element of gravity — Seriousness	Sub-elements d	e	f	g	h	Element of gravity — Urgency
1979 Convention On The Conservation Of Migratory Species Of Wild Animals	Concerned particularly with those species of wild animals that migrate across or outside national jurisdictional boundaries.	X	X		Conscious of the ever-growing value of wild animals from environmental, ecological, genetic, scientific, aesthetic, recreational, cultural, educational, social and economic points of view.		X		X	X	
	Aware that each generation of man holds the resources of the earth for future generations and has an obligation to ensure that this legacy is conserved and, where utilized, is used wisely.			X							
1980 Convention On The Conservation Of Antarctic Marine Living Resources	Noting the concentration of marine living resources found in Antarctic waters and the increased interest in the possibilities offered by the utilisation of these resources as a source of protein.	X	X								Conscious of the urgency of ensuring the conservation of Antarctic marine living resources.

International Environmental Agreements	Element of gravity	Sub-elements			Element of gravity	Sub-elements					Element of gravity
	Size	a	b	c	Seriousness	d	e	f	g	h	Urgency
1982 United Nations Convention On The Law Of The Sea	Conscious that the problems of ocean space are closely interrelated and need to be considered as a whole.	X			N/A						N/A
	Desiring by this Convention to develop the principles embodied in resolution 2749 (XXV) of 17 December 1970 in which the General Assembly of the United Nations solemnly declared inter alia that the area of the seabed and ocean floor and the subsoil thereof, beyond the limits of national jurisdiction, as well as its resources, are the common heritage of mankind, the exploration and exploitation of which shall be carried out for the benefit of mankind as a whole, irrespective of the geographical location of States.	X	X	X							

International Environmental Agreements	Element of gravity — Size	Sub-elements a	b	c	Element of gravity — Seriousness	Sub-elements d	e	f	g	h	Element of gravity — Urgency
1985 Convention for the Protection of the Ozone Layer (Vienna Convention)	Recalling the pertinent provisions of the Declaration of the United Nations Conference on the Human Environment, and in particular principle 21, which provides that States have………the responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction.	X			Aware of the potentially harmful impact on human health and the environment through modification of the ozone layer.	X	X				N/A
1985 Convention On The Control Of Transboundary Movements Of Hazardous Wastes And Their Disposal	Aware of the risk of damage to human health and the environment caused by hazardous wastes and other wastes and the transboundary movement thereof.	X			Aware of the risk of damage to human health and the environment caused by hazardous wastes and other wastes and the transboundary movement thereof, …	X					N/A
	Mindful of the growing threat to human health and the environment posed by the increased generation and complexity, and transboundary movement of hazardous wastes and other wastes.	X			Mindful of the growing threat to human health and the environment posed by the increased generation and complexity, and transboundary movement of hazardous wastes and other wastes.	X	X				

International Environmental Agreements	Element of gravity — Size	Sub-elements			Element of gravity — Seriousness	Sub-elements					Element of gravity — Urgency
		a	b	c		d	e	f	g	h	
1992 Convention on biological diversity	Affirming that the conservation of biological diversity is a common concern of humankind.	X			Conscious also of the importance of biological diversity for evolution and for maintaining life sustaining systems of the biosphere.			X			Aware of the general lack of information and knowledge regarding biological diversity and of the urgent need to develop scientific, technical and institutional capacities to provide the basic understanding upon which to plan and implement appropriate measures.
	Determined to conserve and sustainably use biological diversity for the benefit of present and future generations.			X	Concerned that biological diversity is being significantly reduced by certain human activities.	X					
					Aware that conservation and sustainable use of biological diversity is of critical importance for meeting the food, health and other needs of the growing world population, for which purpose access to and sharing of both genetic resources and technologies are essential.		X			X	

International Environmental Agreements	Element of gravity — Size	Sub-elements a	b	c	Element of gravity — Seriousness	Sub-elements d	e	f	g	h	Element of gravity — Urgency
1992 United Nations Framework Convention on Climate Change	Acknowledging that change in the Earth's climate and its adverse effects are a common concern of humankind. Acknowledging that the global nature of climate change calls for the widest possible cooperation by all countries and their participation in an effective and appropriate international response, in accordance with their common but differentiated responsibilities and respective capabilities and their social and economic conditions.	X		X	Concerned that human activities have been substantially increasing the atmospheric concentrations of greenhouse gases, that these increases enhance the natural greenhouse effect, and that this will result on average in an additional warming of the Earth's surface and atmosphere and may adversely affect natural ecosystems and humankind. Recognizing further that low-lying and other small island countries, countries with low-lying coastal, arid and semi-arid areas or areas liable to floods, drought and desertification, and developing countries with fragile mountainous ecosystems are particularly vulnerable to the adverse effects of climate change.		X	X		X	Recognizing also the need for developed countries to take immediate action in a flexible manner on the basis of clear priorities, as a first step towards comprehensive response strategies at the global, national and, where agreed, regional levels that take into account all greenhouse gases, with due consideration of their relative contributions to the enhancement of the greenhouse effect.
1994 Agreement Relating To The Implementation Of Part XI Of The United Nations Convention On The Law Of The Sea	Reaffirming that the seabed and ocean floor and subsoil thereof, beyond the limits of national jurisdiction (hereinafter referred to as "the Area"), as well as the resources of the Area, are the common heritage of mankind.	X		X	N/A						N/A
1994 WTO agreement on the Application of Sanitary and Phytosanitary Measures	N/A				N/A						N/A

International Environmental Agreements	Element of gravity — Size	Sub-elements			Element of gravity — Seriousness	Sub-elements					Element of gravity — Urgency
		a	b	c		d	e	f	g	h	
1995 Agreement for the implementation of the provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the conservation and management of straddling fish stocks and highly migratory fish stocks	Determined to ensure the long-term conservation and sustainable use of straddling fish stocks and highly migratory fish stocks.	X	X	X	Seeking to address in particular the problems identified in chapter 17, programme area C, of Agenda 21 adopted by the United Nations Conference on Environment and Development, namely, that the management of high seas fisheries is inadequate in many areas and that some resources are overutilized.	X					
					Conscious of the need to avoid adverse impacts on the marine environment, preserve biodiversity, maintain the integrity of marine ecosystems and minimize the risk of long-term or irreversible effects of fishing operations.		X		X		
2000 Convention on the Conservation and Management of the Highly Migratory Fish Stocks of the Western and Central Pacific Ocean	Determined to ensure the long-term conservation and sustainable use, in particular for human food consumption, of highly migratory fish stocks in the western and central Pacific Ocean for present and future generations.	X	X	X	Conscious of the need to avoid adverse impacts on the marine environment, preserve biodiversity, maintain the integrity of marine ecosystems and minimize the risk of long-term or irreversible effects of fishing operations.	X	X		X	X	N/A

International Environmental Agreements	Element of gravity — Size	Sub-elements			Element of gravity — Seriousness	Sub-elements					Element of gravity — Urgency
		a	b	c		d	e	f	g	h	
2001 International Convention On The Control Of Harmful Anti-Fouling Systems On Ships	N/A				Noting that scientific studies and investigations by Governments and competent international organizations have shown that certain anti-fouling systems used on ships pose a substantial risk of toxicity and other chronic impacts to ecologically and economically important marine organisms and also that human health may be harmed as a result of the consumption of affected seafood.	X	X	X		X	N/A
					Recognizing the importance of protecting the marine environment and human health from adverse effects of anti-fouling systems.				X		
2001 International Treaty On Plant Genetic Resources For Food And Agriculture	Cognizant that plant genetic resources for food and agriculture are a common concern of all countries, in that all countries depend very largely on plant genetic resources for food and agriculture that originated elsewhere.	X	X	X	Alarmed by the continuing erosion of these resources.					X	N/A
	Aware of their responsibility to past and future generations to conserve the World's diversity of plant genetic resources for food and agriculture.			X							

International Environmental Agreements	Element of gravity	Sub-elements			Element of gravity	Sub-elements					Element of gravity
	Size	a	b	c	Seriousness	d	e	f	g	h	Urgency
2001 Convention on Persistent Organic Pollutants	Recognizing that persistent organic pollutants possess toxic properties, resist degradation, bioaccumulate and are transported, through air, water and migratory species, across international boundaries and deposited far from their place of release, where they accumulate in terrestrial and aquatic ecosystems.	X			Aware of the health concerns, especially in developing countries, resulting from local exposure to persistent organic pollutants, in particular impacts upon women and, through them, upon future generations. Acknowledging that the Arctic ecosystems and indigenous communities are particularly at risk because of the biomagnification of persistent organic pollutants and that contamination of their traditional foods is a public health issue.	X	X				N/A

International Environmental Agreements	Element of gravity — Size	Sub-elements a	Sub-elements b	Sub-elements c	Element of gravity — Seriousness	Sub-elements d	Sub-elements e	Sub-elements f	Sub-elements g	Sub-elements h	Element of gravity — Urgency
2004 International Convention For The Control And Management Of Ships' Ballast Water And Sediments	Recognizing further that several States have taken individual action with a view to prevent, minimize and ultimately eliminate the risks of introduction of Harmful Aquatic Organisms and Pathogens through ships entering their ports, and also that this issue, being of worldwide concern, demands action based on globally applicable regulations together with guidelines for their effective implementation and uniform interpretation.	X			Conscious that the uncontrolled discharge of Ballast Water and Sediments from ships has led to the transfer of Harmful Aquatic Organisms and Pathogens, causing injury or damage to the environment, human health, property and resources.	X	X			X	N/A
2006 International Tropical Timber Agreement	Taking into account the linkages of the tropical timber trade and the international timber market and wider global economy and the need to take a global perspective in order to improve transparency in the international timber trade.	X			N/A						N/A
2009 Agreement on Port State Measures to prevent deter and illuminate illegal, unreported and unregulated fishing	N/A				Deeply concerned about the continuation of illegal, unreported and unregulated fishing and its detrimental effect upon fish stocks, marine ecosystems and the livelihoods of legitimate fishers, and the increasing need for food security on a global basis.	X				X	N/A

International Environmental Agreements	Element of gravity — Size	Sub-elements			Element of gravity — Seriousness	Sub-elements					Element of gravity — Urgency
		a	b	c		d	e	f	g	h	N/A
2013 Minamata Convention on Mercury	Recognizing that mercury is a chemical of global concern owing to its long-range atmospheric transport, its persistence in the environment once anthropogenically introduced, its ability to bioaccumulate in ecosystems and its significant negative effects on human health and the environment.	X			Aware of the health concerns, especially in developing countries, resulting from exposure to mercury of vulnerable populations, especially women, children, and, through them, future generations. Noting the particular vulnerabilities of Arctic ecosystems and indigenous communities because of the biomagnification of mercury and contamination of traditional foods, and concerned about indigenous communities more generally with respect to the effects of mercury, Recognizing the substantial lessons of Minamata Disease, in particular the serious health and environmental effects resulting from the mercury pollution, and the need to ensure proper management of mercury and the prevention of such events in the future.	X	X				F

Annex V

Supplementary information to Chapter 9 (International Agreement)

Table of contents

A.   The "sovereign right to exploit the own resources" principle in view of depletion of geologically scarce mineral resources

The sovereign right principle is considered a general principle of international law (Sands et al. 2012). In 1962, the United Nations General Assembly adopted Resolution 1803 (XVII) on the "Permanent Sovereignty over Natural Resources". This happened within the framework of the decolonization process. The resolution "*provides that States and international organizations shall strictly and conscientiously respect the sovereignty of peoples and nations over their natural wealth and resources in accordance with the Charter of the United Nations and the principles contained in the resolution. These principles are set out in eight articles concerning, inter alia, the exploration, development and disposition of natural resources, nationalization and expropriation, foreign investment and other related issues*" (United Nations, 2015). The sovereign right to exploit resources includes the right to be free from interference over their exploitation.

Principle 21 of the Stockholm Declaration (1972) applies the principle of sovereignty over resources providing that *"States have, in accordance with the Charter of the United Nations and the principles of international law, the sovereign right to exploit their own resources pursuant to their own environmental policies, and the responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction."*

The second part of Principle 21 of the Stockholm Declaration, regarding the responsibility not to cause environmental damage to the environment of other States, does not appear to be directly relevant in the context of the conservation and sustainable use of geologically scarce mineral resources. Mining activities could cause damage to the environment so reduction of mining activities is beneficial to the environment. Exhaustion of resources causes economic problems in the first place but – as such – no direct damage to the environment.

The wording of the Stockholm Declaration on sovereign rights is repeated in the Rio Declaration (1992) and is considered a basic obligation in international environmental law. The "sovereignty over resources" principle comes back in various forms in many international treaties (for instance the Ramsar Convention on Wetlands, 1971, the International Tropical Timber Agreement, 1983, the Basel Convention on Wastes, 1989, the UN Framework Convention on Climate Change, 1992 and the Biodiversity Convention, 1992).

B.   The Common Concern of Mankind principle in view of depletion of geologically scarce minerals

The principle of "*sovereignty over natural resources*" is counter-balanced by the notion of "*common concern of mankind*". This principle is included in e.g. the preamble of the 1992 United Nations Framework Convention on Climate Change (*"Change in the Earth's climate and its adverse effects are a common concern of mankind"*) and in the preamble of the 1992 Biodiversity Convention (*"biological diversity is a common concern of mankind")*. According to the report of the 2014 Washington Conference of the International Law Association on legal principles relating to climate change, the language "*common concern of humankind*" in the preamble of the UNFCCC implies that permanent sovereignty should be exercised for the benefit of humankind, which consists of present and future generations. This point of view is shared by other scholars (Brunnée, 2007, Schrijver, 2008, Perrez, 2000).

Although, thus far, depletion of geologically scarce mineral resources has not been specifically identified as a *"common concern of mankind"*, the "common concern of mankind" principle is generally accepted as approach to address global problems that are not directly related with public goods or *"common heritage"*. The principle provides states with a *"legitimate interest in resources of global significance and a common responsibility to assist in their sustainable development"* (Cottier et al., 2014, p 24).

C.   Common but differentiated responsibilities in view of depletion of geologically scarce minerals

Principle 7 of the 1992 Rio Declaration introduced the concept of Common but Differentiated Responsibilities: *"In view of the different contributions to global environmental degradation, States have common but differentiated responsibilities. The developed countries acknowledge the responsibility that they bear in the international pursuit of sustainable development in view of the pressures their societies place on the global environment and of the technologies and financial resources they command".* According the 1992 UN Framework Convention on Climate Change parties should act to protect the climate system *"on the basis of equality and in accordance with their common but differentiated responsibilities and respective capabilities".*

Stone (2004) distinguishes three versions of the Common but Differentiated Responsibilities (CDR) principle: (1) rational bargaining CDR, (2) equitable CDR and (3) inefficient CDR. In this context "efficient" Is meant in the sense of being Pareto-positive: at least one party is better off and no party is worse off.

In the rational bargaining CDR the negotiators pursue their own advantage. Outcomes are always Pareto positive. The equitable CDR introduces conditions for the outcome of the bargaining process, e.g. that the poor must be better off at the end of the negotiations. The overall result is still Pareto positive, meaning that no party is worse off. In the inefficient CDR, it is accepted that some parties may be worse off, e.g. the rich parties. In the latter example of an "inefficient CDR", there is a net wealth transfer from rich to poor.

The equitable resource distribution system that is prosed in section 9.5.2, meets the principle of common but differentiated responsibilities. The elaborated example in section E of the Supplementary Data will clarify this further.

D. Polluter pays principle in view of depletion of geologically scarce minerals

In the framework of depletion of geologically scarce mineral resources, the consumer can be considered as the "polluter". With an agreement on the conservation and sustainable use of geologically scarce mineral resources, eventually, the consumer will pay a considerably higher price for products that contain the respective scarce material or for products in which the original scarce material has been substituted. According to Principle 16 of the 1992 Rio Declaration on Environment and Development, *"national authorities should endeavor to promote the internalization of environmental costs and the use of economic instruments, taking into account the approach that the polluter should, in principle, bear the cost of pollution, with due regard to the public interest and without distorting international trade and investment."*

The conclusion is that the price mechanism of the free market system in combination with the measures proposed in sections 9.5.1 and 9.5.2, will automatically lead to compliance with the internationally accepted responsibility assignment principles:
- Poor countries will be spared compared to rich countries.
- Poor citizens, both in poor and rich countries, will be spared compared to rich citizens.

E. Comparison of the financial impact of the proposed agreement for rich and poor countries

The financial impact of the proposed system on developing countries as compared to the impact on developed countries is elaborated via a concrete example in the below Table. The conclusion is that the system will, in principle, lead to a relative profit for countries with a low per capita use of the resource compared to countries with a high per capita use of the resource.

Table: Expenses and income of a poor country (A) and a rich country (B) connected with the use of a geologically scarce mineral resource. Assumptions are: (1) distribution to user countries in year x: 1kg/capita; (2) fixed price to be paid to resource countries (including transaction and compensation costs): 1 US$ per kg raw material; (3) market price of raw material 2 US$ per kg and (4) product price 4 US$ per kg equivalent of the raw material.[14]

	Expense	Income	Net costs
Country A with 100 million people and an annual resource use in products of 0.5 kg/capita	Payment for distributed resource: $1*10^8$ US$ Payment for products: $2*10^8$ US$ Total expense: $3*10^8$ US$	Sale of distributed resource to processing industry: $2*10^8$ US$	 $1*10^8$ US$
Country B with 100 million people and an annual resource use in products of 5 kg/capita	Payment for distributed resource: $1*10^8$ US$ Payment for products: $20*10^8$ US$ Total expense: $21*10^8$ US$	Sale of distributed resource to processing industry: $2*10^8$ US$	 $19*10^8$ US$

In this example, the costs of the poor country A would be equal to its average costs before the extraction reduction, assuming that the total costs for the resources that have been received by the distribution system are approximately equal to the total costs of (the higher amount of) the respective resource that the country imported before implementation of the extraction reduction scheme. The costs of rich country B would be approximately 19 times higher than before if its citizens continue their high use of the services provided by the scarce mineral and its substitutes.

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14 Kg equivalent of raw material represents the value of the services that originally (before extraction reduction) were delivered by 1 kg of raw material

F. Draft Framework Agreement on the Conservation and Sustainable Use of Geologically Scarce Mineral Resources

Preamble

The Parties to this Agreement

Acknowledging that the conservation and sustainable use of geologically scarce mineral resources is a common concern of mankind,

Concerned about the depletion of a number of geologically scarce mineral resources, such as, but not limited to, antimony, gold, molybdenum, rhenium and zinc,

Aware of the urgent need to reduce the extraction of geologically scarce mineral resources,

Bearing in mind the interests of future generations,

Reaffirming the principle of sovereignty of States in international cooperation to address the depletion of mineral resources,

Noting the principle of common but differentiated responsibilities in addressing the depletion of mineral resources, and emphasizing the need to take into account the interests of developing States,

Recognizing the need for suitable substitutes for geologically scarce mineral resources, and of recycling technologies,

Noting the suitability of market mechanisms to address global governance failures, while recognizing that the sole reliance on market mechanisms may not automatically lead to the timely and sufficient reduction of the use of geologically scarce mineral resources.

Have agreed as follows:

ARTICLE 1 – DEFINITIONS

For the purpose of this Agreement:

Mineral resources are defined as geologically scarce, when they will be depleted within less than 1000 years assuming a 3 % growth of their use between 2010 and 2050, where after the extraction stabilizes.

The extraction rate of a mineral resource is defined as sustainable if a world population of 9 billion people can be provided with the resource for a period of at least 1000 years assuming that the average per capita consumption of the mineral is equally divided over the world's countries.

The Resource State is defined as the State on whose territory extraction of mineral resources takes place.

The User State is defined as the State on whose territory mineral resources are used, consumed, or processed. Every State is considered to be a user State.

ARTICLE 2 – OBJECTIVE

The ultimate objective of this Agreement and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Agreement, the conservation and sustainable use of geologically scarce mineral resources.

ARTICLE 3 – PRINCIPLES

In their actions to achieve the objective of the Agreement and to implement its provisions, the Parties shall be guided, *inter alia*, by the following:

The Parties commit themselves to the conservation and sustainable use of geologically scarce mineral resources for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities.

The specific needs and special circumstances of developing country Parties should be given full consideration.

Market mechanisms, in particular the tradability of extraction quota by resource States and distribution quota by user States, can ensure efficient conservation and sustainable use of geologically scare mineral resources, as well as equity.

ARTICLE 4 – PRIORITY-SETTING AND EXTRACTION REDUCTION GOAL

At its first review session, the Conference of the Parties will decide on which minerals should receive priority as far as extraction reduction is concerned. In its selection process, the Conference of the Parties will be guided by the following selection criteria:

The geological scarcity of the mineral.

The extent to which a mineral is critical for society, in particular elements that are essential for life and cannot be substituted by other elements, and the strategic value of applications. For each of the selected minerals the Conference of Parties will establish an extraction reduction goal. The decisions on priorities and goals will be laid down in a separate Protocol.

ARTICLE 5 – PHASING DOWN SCHEME

The Parties shall phase down the extraction of geologically scarce mineral resources. At its first review session, the Conference of the Parties will adopt a phasing down scheme for each selected mineral, to be laid down in separate Protocols. A phasing down period lasts at least five years. In making its determination, the Conference will take into account such factors as the time needed for the technical development of suitable substitutes and recycling technologies, as well as the time needed to realize the necessary new industrial facilities and to amortize existing facilities.

ARTICLE 6 – EXTRACTION LIMITATIONS

The Parties shall reduce the rate of extraction so as to render extraction sustainable. To this effect, the Parties shall allocate annual extraction quota to the resource States. At its first review session, the Conference of the Parties shall determine an allocation system for extraction quota and the annual extraction quota. The allocation system and the annual extraction quota will be laid down in separate Protocols.

The extraction quota are tradable among resource States.

ARTICLE 7 – COMPENSATION OF RESOURCE STATES

The Parties shall compensate the resource States for the loss of income as a result of the extraction limitations implemented pursuant to Article 6 of the Agreement.

The resource States shall receive full compensation for the extraction reduction. Full compensation means that the total income of a resource State generated by resource extraction must remain approximately equal to the income that would have been generated without agreement.

Compensation will be ensured through a fixed resource tonnage price, annually set by the Conference of the Parties on the basis of advice given by the Subsidiary Body for Scientific and Technological Advice. Compensation payments will be administered by the Subsidiary Body for Implementation.

At its first review session, the Conference of the Parties will make arrangements to implement these provisions.

ARTICLE 8 – DISTRIBUTION OF EXTRACTED RESOURCES TO USER STATES

The amount of extracted resources shall be distributed to user States on the basis of an equitable formula to be adopted by the Conference of the Parties at its first review session, and laid down in a separate Protocol.

User States shall pay a fixed tonnage price, decided in accordance with the procedure set out in Article 7.3 of this Agreement, for the amount of resources distributed to it. Payments are administrated by the Subsidiary Body for Implementation.

User States are allowed to trade the mineral resources distributed to them.

ARTICLE 9 – CONTROL OF TRADE WITH NON PARTIES

Each State party shall ban the export of geologically scarce minerals falling within the scope of this Agreement to any State not party to the Agreement.

Each State party shall ban the import of geologically scarce minerals falling within the scope of this Agreement from any State not party to the Agreement

For the purposes of this Article, the term "State not party to this Agreement" shall include, with respect to a particular mineral, a State that has not agreed to be bound by the Agreement

ARTICLE 10 – CONFERENCE OF THE PARTIES

1. A Conference of the Parties is hereby established.
2. The Conference of the Parties, as the supreme body of this Agreement, shall keep under regular review the implementation of the Agreement and any related legal instruments that the Conference of the Parties may adopt, and shall make, within its mandate, the decisions necessary to promote the effective implementation of the Agreement. To this end, it shall:
    (a)   Adopt the necessary Protocols to implement this Agreement, in particular with respect to priority-setting (Article 4), the phasing down scheme (Article 5), the extraction limitations (Article 6), a system for allocation of annual extraction quota

to resource countries (Article 6), the compensation of resource States (Article 7), and a system of distribution of extracted resources to user States (Article 8).

(b) Periodically examine the obligations of the Parties and the institutional arrangements under the Agreement, in the light of the objective of the Agreement, the experience gained in its implementation and the evolution of scientific and technological knowledge;

(c) Assess the implementation of the Agreement by the Parties and the overall effects of the measures taken pursuant to the Agreement;

(d) Review reports submitted by its subsidiary bodies and provide guidance to them;

(e) Agree upon and adopt, by consensus, rules of procedure and financial rules for itself and for any subsidiary bodies;

(f) Exercise such other functions as are required for the achievement of the objective of the Agreement as well as all other functions assigned to it under the Agreement.

ARTICLE 11 – SECRETARIAT

1. A secretariat is hereby established.
2. The functions of the secretariat shall be:
   (a) To make arrangements for sessions of the Conference of the Parties and its subsidiary bodies established under the Agreement and to provide them with services as required;
   (b) To compile and transmit reports submitted to it;
   (c) To facilitate assistance to the Parties, on request, in the compilation and communication of information required in accordance with the provisions of the Agreement;
   (d) To prepare reports on its activities and present them to the Conference of the Parties;
3. The Conference of the Parties, at its first session, shall designate a permanent secretariat and make arrangements for its functioning.

ARTICLE 12 – SUBSIDIARY BODY FOR SCIENTIFIC AND TECHNOLOGICAL ADVICE

1. A subsidiary body for scientific and technological advice is hereby established to provide the Conference of the Parties and, as appropriate, its other subsidiary bodies with timely information and advice on scientific and technological matters relating to the Agreement. This body shall be open to participation by all Parties and shall be multidisciplinary. It shall comprise government representatives competent in the relevant field of expertise. It shall report regularly to the Conference of the Parties on all aspects of its work.

2. Under the guidance of the Conference of the Parties, and drawing upon existing competent international bodies, this body shall:
   (a) Provide assessments of the state of scientific knowledge relating to the sustainable extraction of mineral resources;
   (b) Evaluate whether the extractable reserves remain in accordance with the assumptions that were the basis of the extraction reduction scheme;

(c)   Prepare scientific assessments on the effects of measures taken in the implementation of the Agreement;

(d)   Respond to scientific, technological and methodological questions that the Conference of the Parties and its subsidiary bodies may put to the body.

3. The functions and terms of reference of this body may be further elaborated by the Conference of the Parties.

ARTICLE 13 - SUBSIDIARY BODY FOR IMPLEMENTATION

1. A subsidiary body for implementation is hereby established to assist the Conference of the Parties in the assessment and review of the effective implementation of the Agreement. This body shall be open to participation by all Parties and comprise government representatives who are experts on matters related to the sustainable extraction of geologically scarce mineral resources. It shall report regularly to the Conference of the Parties on all aspects of its work.

2. Under the guidance of the Conference of the Parties, this body shall:

(a)   Administer payments made by user States in accordance with Article 8.2, and compensation payments made to resource States in accordance with Article 7.

(b)   Monitor compliance by the resource States with the extraction limitations imposed on the basis of Article 6.

(c)   Assess the overall aggregated effect of the steps taken by the Parties to reduce the extraction of mineral resources in accordance with the extraction limitations agreed on by the Parties, on the basis of Article 6 of the Agreement.

(d)   Assist the Conference of the Parties, as appropriate, in the preparation and implementation of its decisions.

ARTICLE 14 – FINANCIAL ARRANGEMENTS

The operational expenses of the Secretariat and the various subsidiary bodies established on the basis of this agreement shall be covered by a transaction fee imposed on the user States. The transaction fee shall be calculated as a percentage of the fixed tonnage price per mineral. The Conference of the Parties will decide on the amount of the transaction fee per mineral, taking into account the number of resource States, the total size of the market, and the number of scarce resources for which extraction reduction is required.

ARTICLE 15 – INTERNATIONAL COOPERATION

Parties shall share information and knowledge regarding the reserves of extractable resources on their territory with other Parties, as well with the Subsidiary Body for Scientific and Technological Advice.

ARTICLE 16 – SETTLEMENT OF DISPUTES

1. In the event of a dispute between any two or more Parties concerning the interpretation or application of the Agreement, the Parties concerned shall seek a settlement of the dispute through negotiation or any other peaceful means of their own choice.

2. When ratifying, accepting, approving or acceding to the Agreement, or at any time thereafter, a Party may declare in a written instrument submitted to the Depositary that, in respect of any dispute concerning the interpretation or application of the Agreement, it recognizes as compulsory *ipso facto* and without special agreement, in relation to any Party accepting the same obligation:

   (a) Submission of the dispute to the International Court of Justice, and/or

   (b) Arbitration in accordance with procedures to be adopted by the Conference of the Parties as soon as practicable, in an annex on arbitration.

3. The provisions of this Article shall apply to any related legal instrument which the Conference of the Parties may adopt, unless the instrument provides otherwise.

ARTICLE 17 – AMENDMENTS TO THE AGREEMENT

1. Any Party may propose amendments to the Agreement.
2. Amendments to the Agreement shall be adopted at an ordinary session of the Conference of the Parties.
3. The Parties shall make every effort to reach agreement on any proposed amendment to the Agreement by consensus. If all efforts at consensus have been exhausted, and no agreement reached, the amendment shall as a last resort be adopted by a three-fourths majority vote of the Parties present and voting at the meeting.

ARTICLE 18 – PROTOCOLS

1. The Conference of the Parties may, at any ordinary session, adopt protocols to the Agreement.
2. The requirements for the entry into force of any protocol shall be established by that instrument.
3. Only Parties to the Agreement may be Parties to a protocol.

ARTICLE 19 – DEPOSITARY

The Secretary-General of the United Nations shall be the Depositary of the Agreement and of protocols adopted in accordance with Article 15.

ARTICLE 20 – SIGNATURE

This Agreement shall be open for signature by States Members of the United Nations or of any of its specialized agencies or that are Parties to the Statute of the International Court of Justice.

ARTICLE 21 – RATIFICATION, ACCEPTANCE, APPROVAL OR ACCESSION

The Agreement shall be subject to ratification, acceptance, approval or accession by States. It shall be open for accession from the day after the date on which the Agreement is closed for signature. Instruments of ratification, acceptance, approval or accession shall be deposited with the Depositary.

ARTICLE 22 – ENTRY INTO FORCE

The Agreement shall enter into force on the ninetieth day after the date of deposit of the fiftieth instrument of ratification, acceptance, approval or accession.

ARTICLE 23 – RESERVATIONS

No reservations may be made to the Agreement.

ARTICLE 24 – WITHDRAWAL

At any time after three years from the date on which the Agreement has entered into force for a Party, that Party may withdraw from the Agreement by giving written notification to the Depositary.

ARTICLE 25 – AUTHENTIC TEXTS

The original of this Agreement, of which the Arabic, Chinese, English, French, Russian and Spanish texts are equally authentic, shall be deposited with the Secretary-General of the United Nations.

REFERENCES IN ANNEX V

Brunnée, J., 2007, Common areas, common heritage and common concern in D.Bodansky, J.Brunnée and E.Hey (eds) Oxford Handbook of International Environmental Law, Oxford University Press, Oxford

Cottier, T., Aerni, P., Matteotti, S., de Sépibus, J., Shingal, A., 2014, The principle of Common Concern and Climate Change, NCCR Trade regulation, Swiss National Centre of Competence in Research, Working Paper No 2014/18, June 2014,(http://www.nccr-trade.org/fileadmin/user_upload/nccr-trade.ch/wp5/publications/Cottier_et_al_Common_Concern_and_Climate_Change_Archiv_final_0514.pdf)

Perez, F.X., 2000, Cooperative Sovereignty: From Independence to Interdependence in the Structure of International Environmental Law, Kluwer Law International, The Hague

Sands, P., Peel, J., Fabra A., MacKenzie, R., 2012, Principles of International Environmental Law, Cambridge University Press

Schrijver, N., 1997/2008, Sovereignty over natural resources: balancing rights and duties, 1997, reprinted in 2008, Cambridge University Press, Cambridge

Stone, C.D., 2004, Common bit differentiated responsibilities in international law, The American Journal of International Law 98,276-301

United Nations, 2015, http://legal.un.org/avl/ha/ga_1803.html, 5 October 2015