ECO-EFFICIENCY IN INDUSTRY AND SCIENCE

VOLUME 19

Series Editor: Arnold Tukker, TNO-STB, Delft, The Netherlands

Editorial Advisory Board:

Martin Charter, Centre for Sustainable Design, The Surrey Institute of Art & Design, Farnham, United Kingdom
Gjalt Huppes, Centre of Environmental Science, Leiden University, Leiden, The Netherlands
Reid Lifset, Yale University School of Forestry and Environmental Studies, New Haven, U.S.A.
Theo de Bruijn, Center for Clean Technology and Environmental Policy (CSTM), University of Twente, Enschede, The Netherlands

The titles published in this series are listed at the end of this volume.
Sustainable Metals Management
Securing our Future - Steps Towards a Closed Loop Economy

Edited by

Arnim von Gleich
University of Bremen, Germany

Robert U. Ayres
INSEAD, Fontainebleau Cedex, France

and

Stefan Gößling-Reisemann
University of Bremen, Germany

Springer
Contents

Acknowledgements vii
Foreword ix
Preface xi

Sustainability and Metals 1
1 Outlines of a Sustainable Metals Industry Arnim von Gleich 3
2 Metallic Raw Materials – Constituents of our Economy Friedrich-Wilhelm Wellmer, Markus Wagner 41

Economy, Thermodynamics, and Sustainability 69
3 Aluminium W. Kuckshinrichs, W.R. Poganetz 71
4 Prospects for a Sustainable Aluminum Industry P.N. Martens, M. Mistry, M. Ruhrberg 97
5 Towards a Sustainable Copper Industry? Frank Messner 113
6 An Application of Exergy Accounting to Five Basic Metal Industries Robert U. Ayres, Leslie W. Ayres, Andrea Masini 141
7 Entropy as a Measure for Resource Consumption—Application to Primary and Secondary Copper Production Stefan Gößling-Reisemann 195
8 Dematerialization of the Metals Turnover Sten Karlsson 237
<table>
<thead>
<tr>
<th>Contents</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>9  <strong>Sustainability Strategies in Field Trial</strong></td>
<td>A. von Gleich, M. Göttschick, D. Jepsen, K. Sanders 249</td>
</tr>
<tr>
<td><strong>Metals Materials Flows</strong></td>
<td></td>
</tr>
<tr>
<td>10 <strong>Limits of Metal Recycling</strong></td>
<td>Georg Rombach 295</td>
</tr>
<tr>
<td>11 <strong>Secondary Materials in Steel Production and Recycling</strong></td>
<td>D. Janke, L. Savov, M.E. Vogel 313</td>
</tr>
<tr>
<td>12 <strong>Optimisation Possibilities of Copper Smelting and -Processing</strong></td>
<td>Joachim Krüger 335</td>
</tr>
<tr>
<td>13 <strong>The Hamburger Aluminium-Werk GmbH’s Contribution to a Sustainable Closed Loop Aluminium System</strong></td>
<td>Hans-Christof Wrigge, Hans Albers 347</td>
</tr>
<tr>
<td><strong>Ecological, Social, Toxicological, and Cultural Effects</strong></td>
<td></td>
</tr>
<tr>
<td>15 <strong>Heavy Metals in the Netherlands</strong></td>
<td>Ester van der Voet, Jeroen B. Guineé, Helias A. Udo de Haes 377</td>
</tr>
<tr>
<td>16 <strong>Toxic Effects of Metals and Metal Compounds</strong></td>
<td>Peter Wardenbach 393</td>
</tr>
<tr>
<td>17 <strong>Metallurgical Plants and Chemicals Industry as Challenges to Environmental Protection in the 19th Century</strong></td>
<td>Arne Andersen 403</td>
</tr>
<tr>
<td>18 <strong>Copper Mining and Metallurgy in Prehistoric and the More Recent Past</strong></td>
<td>Joachim Krüger 417</td>
</tr>
<tr>
<td>19 <strong>Social and Ecological Consequences of the Bauxite-Energy-Aluminium Product Line</strong></td>
<td>Clarita Müller-Plantenberg 449</td>
</tr>
<tr>
<td>20 <strong>The Ok Tedi Pages</strong></td>
<td>Klaus Baumgardt 483</td>
</tr>
<tr>
<td><strong>Product Design and Use</strong></td>
<td></td>
</tr>
<tr>
<td>21 <strong>Metals and Plastics - Competition or Synergy?</strong></td>
<td>Martin Baitz, Marc-Andree Wolf 519</td>
</tr>
<tr>
<td>22 <strong>Sustainability-Optimised Material Selection and Product Design at Audi</strong></td>
<td>Siegfried Schäper 535</td>
</tr>
<tr>
<td>23 <strong>Recycling of Electronic Waste Material</strong></td>
<td>Matthias Teller 563</td>
</tr>
<tr>
<td>24 <strong>Sustainable Development of Microelectronics Industry</strong></td>
<td>Hansjörg Griese, Jutta Müller, Herbert Reichl, Karl Heinz Zuber 577</td>
</tr>
<tr>
<td>25 <strong>The Role of Metals for Designing Products and Solutions in the Context of a Sustainable Society</strong></td>
<td>Walter R. Stahel 593</td>
</tr>
</tbody>
</table>
Acknowledgements

We would like to thank the Hamburg University of Applied Sciences (HAW) for their support in hosting the lecture series that led to this publication and their financial support in making this book. Furthermore, we would like to thank the German Ministry of Education and Research (BMBF), the Körber Foundation, and the Ditze Foundation for their generous sponsorship.

The completion of this book was only possible with the help of Dipl. Ing. Marco Braun, Mrs. Marlies Timmermann and the translators Michael Forrest, Anne Wallace, Antoinette Bismark, and Parisa Fathi. They have our sincerest gratitude.

The Editors
What’s in a name?

What, in particular, is ‘metals management’ all about? I suspect that my colleagues assumed that I would have a good answer, given that the endowed Sandoz Chair I occupied from 1992 until my retirement in 2000 was entitled “Environment and Management”, and at INSEAD I created a Center for Management of Environmental Resources (CMER). Metals are a subset of resources, et voila!

However, in all honesty, management, as such, was never my core competence (to use another phrase popularized by business schools). Here comes the shocking secret. We used the word management in those titles because INSEAD is a business school where everything has to have an application to business. For my colleagues at INSEAD management is what we supposedly teach. Good management, they (we) think, distinguishes successful enterprises from unsuccessful ones. For some of our graduates, management is what they give professional advice to corporate clients about. For the rest of our graduates it is the umbrella word that describes their choice of career.

The implication conveyed by our choice of words is that metals can be regarded as one category of environmental resources, and that resources – including environmental resources – can be managed, in somewhat the same way that a corporation can be managed. It is not even too far-fetched to suggest that long run sustainability might be a management problem. However, there is a crucial difference between managing an enterprise, which has a hierarchical structure, and managing a system or a category of resources, where nobody is in charge. It is sometimes tempting to imagine that there exists, or could exist, a benign economic or environmental ‘Czar’ and to discuss the issues such a godlike person would have to contend with. This is why so many economists still think in terms of optimizing models. However the second shocking secret is that, while such models might have some value to a hypothetical central planner, they have virtually no relevance to the real world. This is why no such models are described in this book.
We start from the clear understanding that we are talking about a system involving one category of resources – metals – characterized by certain physical attributes. The system includes many actors. Among them are a number of competing private enterprises, consumers, government agencies and special interest groups. In such a heterogeneous system there is no central management authority. Indeed there is no ‘center’. Heterogeneity per se is the most important attribute of the system we have undertaken to consider, in this book. It is not a deficiency. It is the ‘name of the game’.

To be sure, some of the enterprises that mine, or smelt, or shape metals are themselves hierarchically organized, with central management. Those individual enterprises can to some extent, think in terms of optimization, subject to a host of external constraints. Nevertheless, there is a significant range of disagreement among the ‘would-be optimizers’ over objective functions and methodologies.

Much of this book is about the larger system in which the enterprises must function. In some respects I would have preferred to entitle this book “The Industrial Ecology of Metals”, to distinguish it from books specifically about mining, metallurgy, or applications, economics and markets. However, as a practical matter, the market for a book about metals, with the word “ecology” in the title would be very limited, if only because that title suggests a focus mainly on flows, wastes, recycling and sustainability. This book certainly includes a number of discussions of those issues, from various points of view. But it also covers a broader spectrum of topics, including some interesting historical background, trade and macroeconomic aspects, thermodynamic analysis, life cycle studies of particular metals, case studies that highlight the problems of making an extractive industry sustainable, and broader policy-relevant issues.

With respect to some of the ‘core issues’ of ‘Industrial Ecology’ like accounting, modeling and assessing material streams and resource use this book indicates an important step which is currently being taken: the step from quantity to quality.

Of all ‘non regenerative resources’ metals have the highest potential for a more sustainable closed loop economy, but we still are not able to adequately use this potential. This is not only a problem of still too high dissipative losses and still too low recycling rates. In the long run, the biggest problem of a closed loop metals economy will be the loss of quality, the level of recycling (products, components or materials) and the contamination and degradation of metals streams by tramp elements.

Robert U. Ayres, Gothenburg
Preface

According to the different view points one can assume when analysing the meaning and the impacts of metals in the technosphere and the environment, the articles in this book are grouped under five headings. After an introductory section detailing the concepts of a sustainable metals management and a survey of the historic development of metals production and use, economic and thermodynamic aspects of a sustainable metals management are the subject of seven articles in the second section. In a following section, the actual material flows of metals are investigated in another five articles. The ecological, social, toxicological and cultural effects of metals are discussed in further six articles in the next section, while in the final section five articles are dealing with the meaning of metals for a sustainable product design and use. “The articles represent the current state of research in their field. However, due to the long production process for this book, references to the legislation process of some laws and regulations might have become outdated by now. We have to apologize for that.”

In the introductory section, von Gleich presents a comprehensive summary of the status of the metals industry and the challenges it is facing on the way to sustainability. His analysis reveals that one of the most promising approaches to the multifaceted problems of a sustainable metals management is recycling, which has to include securing the quality of metals streams and avoiding dissipative losses. Good recyclability was always a distinctive feature of metals. Among other advantages, this made them superior and sought after materials even more than 5000 years ago. Elaborating more on this, Wellmer and Wagner take us on a journey through the historical development of metals in our economy, from the stone age and its fascination with precious metals, to the use of metals for making tools and weapons in the bronze age, and eventually to modern times and the importance of metals in the context of a sustainable development.

In the second topical section, Kuckshinrichs and Poganietz are focussing on aluminium, discussing the development of the production and trade of bauxite, alumina, and primary aluminium on a global scale. They analyse the determinants for this development and use them for creating a quantitative model simulating the trade and production in the current decade. In another article, Martens, Mistry & Ruhrberg highlight the influence quantitative modelling and resource management systems can have on the resource utilisation in the modern aluminium industry.
They present models of the current state and future scenarios with a specific focus on material and energy flows. The authors then describe the development of management systems from reactive “end-of-the-pipe” thinking to proactive approaches on the way to a sustainable aluminium industry leading to dramatic changes in the ways the industry sees itself. On a similar note, but moving on towards copper, Messner presents in his article an analysis of the trends in the global copper industry concerning resource use, environmental impacts and possible substitution processes. The final question he tackles is “Can the copper industry become sustainable?”. With the question of substitution the qualitative aspects of the materials and products come into view, broadening the scope of the hitherto rather quantitative analysis. Another step in the direction of combining qualitative and quantitative analysis is the introduction of thermodynamic aspects to material and energy flow analysis. In their article, Masini, Ayres & Ayres apply the exergy concept to five basic metal industries in the U.S. on an “ore-to-ingot” basis. As a feature of thermodynamic analysis, this survey highlights the life cycle stages with the highest consumption of natural resources (as opposed to identifying only the stages with the highest throughput of matter and energy) and thus pinpoints the starting points for an overall process optimisation. In addition, the five metals can be ranked according to the exergy losses occurring in their production, leaving aluminium at the top and steel at the bottom of the chart. Using an alternative approach, Gößling-Reisemann analyses the entropy production of copper making from primary and secondary sources on a plant level (i.e. from gate-to-gate). Just as exergy loss, entropy production is the physical measure for resource consumption and at the same time a measure for the quality of the processes. The entropy analysis thus reveals process inefficiencies and measures the actual transformation of resources inside the processes. The author then compares his results with the one from the more traditional exergy analysis and discusses the applicability of the concept, yielding some insight into the interpretation of consumption as a qualitative change in the material and energy flows. Both approaches, exergy and entropy, are examples for the shift towards qualitative analysis of the industrial metabolism that is currently developing in the scientific community. In the following article, Karlsson is investigating the prospects for dematerialising the metals turnover of the technosphere. He further tackles the question of the meaning of dematerialisation for solving the perceived environmental problems, such as emissions. Karlsson describes current flows of metals, rates of extraction, current reserves, and rates of consumption for the major metals, yielding limiting factors for potential future technologies, especially in the energy sector. In addition, he shows the importance of a metal flow quality management in order to avoid down-cycling. Following a similar line of thought, von Gleich discusses the gradual degradation and dissipation of non-renewable resources in the technosphere. He then presents results from a research project in the region of Hamburg dealing with the optimisation of material flow management, regional cooperation, and product line management. In conclusion he introduces a criteria matrix for integrated sustainability assessment and proposes an extension of the life cycle assessment approach to include entropy analysis as a tool for assessing the qualitative changes in materials and energy.

The next section on material flows is started by an article by Rombach on the limits of metal recycling. The article describes and evaluates the recycling potentials of copper, zinc, and aluminium and sheds some light on the limiting factors. Again,
it transpires that it is the quality of material flows and the way the materials are handled which is of great importance in this context. Rombach also clarifies the often misleadingly interpreted terms recycling quota and recycled content. The focus remains on materials quality in the following article by Janke, Savov & Vogel: they describe the problems arising from tramp elements in the steel cycle. These elements are of great importance in steel making, since they do not only appear in ever growing amounts, due to the increasing demands on material quality, but also they are fully returned to the production process, due to the almost complete recycling of scraps. The authors describe the effects of impurities on the steel quality and discuss methods for removal. The discussion is not limited to the actual products of steel making, but also extends to the by-products and wastes. This is another example for the necessity of an integrated approach to the management of metals. Moving on towards the quality of processes, Krüger gives us an overview of the optimisation potentials of copper making and processing. While it was energy consumption and emissions which were the main targets between 1950 and 1980, it is the process control which is mostly being optimised since then. Krüger shows how, with increasing efficiency of the processes, the personnel needed for operation is decreasing. A typical win-lose situation in terms of the three-dimensional sustainability framework. Here we already get a glimpse of the complexity of sustainable development, a topic that is more elaborated on in the following section. This section, however, moves on with an article from the viewpoint of a metals manufacturer: Wrigge & Albers present the contributions to a sustainable aluminium cycle made by the Hamburger Aluminium Werke, one of the largest German aluminium smelters. With the plant being located close to the metropolitan region of Hamburg, they needed to implement emission control at an early stage and are still working on the reduction of resource use and emissions. As they argue, it is the recyclability of the metal which makes it a well-suited choice in terms of sustainability. However, the technical properties of a material alone cannot suffice to assess its recycling potential and the suitability for sustainable development. It is imperative to look at recycling from an economy-wide perspective. This is the focus of the article by Scharp & Erdmann, who discuss strategies for a sustainable development and use of copper. Alongside with the consistency and sufficiency approach, the authors find efficiency to be the most promising route towards a sustainable development. They share the view that the recyclability of a metal is essential for its efficient use, but the actual recycling rate is also heavily influenced by economic factors, which is demonstrated here.

The fifth topical section deals with ecological, social, toxicological, and cultural effects of metals management. Here the true complexity of sustainability shines through. While the material flows covered in the previous section can be described and evaluated in mostly technical and economic terms and with high precision, the effects discussed in this section are rather difficult to measure and often interrelated. The first article by van der Voet, Guinée & de Haes analyses the fate of four heavy metals in the Netherlands. Though it was believed that these metals are well under control, the authors conclude the contrary and identify the continuous rise of the metal contents in stocks of products as the main cause for a predicted risk for the health of humans and the eco-systems in the Netherlands. Wardenbach goes into more detail when presenting the effects of metals on human health. He gives insight into the toxic effects and potential diseases resulting from short-term and prolonged
exposure to metals. There is an ongoing discussion about the classification of alloys with respect to their toxicological properties. Wardenbach presents a classification scheme which could help clarify this question. The topic of environmental and human health risks is continued with an article by Andersen, who sheds some light on the historical development of how the metallurgical and chemical industries dealt with environmental and health issues. Andersen shows how the thinking in terms of end-of-the-pipe technology and emission and exposure limits, which is still prevalent today, has come about in the second half of the 19th century. As metal ores are mostly mined, and also partly processed, in developing countries with little or no control over social, environmental and health effects, a sustainability related analysis of metals management must include the production stages in these countries. Müller-Plantenberg presents such analyses for the bauxite-energy-aluminium product-line in Brazil, Surinam, and Venezuela. The author investigates every stage of the production of aluminium in the region with regards to the ecological, economic, and social impacts, including health and safety of workers, using the product-line-analysis tool. She concludes that it is mandatory to include the people affected in the decision making process if sustainable development is aimed at. Here again we have an indication for the complexity of sustainability and its multi-dimensionality, inter-linking economic, social, environmental and toxicological effects. A vivid example of how the effects of ore mining in the developing countries can be felt by a metal producer in the industrialised world is given in the article by Baumgardt. The author reports on an assessment of the social effects of copper ore mining in Papua New Guinea carried out by a delegation of a German NGO. Since the NGO also became shareholder of the copper smelter in question, they could exert a minimum, but effective, amount of pressure on the management and thus reminded them of their responsibility for impacts induced by ore mining in Papua New Guinea. It is remarkable that the copper smelter’s management was willing to join the NGO on a journey to the mining sites, and agreed to use its power as a customer to improve the situation. Though it remains to be seen if this potential influence is suitably used, these events show how a linkage between shareholders and stakeholders can be brought about.

An opinion shared by many of the authors in this book is that given the limited influence the industry and the consumer in the industrialised countries have on the overall metal cycle, the main concept for achieving sustainability is the sustainable handling of metals within the respective economy. It might be difficult to exert pressure on foreign governments or remote mining companies, but it is surely in the reach of local decision makers to design a management framework that helps minimising the impacts from metal production and use. The routes towards this goal can be manifold: increasing efficiency, substitution of metals by other materials, increasing recycling, prolonging the use phase of metals, et cetera. The last section on this book focuses on some of these issues. It is started off by an article comparing metals and plastics as the chosen material for different applications using an extended life-cycle analysis approach, called life-cycle engineering. The authors, Baitz & Wolff, present case studies which nicely show the areas of competition, and those of synergy of the two materials. Their analyses thus demonstrate how the material choice influences the overall environmental impacts of a product. In connection with the included economic and technical feasibility analysis these results can be taken as grounds for sustainability orientated decision making. Since
the analysed environmental effects are not limited to the local environment, they are usually rather global in nature, the decisions derived from this approach will surely influence the environmental burden in the mining countries. Even on a smaller scale, life-cycle analysis always enhances the transparency of production processes, which in most cases leads to an increased efficiency and decreased emissions. In the following article, Schäper uses an energy focussed life-cycle analysis to demonstrate the superiority of light-weight vehicle construction. He presents some evidence, that in specific AUDI models the increased energy consumption for the production of aluminium based car bodies is over-compensated by decreased fuel consumption during the use phase. However, he argues that these advantages of light-weight construction might be impaired by legislative attempts at increasing overall recycling rates using fixed weight-based ratios. This conflict can surely not be solved by focusing on energy and recycling rates alone, other life-cycle impacts have to be included to make reasonable decisions and construct suitable policies in this field. Recycling, on the other hand, is one of the most promising tools for enhancing the sustainability of metals management. There is no question about whether to recycle or not, only about where and to what extent. Besides the life-cycle considerations mentioned above, these questions also have a technical aspect. Especially in the electronics sector there are some hurdles to overcome with respect to recycling. Teller discusses these difficulties and presents some technical solutions in his article on recycling electronic wastes. Though electronic wastes only comprise a few percent of the total amount of wastes, they have quite some importance regarding their role as a source for valuable non-ferrous metals, as the author points out. With regards to gold, palladium, and platinum, there is no doubt about the justification of recycling, ecologically as well as economically. However, as the article shows, the prevailing trends of miniaturisation and integration make recycling and re-use more difficult, even for such valuable metals. A different aspect of metals in electronic products is their toxicity, which is the main topic of the article by Griese, Müller, Reichel & Zuber. Especially with the growing share of products sold in countries with little or no end-of-life policy this issue grows in importance. In Europe and the USA it is the legislation, banning certain toxic materials in products, that is driving the development of substitution materials. This article describes the search for less toxic interconnection technologies which can replace the lead solders now in practice. It further reports on the development of cyanide-free gold plating and more environmentally friendly recycling processes. The authors conclude that in the future electronic products must take environmental concerns much more serious. Stahel, in the following article, takes this kind of analysis even one step further and predicts some major challenges for the metals industries with respect to recycling as a consequence of new and emerging technologies, like nano-technology, thin-film technology, and the use of metal powders. With the increasing sophistication of processes and products, he argues, also grows the loss of metals to the environment, with sometimes negative effects on the health of eco-systems and humans. He votes for the shift from a throughput oriented “river economy” to a service and knowledge oriented “lake economy”.

This brings us back to the mentioned shift from focussing on quantity to focussing on quality of material streams and processes. In a service oriented economy it is much more the quality of the service that is defining its value than the
quantity of the material flows involved. In this manner a development towards a more sustainable metals management seems possible.

Stefan Gößling-Reisemann
SUSTAINABILITY AND METALS
Chapter 1

OUTLINES OF A SUSTAINABLE METALS INDUSTRY

Arnim von Gleich

University of Bremen

1. METALS AS A MATERIAL AND A RESOURCE

The metals group comprises approximately two-thirds of all chemical elements occurring naturally on earth. Only a very few of them – and in particular precious metals – also occur in nature in ‘native’ metal form. Metals are valued especially as materials. The most important properties of metals include their brilliance (metallic brilliance, high reflective characteristics), good electrical and heat conductivity, high strength, hardness and toughness as well as good plastic formability properties. These properties are based on the specific form of the metallic bond, in which the atoms involved in bonding release their external electrons in a joint ‘electron gas’. They are only loosely bonded in the gas and can thus be easily moved. The ‘electron gas’ in turn causes the atom bodies to be tightly packed in crystal lattices, which – in combination with existing lattice defects – has the effect of good formability. The ability to form alloys, likewise typical of metals, is due to the fact that metal atoms in the lattice can easily be replaced by other metals within certain limits.

Metals can be categorised in accordance with their specific weight and their specific melting point. Technically important light-weight metals include e.g. magnesium, aluminium and titanium. Heavy metals with a low melting point include e.g. zinc, cadmium, tin, lead and mercury. Heavy metals with a high melting point include e.g. iron, chromium, cobalt, nickel, platinum and palladium, and those with a very high melting point include tungsten, tantalum, molybdenum and niobium. The precious metals silver, gold and the group of platinous metals are characterised by especially good resistance to corrosion.
1.1 Fascination and advantage of metals

Metals have played an increasingly important role in human history. Native metals seem to have fascinated people right from the very start. In many cultures gold has become synonymous with value. Money or currency developed on the basis of metallic coins. It was not until the end of the 20th century that the ‘value of money’ was disconnected from the ‘value of gold’. Native gold, silver and copper was able to be processed into jewellery using comparatively simple technical methods\(^1\). The early development of metallurgy, the ability to extract copper and produce bronze (which is a much harder copper-tin alloy) and subsequently iron from ores are milestones in human history, with the result that entire eras were named after these materials\(^2\), such as the Stone Age, followed by the Bronze Age (from around 2700 B.C. to around 1200 B.C.) and the subsequent Iron Age. While the use of bronze still concentrated largely on religious objects, jewellery and weapons, the main use for iron and steel, besides being used to make weapons, was increasingly for tools and objects of utility.

Regarding its cultural, technical and economic significance, the Iron and Steel Age appears to have surpassed its zenith now at the start of the third millennium. For years now the transition to the ‘information society’ has been the subject of much discussion, and copper and silicon as the basis of that are very important. Coal, iron and steel were, however, at the heart of the industrial revolution in the first half of the last century. They shaped entire industrial conurbations, such as the Ruhr Basin in Germany. Here too weapons technology played an important role for further technical developments. Vehicles and aircraft construction are largely the reason for the increased importance of light metals.

With the ability to generate and use electricity, the electrical conductivity of metals, and especially copper, gained importance at high speed. Silver, copper, gold and aluminium are among the best electrical conductors. For technology and goods, copper is generally used, or in some instances also gold and silver for especially ‘delicate’ contacts in computer technology, and aluminium in cross-country transmission lines for reasons of weight and cost. Other, in some cases much rarer, metals such as selenium, gallium, indium and germanium, are used in electronics and semi-conductor technology, telecommunications, consumer electronics and IT as well as photovoltaics. Platinum group metals are becoming more and more important in their areas of use as catalytic converters (e.g. in chemical process technology, emission protection and presumably also in fuel cells).

Aluminium, titanium and magnesium became more important with the advent of light-weight construction techniques, as a way to reduce energy consumption and emissions. And for high-performance uses and/or for extreme conditions (e.g. with regard to temperature, conductivity and corrosiveness) more and more ingenious alloys were developed. In addition to classic alloys such as vanadium, chromium, nickel, manganese, tungsten and molybdenum, other metals are also increasingly used, such as antimony, lithium, niobium, hafnium, yttrium and tantalum, which are used more rarely today. Important trends, which are already evident today and which may create further diversification in demand within the metals group, are also ‘intelligent’, i.e. smart materials in the area of structural materials, the use of their
electromagnetic properties in the area of functional materials and not least of all the use of the catalytic functions of metals in chemical reactions.

Three aspects thus become evident: firstly, a shift in the technical and economic relevance within the metals group; secondly, an increase in the variety of uses for metals (and of metals in use); and thirdly, despite certain opportunities to substitute metals (e.g. by plastics) and despite improvements in the resource efficiency and miniaturisation in electronics, the manufacture and use of metals will probably continue to increase as a whole even in the ‘electronic age’. All indications point to continued growth in demand for metals, within the industrialised nations and especially in the course of ‘follow-up-industrialisation’ and/or equalising development in the newly industrialising countries and in the developing countries. Demand for metals will continue to increase both quantitatively and qualitatively; greater volumes and a wider range of metals and metal alloys will be required. This raises the question whether and how such future requirements can be satisfied in a sustainable way.

Material flows – development trends in the manufacture and use of metals

In 1998 a total of approximately 320,000 million tonnes of non-renewable minerals and energy resources were excavated and recorded statistically. Of this figure, approximately 6,300 million tonnes were metals, i.e. almost 2% of the total volume. By way of comparison: fossil energy sources alone accounted for 32.9%. The fact that metals only account for 2% in weight of total global output may initially be a surprising fact. However, this figure only shows the actual volumes of metals excavated. It does not account for e.g. volumes of excavated material, which has to be removed and/or separated in order to excavate the ore, or the volumes of non-metalliferous accompanying stones, the water used and the sludge from the enrichment plants as well as the corresponding accompanying material flows and the use of energy. The entire ‘ecological rucksacks’ in metal excavation are thus not contained in these figures. Depending on accessibility, extraction technology and especially the metal concentration of ore, an ecological rucksack to the order of 1:350,000 for gold and platinum, 1:7500 for silver, 1:420 for copper and 1:14 for iron has to be added to the quantities of extracted metals.

If, by way of comparison, the added value in relation to the excavated resource quantities is shown, it can be established that the energy and materials expenditure connected with prospecting and processing primary materials is at least partly reflected in the value. The approximately 320,000 million tonnes of non-renewable minerals and energy sources excavated in 1998 had an approximate value of € 8.2 billion, of which metals accounted for almost 8%. If the percentage proportion of metals in the total volumes of all mineral resources excavated is compared, i.e. in this case the 2% proportion of the total volume, with the 8% value of metals of the total value, the volume/value ratio is 1:4. Fossil energy sources account for 32.9% of the total volume and 88.5% of the total monetary value. This is equivalent to a calculated volume/value ratio of 1:2.7. The volume/value ratios in the case of copper (1: 3000) and diamonds (1:7900) are particularly remarkable, which at least partly also reflects the low concentrations in the bedrock.

The development towards these current material volumes and production volumes is characterised by generally accelerating growth, see figures 5-2 and 5-3 in
the article by Messner in this volume (pp 118f). This growth in production volumes more or less closely follows general economic growth.

Neither economic growth nor the development of related material and energy volumes were so constant, as is suggested by average growth rates. In addition to recurring historic (i.e. wars) and economic slumps or boosts in growth, both developments show two particularly intensive growth phases and a typical slump. The following aspects are especially significant:
1. The phase of primary intensive industrialisation as of the second half of the 19th century.
2. The steepest growth phase to date after the Second World War in the 1950s and 1960s.
3. A slump in this steep rise in the mid 1970s. This slump is often associated with the oil price shock (or oil crisis, as it was referred to) followed by a slump in the economic climate.
4. One stage during the 1990s, of which some authors believe that they were able to observe a trend towards decoupling economic growth from the related consumption of primary materials and energy8.

From aspects of sustainability, i.e. especially relating to the consumption of non-renewable resources and related emissions and waste, such decoupling of economic growth from the consumption of resources would evidently be extremely welcome. This hope is based on a whole series of assumptions:
1. The economic structural change causes a shift in focus to the tertiary sector, while the development towards a service society is linked with a reduction of material and energy flows and the related environmental burdens (cf. Jähnicke et al 1992).
2. The trend towards ‘dematerialisation’ of economic activities is a characteristic feature of the information society, together with miniaturisation, which is clearly present in information technology (cf. Heiskanen et al 2000 and 2001).
3. Rationalisation endeavours following general economic logic also include environmental and resource consumption. They are more directed at increasing efficiency with regard to substance and energy flows, i.e. improvement of resource efficiency by better exploitation of resources, higher efficiency levels, higher recycling rates, intensification of usage and extension of the service duration of products (cf. Schmidt-Bleek 1994, Stahel 1994 and 1999).
4. Basic innovations (change of technological path) open up new opportunities for very far-reaching improvements of resource productivity including the ‘general learning curve’, which starts again after every innovation, which serves to improve efficiency progressively (cf. Huber 2000).

However, the reality is unfortunately different. Resource consumption continues to rise (at least on a global level). These growth rates still create the most serious challenges for each strategy in relation to a sustainable metals industry both under the aspect of resource protection and also with a view to the related environmental burdens. The shift in economic structures towards a greater significance of services, the process of computerisation and miniaturisation, basic innovations, learning curve
effects and a gradual improvement of resource productivity are in fact all conceivable and also observable processes in some cases. However, all previous attempts to demonstrate in a significant way a ‘general’ disengaging of economic growth from the consumption of resources also from a statistical aspect do not appear to be able to withstand critical examination of the methods involved (cf. Cleveland, Ruth 1999). This means that economically immanent trends can occasionally comply with sustainability objectives in certain instances. However, it is and will remain highly improbable that sustainability problems will resolve themselves in this way.

How much material consumption in the global economy has increased particularly in the past five to six decades can be illustrated by the indication that, according to current knowledge, humanity has consumed more mineral primary materials since the end of the Second World War than it had done in the course of its entire history prior to that. A correspondingly longer-term consideration of the development of global copper production in the past 5000 years is shown in a logarithmic presentation in figure 1-1.

![Figure 1-1. Global development of copper extraction in the past 5000 years (from: Ayres et al 2002 on the basis of Landner; Lindeström 1999).](image)

Figure 1-2 shows a development of copper production in the ‘western world’ between 1810 and 1995 based on more reliable statistics.
Figure 1-2. Copper extraction between 1810 and 1999 in the ‘western world’ (from: Ayres et al 2002 on the basis of Landner & Lindeström 1999).

Figure 1-3 shows global primary copper production in the 20th century. The major boost to growth since the start of the 1950s, the slump in the 1970s and after that the comparatively constant growth are quite clearly visible particularly in these two diagrams (1-2, 1-3).

Figure 1-3. Global primary copper production in the 20th century (x-axis = annual figures) (from: Handke 2002)

It is striking that all these prominent boosts to demand were not linked to corresponding price rises. On the contrary, a signal of economic shortages is absolutely not in evidence. The inflation-adjusted price trend for copper demonstrates — albeit with major leaps upwards and downwards — a continuous downwards trend as a whole from 1870 to 2000 (cf. figure 1-4).
Copper-producing enterprises have thus continued to increase their production and have rather accepted a trend of falling prices. However, they were able to (and also had to) once again compensate for the trend of falling prices linked with a corresponding increase in supply and intensification of competition by increasing their productivity, especially with economies of scale, but also with higher output rates of copper from ore. The fact that this has apparently succeeded is all the more remarkable as during the same period the average copper content in the ores being excavated declined significantly in the USA between 1900 and 2000 from 2.1% to 0.8%, and the world average between 1949 and 2000 declined from 4.0% to 1% (cf. Wellmer; Dalheimer 2001).

In order to be able to assess and/or judge better the question as to future requirements and future availability of metallic resources, we can firstly look at historical examples – i.e. metal volumes produced globally to date – and secondly at expected demand in the future, once the current developing and newly industrialising countries adjust their level of consumption to that of the industrialised countries. Of course, both are likewise comparatively uncertain speculations. The accumulated global copper production to date, for example, is estimated to be in the region of 434 m. tonnes. An interesting question is how much of this is still in circulation and is basically available today; another more interesting question is what proportion of the stocks of accessible ores with a certain minimum concentration we have already consumed. A per capita figure could be of assistance as an initial approximation with regard to future consumption levels. Karlsson e.g. estimates global lead reserves in ores to be 7 kg per capita, the reserve base 12 kg per capita and global resources 140 kg per capita. He then compares this with the 290 kg per capita, which were introduced as a net figure into the Swedish economy between 1880 and 1980\textsuperscript{10}.
For most metals, at least seen globally, a continued increase in demand and production must be assumed. There are neither signs of saturation on the demand side, nor are there signs of shortages on the supply side. Lead is the only mass metal, for which a significant – albeit not only temporary – global decline of primary production can be noted at least between the mid 1970s and 1998 (cf. figure 1-5).

This decline should, however, essentially be due to two reasons that are specific to lead: firstly, the severe restriction in the dissipative use of lead open to the environment (e.g. as an additive in petrol), which was enforced by regulations, against the background of its extremely problematic toxicological and ecotoxicological properties (blocking of haemoglobin synthesis, nervous damage, probably carcinogenic, accumulation in the food chain) and secondly the specific conditions in the main area of use ‘automotive starter batteries’. A return and recycling system that functions well was able to be established in this field at an early stage. The further increase in primary production noticeable as of 1998 could be due to the (still) rising demand for cathode-ray tubes with lead glass, which is used for radiation protection, although substitutes are quickly gaining ground in this area too (e.g. LCD screens). It is possible that the example of lead – essentially triggered both by regulative reactions to its (eco)toxicological properties as well as substitution and/or innovation – will produce the at least conceivable situation that lead supplies in the global technosphere (i.e. in products and in scrap) are sufficient to essentially satisfy economic demand by means of effective recycling. Then only ‘dissipative losses’, which are naturally also to be expected in a very highly developed recycling management system, must be compensated for by new production of lead from ores.
2. SUSTAINABILITY DEFICITS IN THE METALS INDUSTRY

The availability of resources is only one of many problems related to sustainability that the metals industry has to contend with, although it is one of the most extensive problems. Sustainability problems exist in all three dimensions of sustainability: ecological, economic and social. These sustainability deficits also have varying ranges in all three areas. As part of a scientifically established sustainability strategy, it is recommended to weigh up the problems and to concentrate on those sustainability problems, which have especially far-reaching consequences in both space and time. The most serious sustainability problems are those with both global and irreversible problematic consequences. Scientific knowledge as the basis of sustainability strategies is required especially for the clarification and representation of those developments, which occur more stealthily and hardly provoke any acute problems and concerns, but which do have irreversible consequences and can therefore no longer be managed once they have become ‘perceivably acute’ problems. Precisely with a view to such long-term, furtive processes, which are at the same time global and irreversible in their results, the scientific world has an especially important contribution to make

One important aspect of the economic dimension of sustainability is (as an unavoidable minimum prerequisite) the (international) competitiveness of companies, regions and branches of industry. At the same time, the ability to be innovative is an extremely vital element in (strategic, longer-term) competitiveness. The ability to be innovative is also one of the basic prerequisites for the ability to change our economic activities and lives into sustainable activities. From a perspective of the global supply chain level, the shortcomings in the ability to be innovative and in the competitiveness of the metals industry in the industrialised nations, however, do appear relatively small in comparison with the economic structural and competitive problems of the relevant sectors in the developing and newly industrialising countries, where a majority of the primary materials processed in the industrialised countries originate.

In addition to the rather short-term and current problems of economic competitiveness, the subject of ‘economic sustainability’ is however particularly concerned with securing the economic basis for enterprises, regions and nations over the long term. The essence of this is the ability to reproduce the basis of existence of these socio-economic systems, i.e. their natural resources (material and energy sources and ecosystemic sinks), their social and institutional resources (state, legal system, social system) as well as human resources (manpower, qualifications, social stability, health and cultural identity). The self-reproduction of systems in a dynamic environment – especially under the conditions of intensified competition as the result of globalisation and market saturation – is essentially preceded by the ability for self-change and innovation. In the ore-producing countries, in addition to the acute problems already stated, the essence is to prepare for the situation in sufficient time once national ore deposits are exhausted (and/or are no longer competitive).

Important elements of the social dimension of sustainability are also alluded to by the reference to the economic problems in the ore-producing countries. The most important acute social problems of the global metals industry doubtless include the
social faults connected with resource exploitation in not only ecologically, but also especially socially and culturally highly sensitive areas, such as e.g. the Amazon Basin or Papua New Guinea. In addition, the focus should also be directed more at the long-term and not so directly perceivable problems of intergenerational justice, especially the issue of the ‘legacy’ that the present generation will leave behind for future generations. The problems of the long-term availability and also the spatial distribution of metallic resources play an important role here. Answers to a whole series of questions are to be found here: How long will ore resources last? What economic and social consequences exist for present primary material countries once their national (primary) resources are ‘exhausted’? What precisely is meant by ‘exhaustion’ of ore resources? What are the effects in the economic and ecological dimensions of having to extract ores whose quality is becoming poorer and poorer? What does it mean if, on the other hand, in the industrialised nations a growing stock of recyclable metals is being accumulated and countries that were poor in primary materials to date suddenly thus become ‘resource-rich’ countries? In which quality do we want or will we be able to hand this ‘metal stock’ accumulated in the technosphere down to subsequent generations? With regard to the long-term sustainability target, the sustainability deficits addressed here, which are currently not so urgent, seem to be some of the more significant deficits. The missing direct perceptibility and acuteness is a problem that should not be underestimated for the development of practical solution strategies. Naturally, the problems of occupational safety and health protection, which are still related to metal production and processing in the industrialised nations, are also part of the social sustainability deficits. Great progress has, however, been achieved in this respect in the industrialised nations over the past decades. Therefore here too the following is applicable: the main problems related to occupational safety and health protection in the metals industry are not (or rather no longer) to be found in the industrialised nations; as is the case with ore extraction and processing, they are also to be found in the developing and newly industrialising countries, which increasingly aim to adopt these processing stages as part of the process of securing and expanding their own national added value. However, in the industrialised nations also, it is necessary to keep track of a very problematic legacy of past ‘transgressions’: metals – and especially heavy metals which are almost always associated with the main metal flows – are highly problematic from toxicological and ecotoxicological aspects. In particular the burden of heavy metals is in fact not only a current toxicological problem. Due to accumulation in the environment and in the food chain, there is a continuous transition to less perceivable long-term and irreversible sustainability problems. Also many flows of accompanying materials connected with metal production and metal processing, including in particular overburden, sludge from processing plants (tailings), emissions from metal manufacturing plants including slag and filter dusts and also flows of subsidiary materials, e.g. coatings applied as corrosion protection, are of further relevance for sustainability with the transition to such long-term intoxications. From this perspective even problems with cooling lubricants in metals processing are among the minor and generally reversible problems, even if solution contributions can be made in all three dimensions of sustainability using precisely this example.
The ecological dimension of sustainability was already introduced with regard to the accumulation of heavy metals in the environment. The largest current deficits are in the developing and newly industrialising countries in this dimension too – as a result of the huge progress made in the field of environmental protection in the industrialised nations. They are especially related to ore extraction and a form of industrial concentrate production (partly meanwhile also metal manufacture), which in many instances is still not at all in line with the standards, which have in the meantime been introduced in western industrialised countries. However, it should not be ignored that, with a view to preserving such standards, it is also worthwhile to examine some sites in western industrialised countries and especially in some Eastern European countries. Currently, the most urgent and the most serious is doubtless the situation in many mines. Large-scale opencast mining as it currently exists is a major intrusion in regional ecosystems. Such intrusions are all the more serious, the more sensitive these systems are, with tropical rain forests and most aquatic systems (fresh-water systems and coastal zones) being the most vulnerable. There are also quantitatively and in part qualitatively, i.e. (eco)toxicologically, significant waste and waste water flows as well as emissions along the metal production chain with their ecotoxicological effects (especially but not exclusively concerning heavy metals), their acidification potential (acid rain) and their contribution to the greenhouse effect. Here too, under the long-term aspect of sustainability, those ecological problems, which entail irreversible and (where applicable) also global effects, must be classified especially serious. These doubtless also include the problem of biodiversity (which is in turn especially virulent in ore mining areas) and also stratospheric ozone depletion (which may occur along the entire product line including recycling, but seems to be only relevant in some specialised applications of surface cleaning), the accumulation of heavy metals and not least of all the greenhouse effect, which is closely linked to energy consumption\textsuperscript{17}.

By way of a conclusion for this cursory passage through sustainability deficits of the metals industry it can be stated that the most extensive sustainability problems, i.e. whose effects are irreversible and mostly also global, are scarcely noticed at present. Although these are irreversible and global developments, contributions to resolve them are not at present considered by most actors to be urgent. On the output side at least the greenhouse effect is perceived to be a problem affecting the energy-intensive metals industry. The metal-producing industry in Germany did in any case react to this by a voluntary agreement to reduce its absolute energy consumption\textsuperscript{18}. A similar development is not evident on the input side. Securing long-term resource availability, both with regard to primary resources in mineral deposits and also secondary resources, in particular the quality of consumed metal stocks and scraps, is hardly perceived to be a problem and, even far less so, actively addressed. The scope of ore deposits is occasionally discussed, but a current need for action – beyond stepping up efforts for prospecting – is not seen. Contamination of scrap and secondary metals by tramp elements is discussed repeatedly, but this too does not at this time result in the creation of precaution-oriented strategies for action.
In the course of the environment and sustainability discussion a shift in focus and theme has taken place between more qualitative and more quantitative views on several occasions over the past 20 to 30 years when examining materials and material flows. In the course of the sustainability debate a first shift in focus moved from the problem of harmful substances (toxicology and ‘chemicals policy’), which initially determined everything to materials flow management and thus from the problematic quality of materials to the problematic quantity of material flows. Three reasons were decisive for this first shift away from the problem of hazardous substances to a quantitative view of materials and material flows. Firstly, experience with the restrictions or even the powerlessness of state regulations governing chemicals, which endeavour to be based on scientifically evident proof of harmful effects. Secondly, experience has played an important role so that increases in materials production, which are harmless from an (eco)toxicological aspect, can be linked to considerable ecological consequences and risks. Besides the problem of contaminants and hazardous substances, there was also the problem of very high volumes of substances, which would not be described as particularly problematic from a qualitative aspect, such as e.g. water (including dissolved salts), carbon dioxide, nutrients such as nitrates and phosphates but also gravel, iron and steel, glass and concrete and similar substances. Thirdly, in the course of the sustainability discussion in a type of second ‘wave’ following the debate on the ‘limits of growth’ in the mid 1970s (Meadows 1973) attention was again directed at the problem of the long-term availability of non-renewable resources.

Linking these two views the problem of the availability of resources – i.e. the sources – is related to the problem of intake capacity of sinks for emissions and waste. In view of impending anthropogenic climate change it is today being debated e.g. whether we will at all still be able to afford to utilise all available fossil energy resources in fact due to the accumulation of CO$_2$ in the atmosphere as a result of the combustion of fossil energy resources. The limits of carrying capacity of the sinks, in this case the consequences of CO$_2$ accumulation in the atmosphere, could become the limiting factor much earlier than the possible depletion of oil, gas and coal sources. This change in perspective will also provide new impulses to the debate about the future availability of metallic resources.

The third important change in perspective that is now imminent again introduces qualitative elements to the debate. However, it is not primarily the (eco)toxicological qualities and effects of materials, which have not lost their topicality, but rather their technical qualities. It is a matter of what we commonly refer to as ‘consumption’, i.e. the reduction of the serviceability of materials in their usage phase. This aspect is of special interest for a sustainable metals industry, because the metals could actually be utilised and recycled almost without any loss in quality due to their physical and chemical properties. This option differentiates them from most natural materials and also from most plastics, in which a loss in quality in the usage phase or in recycling is generally inevitable. The now imminent change in
perspective focuses precisely on this problem of the maintenance and/or loss of technical qualities in (metal) cycles. At present this problem is still being postponed into the future by diluting the contaminated material with ‘fresh material’ that is excavated directly from ores. It will thus become a really severe task in the course of the test to establish a sustainable metals industry primarily on the basis of metal recycling. For this third forthcoming change in perspective we do not as yet have the requisite analytical instruments to a large extent. Exergy and entropy audits (cf. Ayres in this volume, Rechberger 2002a and b, Gößling-Reisemann 2001, in this volume) provide a promising approach for the requisite analytical and modelling exact (i.e. quantifiable) examinations and assessments of such quality losses in materials cycles.

This last stated problem of the technical quality of metal material flows is not already contained therein, but otherwise the ‘management rules for a sustainable materials economy’ reflect the previous two changes in perspectives very well. These management rules were formulated by the Enquete Commission ‘Protection of Humanity and the Environment’ of the 12th and 13th German Parliament with recourse to preliminary works by Herman Daly and the World Business Council for Sustainable Development19.

Management rules for a sustainable materials economy

1. The depletion rates of renewable resources should not exceed their renewal rates. This is tantamount to the demand to preserve the ecology’s efficiency, i.e. (at least) to safeguard the ecological real capital as defined in terms of its functions.
2. Consumption of non-renewable resources should be limited to levels at which they can either be replaced by physically or functionally equivalent renewable resources or at which consumption can be offset by increasing the productivity of renewable or non-renewable resources.
3. Inputs of substances to the environment should be orientated towards the maximum absorption capacity of environmental media, taking into consideration all their functions, not least their “hidden” and more sensitive regulating functions.
4. There must be a balanced ratio between the time scale of man-made inputs to, or interventions in, the environment and the time scale of the natural processes which are relevant for the reaction capacity of the environment.
5. Any hazards and unacceptable risks to human health due to man-made effects should be avoided.

In addition to the obligation to change over to renewable resources – wherever possible – and to use these resources below their natural regeneration rate, here firstly substitution and secondly time ‘stretching’ of the exploitation rate are thus employed with regard to non-regenerative resources. The aim is to increase resource productivity, i.e. improve the effort-utility ratio when using (metal) resources. This should all be combined with the greatest possible caution in the case of interventions in (large-scale) ecosystems and as little technical, toxicological and ecotoxicological risks as possible.
As it can be assumed on the basis of current know-how that a substitute on the basis of renewable resources is available for only comparatively few of the present and future fields of application of metals, there is an obligation to develop ‘ways of sustainable economy activity with metals’, i.e. for a ‘sustainable metals industry’.

The third change in perspective mentioned in order to maintain technical qualities thus becomes essential. The management rules still concentrate on resources and environmental policy (waste and emissions), i.e. on the exchange processes (input-output) at the interfaces between the ecosphere and the technosphere. On the other hand, strategies towards a more sustainable metals industry will have to concentrate much more on handling metals within the technosphere. In comparison with the raw materials and resource policy and/or the waste and emissions policies, ‘product policy’, product manufacture, product utilisation and recycling will thus be of central importance. The objective will be to maintain the quality level of materials in the technical cycles within the technosphere.

The view to the interfaces between ecosphere and technosphere will nevertheless remain important. While economic activity on the basis of renewable resources is also linked with major chances for ‘opening up’ towards the ecosphere, or for ‘engaging in natural cycles’ arranged via agricultural production processes, a ‘sustainable metals industry’ will rather have to close over the transitions between the ecosphere and the technosphere. Here the aim will be to minimise the material transitions, both on the input side (stretching of the resource basis) and even much more on the output side (avoidance of emissions and dissipative losses).

Concerning their material, energy and technical bases, the following requirements for a ‘sustainable metals industry’ can thus be defined20.

A sustainable metals industry is essentially based on a closed loop of metals, which is as far as possible free of quantity and quality losses, in the technosphere. A sustainable metals industry stabilises and increases, as far as possible, the quality of metal flows present in the technosphere. It establishes separate cycles for the various metals and alloys and minimises their contamination. Their primary resource requirement is minimised by high-quality recycling and also avoidance of dissipative losses as far as possible throughout the entire metal chain. Resource productivity, i.e. the ratio of material and energy demand to the desired advantage, is optimised by concentrating on treatment of metals in the technosphere, especially product design and product utilisation.

A sustainable metals industry does not exceed the carrying capacities of regional and global ecosystems with its emissions in the air, water and soil. It contributes to maintaining productivity of the natural capital by avoiding the accumulation of heavy metals and other persistent toxic materials in soils, as well as interventions in especially sensitive ecosystems, such as rain forests for example.

Minimising metallic and metal-induced material flows in relation to the advantage in society both with a view to the long-term availability of resources and also the carrying capacities of the sinks would signify a ‘radical reduction’ of current flows between the ecosphere and the technosphere. It is in a clear contrast with the further rise, which is more in keeping with the trend. The ‘trend reversal’