ECO-EFFICIENCY IN INDUSTRY AND SCIENCE

Sustainable Metals Management

Securing Our Future - Steps Towards a Closed Loop Economy

Arnim von Gleich, Robert U. Ayres
and Stefan Gößling-Reisemann (Eds.)

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SUSTAINABLE METALS MANAGEMENT

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Sustainable Metals Management

Securing our Future - Steps Towards a Closed Loop Economy

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Contents

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The Editors

Foreword

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 view-point 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

1

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 from 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.

A. von Gleich et al.(eds.), Sustainable Metals Management, 3-40.

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[3]. 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'[4] 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[5].

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[6]. 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:

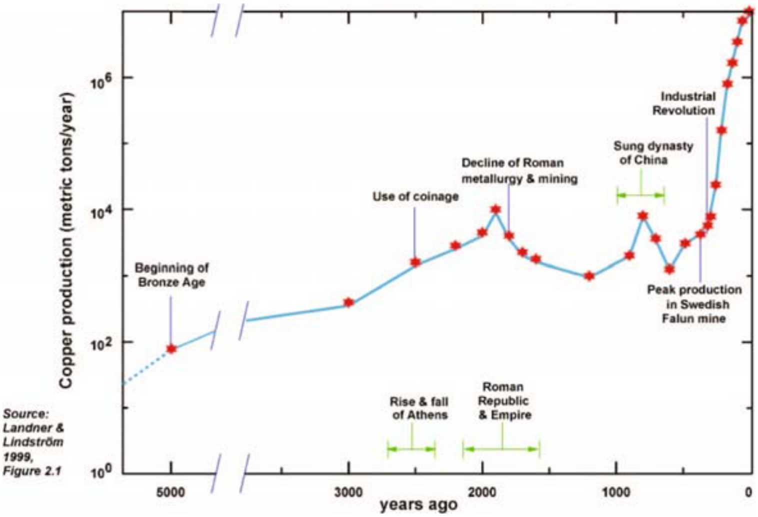
1. The phase of primary intensive industrialisation as of the second half of the 19th century.
2. The steepest growth phase to date after the Second World War in the 1950s and 1960s.
3. A slump in this steep rise in the mid 1970s. This slump is often associated with the oil price shock (or oil crisis, 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 energy[8].

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[9].



Source: Landner & Lindström 1999, Figure 2.1

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).

Figure 1-2 shows a development of copper production in the 'western world' between 1810 and 1995 based on more reliable statistics.

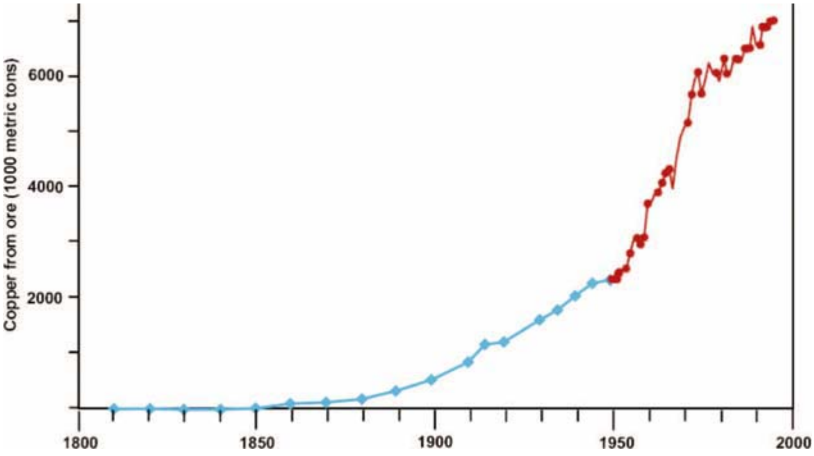


Figure 1-2. Copper extraction between 1810 and 1999 in the 'western world' (from: Ayres et al 2002 on the basis of Landner & Lindeström 1999).

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).

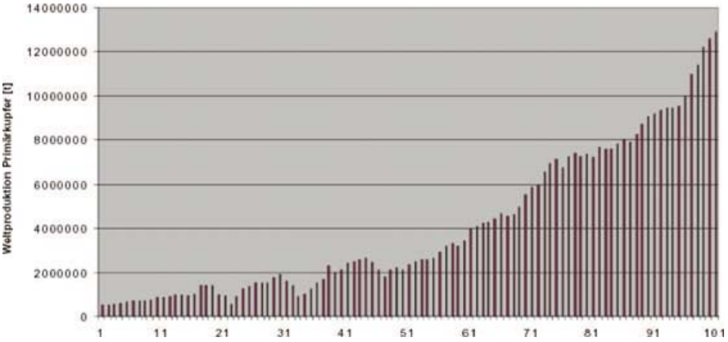


Figure 1-3. Global primary copper production in the 20th century (x-axis = annual figures) (from: Handke 2002)

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).

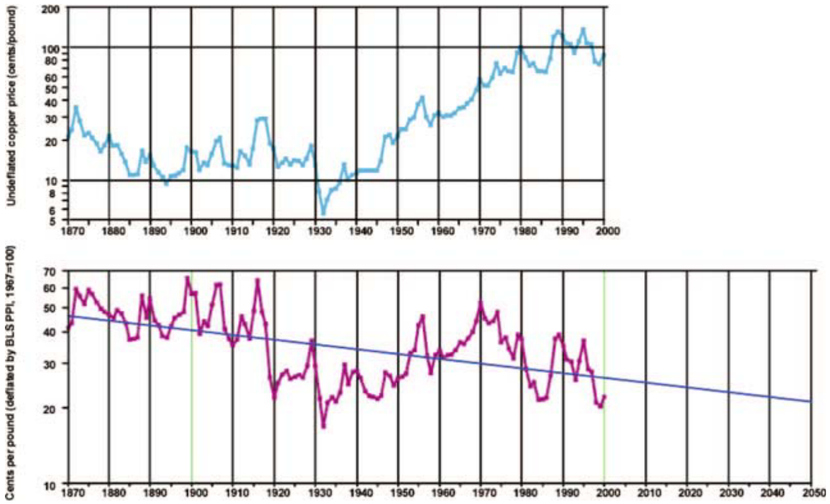


Figure 1-4. Price trend for copper on New York market from 1870 to 2000 in 1987 Dollars (from: Ayres et al 2002)

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[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).

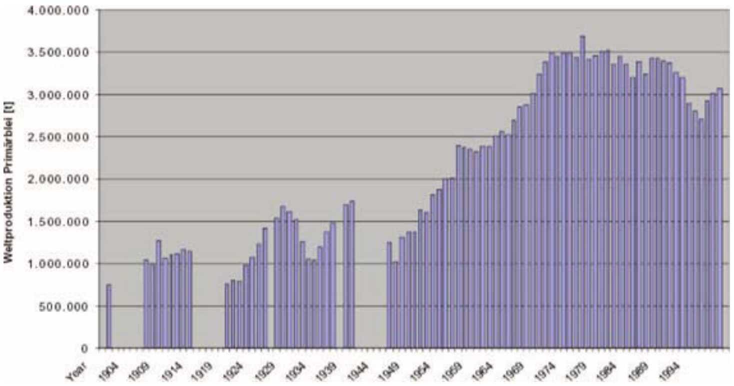


Figure 1-5. Global production of primary lead in the 20th century (from: Erdmann 2002)

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[11].

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)[12].

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[13].

In addition, the focus also in the social dimension of sustainability should, however, 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[14]. 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[15]. 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[16].

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[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[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.

3. QUANTITY AND QUALITY – THE TARGET PERSPECTIVE OF A SUSTAINABLE METALS INDUSTRY

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 Development[19].

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 defined[20].

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' required by this is not only necessary, but it appears also to be possible in principle without extreme social and economic losses. The focus is in fact on ‘cross-border turnovers’. A reduction of the flows between the technosphere and the ecosphere would thus be compatible even with a growing economy, even with a growth of material and energy flows within the technosphere. Even in phases when the flows within the technosphere still remain equal or continue to grow linked to economic growth, ‘cross-border’ flows between the technosphere and the ecosphere can and should decline.

With the demand for minimisation of the exchange processes of a sustainable metals industry with the ecosphere, the question that immediately arises is the target corridor. What magnitude of metallic and metal-accompanying input flows would be sustainable? How long should which resource qualities last? What magnitude of metallic and metal-accompanying output flows do the global and regional sinks support? We do not know the answers to these questions at this stage[21]. However, from the present perspective it is probable that the ‘corridors’, within which future ‘sustainable development’ can move, are considerably larger and/or wider on the input side than they are on the output side. It is less the existence of metals in the earth’s crust, but rather the conditions and consequences of metal extraction and production on the output side, which should turn out to be the decisive limiting factors.

4. METALS AS ‘NON-RENEWABLE’ RESOURCES

In comparison with most other non-regenerative resources for sustainable economic activity the materials group metals has the best potential. Metals do not ‘age’. Manifestations of fatigue are reversible from a metallurgical aspect. Like hardly any other materials group, metals have very good chemical/physical properties for recycling at the same quality level. However, corrosion is a problem. Losses due to corrosion have to be avoided as far as possible. High-quality recycling, increasing of resource productivity and avoidance of dissipative metal losses are thus at the centre of strategies towards a more sustainable metals industry.

We refer to metals and/or ores as ‘non-renewable’ resources. This may require some explanation. Ores are in fact being replenished constantly in the earth’s crust. But replenishment of extractable ores in the earth’s crust and their ‘conveyance’ to near the earth’s surface take place in geological and not in historical time periods[22]. If the exploitation rate of (accessible) ores is several orders of magnitude higher than their replenishment rate, the adjective ‘non-renewable’ is doubtless adequate for a debate about resources in a historical (and lastly also economic) context as part of the discussion about sustainability.

Metals can be easily recycled. This too would be a starting point for ‘resource generation’. The physical principle of ‘material conservation’ (law of conservation of materials) also applies to metals. Metals will thus always exist. The only question is whether they will be utilisable for us. Concerning the usability of resources and not only the existence of chemical elements (or energy), the question is in what ‘thermodynamic form’ the materials (or energies) exist.

Metals can thus not be 'destroyed', but they can be 'used up', i.e. they can be 'devalued' under thermodynamic aspects. The decisive factor for using up is entropy production with the focus on dissipation or mixing entropy respectively. Two aspects thus oppose the perpetual recycling of metals:

- **Dissipative losses** into the surroundings (both inside the technosphere and into the ecosystem). Generally, they cause the metals to be present there in low concentrations and/or in more problematic metallurgical/technical (accompanying) forms[23] than in natural ores. And they can also develop very problematic (eco)toxicological effects in organisms and in ecosystems.
- **Contamination of large metal flows** in the technosphere by other materials (in most cases also metals), which cannot be removed or can only be removed with relatively major effort from these metal flows. This is particularly the case for tramp elements and alloy elements (e.g. accumulation of Cu, Ni and Cr in structural steel).

4.1 Ores and metals as 'products of evolution and heritage of humankind'

Ores are resources for us and as such the result of a cosmic and geological evolution. According to current knowledge, important stages were the evolution of the cosmos and, in this respect, evolution of the elements, that is e.g. the formation of galaxies, stars and planets and in particular the formation of (heavy) metals in cosmic processes, such as e.g. supernova explosions (Samland 2000), then the formation of planet earth with its earth crust (Taylor; McLennan 1985, 1995).

To be utilisable for us, metals have to be enriched at certain points in the earth's crust and also reach those areas that are accessible to us. In particular geophysical and geochemical processes in the earth's crust related to plate tectonics, as well as weathering processes on the earth's surface, play a central role in this process (cf. Taylor; McLennan 1985, 1995). The ores are present in primary or secondary deposits as a consequence of these processes, in the latter case in sediments or in dissolved form e.g. in sea water (e.g. magnesium extraction). However, the concentration is not only decisive for the usability of ores, but also the chemical (bond) form, in which the metals are present in the ores. Extracting copper from sulphide (primary) ores is common practice today. The first copper mining, however, concentrated on sub-surface hydrothermal lixiviation and/or overground weathering products of such primary (in most cases sulphidic) ores. Oxidic copper ores from secondary deposits were easier to process, as the copper was much more enriched in these secondary deposits. People learned to process sulphide ores already in the Bronze Age[24]. Oxide-silicate ores are processed as part of a hydrometallurgical process today.

Ore deposits must be considered – as in general the results of the geological and biological evolution on the earth – thermodynamically as systems that are far from the thermodynamic equilibrium. Thermodynamic forces are required to achieve and maintain this condition. In the case of ore formation, these are on the one hand the nuclear disintegration processes in the earth's core, which drive plate tectonics with its processes of crust melting and crust replenishment and volcanism, as well as on the other hand the solar energy that is responsible for weathering processes and for biological activities. The sun ensures e.g. the concentration of metal ores in secondary deposits[25] via the global water cycles.

From a thermodynamic aspect ores are therefore 'stroke of luck' due to special circumstances and are as such valuable for humans[26]. That is the reason why we call ores 'treasures of the soil'. How important these treasures of the soil are is demonstrated by the sad fact that wars are constantly being waged because of them. From sustainability aspects, i.e. especially with a view to equity between the present and future generations, ores must be considered as nature's input and also as a 'heritage of humankind'. And this heritage has to be used sparingly for the purposes of intergenerational equity. This is of course the same – and if not especially so – for metals already produced. Of course, from sustainability aspects it is a gain and not a loss if we 'consume' ores and bequeath metals to future generations[27].

One prerequisite for this legacy is, however, the minimisation of dissipative losses and also quality is vital for passing down metals. Contamination of metals, particularly by other metals, must be considered as an especially problematic form of dissipation, which – at least in accordance with the latest state-of-the-art – cannot be eliminated or can only be eliminated with extremely extensive efforts. At the latest when we hand down those metals 'used' by us in a contaminated form, which is more problematic than the ores that are conceivably utilisable by future generations, we have to refer to an absolutely dissipative 'loss' in this case too[28]. This can especially be the case for the base metals steel/iron and aluminium[29].

The economic value of ores and metals as 'heritage of humankind' is evident. However, it can hardly be quantified under sustainability aspects. We can indeed assess the 'current (market) value' of deposits according to the best of our capabilities. Usage rights for deposits are in fact also traded. But these 'values' are highly dependent on the current economic climate, demand forecasts, substitution options as well as technical developments. From a sustainability aspect we can also go one step further. We find at least certain clues for the value of 'nature's input', if we apply the effort that we have to expend currently and in the foreseeable future in order to extract metals from ores. From a purely mathematical aspect we can compare the current and, if need be, also the foreseeable effort for the concentration process of e.g. 1.8% ore to 99.99% metal with the natural enrichment factor, i.e. the added concentration from the 'worst case' scenario of a statistical equal distribution of all elements in the earth's crust to a 1.8% ore.

Rough estimates of the average element contents of the earth's crust state that, without the enrichment processes in the earth's history, e.g. the copper content in the earth's crust is equivalent to approximately 0.005%[30]. On average copper ores with a copper content of 1.3% are currently excavated. The lower limit for the profitability to excavate is currently 0.4%[31]. Using the example of copper, an enrichment factor of approximately 80 is thus situated between the average content of the earth's crust and the minimum excavation capacity. This 'natural input' could now be expressed in a second stage – with reference to the subsequent effort of technical metal extraction – as effort in material, energy and monetary units. At least this increasing effort that we have when extracting poorer and poorer ores can be related to this 'input' in this way.

The enrichment factors of some exemplary metals are contained in table 1-1.

Table 1-1. Enrichment factors of average ores currently being extracted[32]

Metal	Position in the frequency of elements in the earth's crust	Average content in the earth's crust	Current minimum content of an exploitable ore	Enrichment factor
Aluminium	3	8%	25%	3
Iron	4	6%	50%	10
Copper	24	0.005%	0.4%	80
Gold	72	0.005 g/t	1 g/t	500

Such 'estimations' and especially the future extrapolations in the next step concerning technical developments, extraction effort and yield rates are naturally highly uncertain. Nevertheless, such attempts to 'economise' on the 'heritage of humankind' should still be pursued, as they probably will play a more important role in the sustainability debate. It is not by chance that integration of the 'nature' factor (at least in the form of resources) as the basis of all economic activity in economic concepts, integration of 'free commodities' (the Commons), which have for far too long been considered to be 'free and available in unlimited supply', in economic calculations, i.e. determination and maintenance of the 'natural capital' characterise most of the economic aspect in the sustainability discussion.

Determination of the 'ore value' as a human legacy in view of the 'economic and technical effort' avoided because of nature's input would also only be a first step. In addition to determining the economic and technical effort for extracting metals from ores, the side-effects and after-effects (at least related to it so far) should then also be taken into account in the social and ecological sustainability dimensions[33]. The socio-ecological consequences of the metals industry are also part of its 'legacy'. In addition to the positive legacy of the values produced (including the stock of metals in the technosphere), we also bequeath the negative sides of this legacy, especially emissions and waste, including irreversible accumulations of metal contaminations in ecosystems and also the irreversible destruction of biotopes during the ore extraction process possibly linked to a reduction in biodiversity.

If the outlined approach to determining the value of the 'natural capital' is defined more precisely and put into operation with regard to assessing ore deposits, we also receive a set of instruments that can be used to evaluate what is the economic significance (including currently externalised costs), if we are in future forced to extract 'poorer' ores with decreasing metal concentrations (and/or existing in more problematic forms).

4.2 Scope of reserves and resources

In a finite system the usability of non-regenerative resources is absolutely limited. This is immediately evident. However, hardly do we begin to discuss how long this or that particular resource will still 'last', than misconceptions begin to be out of control. Misconceptions based on the inaccurate use of clearly defined scientific concepts can be overcome to a certain extent, e.g. by explaining concepts like 'static range' or by creating a clear distinction between the concepts of reserves (including the reserve base) and resources and also by differentiating between various forms and qualities of recycling. Another source of misconception is, however, not at all so easy to overcome. This is the estimation and/or assessment of the range of our knowledge and our knowledge options respectively. This already begins with knowledge about factors that already exist today, such as e.g. the existence of deposits. However, it is much more problematic to make future extrapolations or suppositions about developments in demand, substitution options and/or achievable boosts in resource productivity. We do not know which ore bodies actually do exist in what concentrations and forms in the (at present and in future) accessible areas of the earth's crust. Also due to the basic unpredictable nature of the future, it is only possible to state the probability of how demand for ore will develop in future. Demand is influenced considerably by e.g. developments on the (global) market, the recycling rate, technical developments and in this respect also especially possible substitution options. We do not know which metals we will still use or if we will use metals at all in the future. Reserves and/or resources of flint, one of the most important materials of the Stone Age, are no longer of any interest to anyone today. Will it and can it be a similar fate for metals (or for some metals)? Will the problem of the finiteness of metal resources resolve itself as a result of innovation? It is impossible to answer this question. But we cannot simply rely on innovations and substitutions being available on time. This would be a highly precarious 'strategy', which would rather be similar to flying to new destinations hoping that the people there finish building the runways on time. The substitution of (some) metals would doubtless be a solution to the problem of the finiteness of resource availability. Development of substitutes is in effect intensified by scarcity signals, which must also be reflected by price increases at some point in time. But an 'end of the metals industry' like this can also doubtless not only be portrayed as a 'promising future'. The 'creative destruction', which is always linked to every innovation – as Schumpeter suggested – would hit entire branches of the economy and scores of nations quite hard.

At present, however, there is little to indicate that future innovations will result in the extensive substitution of metals. It is more probable that demand will shift within the metals group, and especially to very rare metals as the basis for functional materials and/or as alloy components. This diversification and specialisation could be linked to an overall increase in metals turnover. One possible reason for this could be that extraction of some very rare metals is still linked (as by-products) to the much larger flows of copper, nickel or aluminium production.

At the latest since the Club of Rome's report concerning the 'limits to growth' the general public is familiar with details about static ranges of non-regenerative resources. As stated, the finiteness of these resources is immediately apparent. At the latest when the range of some global resources such as crude oil e.g. has been estimated at approximately 30 years for more than 30 years now, most people become suspicious. Static ranges are calculated (admittedly quite simply) from the known reserves divided by current global annual production. Static ranges are precisely 'static' statements (momentary records) amid an extremely dynamic situation. Those sites that are already known today and that can be exploited economically using today's technologies are designated as reserves. From this it is apparent that statements about reserves depend on at least three independent variables: 1. Present *knowledge of (and/or intensity of the search for) deposits*, their type (bond form, accompanying elements), their distribution and size as well as the particular ore concentrations, 2. the latest *state-of-the-art*, the effectiveness and efficiency of ore and metal extraction (e.g. ratio of ore to excavated material and accompanying materials, yield rate, operational productivity, material and energy efficiency) and 3. the present *cost and revenue situation*, i.e. return on investment (which is in turn dependent on e.g. the current dollar exchange rate, interest levels and tax rates), operating costs (which are in turn dependent on e.g. the wage level, energy and material costs and the standards of occupational safety and environmental protection) as well as metal prices.

Current 'static ranges' of some metals are contained in figure 2-6 in the text of Wellmer; Wagner contained in this volume. Using this graph the authors clearly demonstrate that we know little about the 'true' range of resources. On the basis of comparisons between the static ranges of various metals, however, at least the need to react to this momentary record can be deduced, e.g. by innovations and not least of all also by exploring additional deposits.

In the debate on ranges at least three concepts should be used by definition: resources, reserve base and reserves. All three concepts share the fact that a certain geological knowledge about the actual existence of deposits is required, albeit with requirements for certainty increasing from resources, via reserve base to reserves. Likewise, from resources to reserves the requirements for approximate cost effectiveness of extraction increase, i.e. from 'possible in the foreseeable future', via 'possible soon' to 'economical employing current technical methods'. Resources are thus defined as "a concentration of naturally occurring solid, liquid, or gaseous material in or on the earth's crust in such a form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible" [34]. Reserves are that "part of the overall resources, which was recorded with a high level of accuracy and can be economically exploited employing current technical methods"[35], and using the concept of the 'reserve base' the probable reserves, which have already have been geologically proven but are as yet part of the sub-economic domain, are also recorded in addition to the secure reserves. Their suitability for extraction is expected in the near future.

For copper and aluminium table 1-2 shows examples of some figures relating to reserves, reserve base and resources.

Table 1-2. Global reserves, reserve base and resources for aluminium and copper[36]

	Reserves	Reserve base	Resources
Aluminium in bauxite	23,000-25,000 m. tonnes	27,000-35,000 m. tonnes	40,000-75,000 m. tonnes
Copper in copper ores	308-340 m. tonnes	590-650 m. tonnes	2,000-2,300 m. tonnes

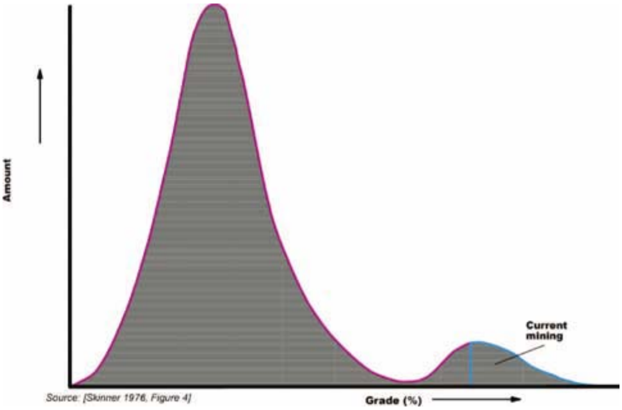
The discussion of sustainability centres on periods in the future, which exceed those in the classical resource economy by far. In this respect further reaching questions have to be raised (and answered, if possible). What an ore is depends on the (expected) economic framework conditions, but not only on these conditions. Statements about ores always contain an economic, but also always a geological and/or mineralogical component. The geologist or mineralogist realises even without any economic calculations that he has a stone with considerably higher metal concentrations (i.e. a potential ore). It is entirely possible to raise the following question: where are we today with regard to the depletion of overall volumes of certain stones with minimum metal concentrations on a global scale? Of course, this also raises the question as to where we wish to draw the boundary. The normal statistical distribution of a metal in the earth's crust (its average incidence) is the starting point (or the background noise). What minimum enrichment factor do we then wish to apply for a 'potential ore', i.e. for the 'considerably higher metal concentration'?

At least two sets of questions thus have to be examined in closer detail with regard to the availability of metallic resources for the sustainability discussion:

1. If we refer to those metal concentrations in stones, which correspond to x-times the average global concentration of certain metals in the earth's crust[37], as 'potential ores', how large is the total volume of available ore? And what proportion of the total metal content of these ores (in this natural stock) have we extracted so far?
2. How is the spread of metal concentrations represented within this overall volume of ores? Are we already forced to extract ever decreasing ore concentrations? Does the technical, economic and ecological effort to exploit metals rise in a linear pattern as metal content of ores declines or can a concentration range be identified from which this effort will increase disproportionately in accordance with current knowledge?.

These questions have hardly been discussed to date. Anyway, as background information for question 2, published estimates do exist concerning the incidence of certain metals in the earth's crust. These details are based on very approximate projections, in which the approximate distribution of mass stone types in the earth's crust with the individual average contents of elements is applied[38]. It is largely unknown how the concentrations of various metals are then specifically distributed in the earth's crust (close to the surface). Recently, however, Ayres with reference to Skinner attempted to make an estimate about the possible distribution of copper, which is a comparatively rare metal from a geochemical aspect, in the earth's crust (cf. figure 1-6). And he also attempted to determine the approximate average global position in extracting copper ores at present.

Such a distribution, demonstrated in two more or less Gaussian distribution curves, in accordance with which the large mass of metals (more than 90%) exists in rather low concentrations, could indeed be close to reality. If we take the much discussed example of copper, it is currently highly debatable whether we have actually exceeded the zenith of the first distribution curve. Wellmer quite rightly points out e.g. that statements concerning oil stocks distributed over certain areas, which can best be taken by carrying out sample drilling, are easier to achieve and are thus 'safer' than statements about more vertically extended ore bodies[39]. He also rightly opposes the apparent 'persuasiveness' of evidence that the average copper content of extracted ores fell dramatically from approximately 4% to 1.3% between 1940 and 1990. This development too can be caused by many factors. The average copper content of ores also rather appears to be stabilising or even to be increasing again slightly between 1980 and 2000[40].



Source: [Skinner 1976, Figure 4]

Figure 1-6. Probable distribution of a geochemically scarce metal in the earth's crust (from: Ayres et al 2002)

For example, the decision by holders of mining rights and/or mine operators as to which ores are next to be extracted and in what form is not only and presumably not even primarily determined by the 'practical constraint' of the available ores. Particularly in the course of the past decades, certain economies of scale could be implemented by reverting to large-scale open-cast mining with the heavy equipment used in that field, which make it appear more economical to extract lower ore concentrations on a large scale as compared with higher ore concentrations in niche areas, for example.

Innovations and changes on the markets and also in the framework conditions of economic activity determine investment decisions in the entire metal chain much more extensively than currently available ore concentrations do[41]. Each individual stage in the metal chain, starting at ore processing via metal production, metal working and processing, product usage and services including maintenance, repair and also, if need be, upgrading, even including dismantling and recycling, is part of an innovation process, in which more and more new solutions are found with regard to the economic, social and ecological sustainability objectives.

5. METAL RECYCLING AS A 'SOLUTION'?

Even if the availability of metal resources is finite and no comparatively sustainable economic activity is thus achievable, as would be possible at least in principle using solar energy and biomass, a considerably more sustainable management of metals can nevertheless be achieved by increasing the resource productivity and by stretching resource consumption. Metal recycling offers very good conditions for this. Metal recycling is as old as metal production is. It has always been easier to use old metal than to extract new metal from ore using a laborious process. Metals were recycled wherever possible just because of their high value. In comparison with other materials metals also offer excellent prerequisites for high-quality recycling due to their physical and chemical properties. If care is taken to avoid corrosion, metals can be used for very long periods thus making it possible to use products made from it on a durable basis. In the service phase they are not subject to ageing processes or any other irreversible quality losses, and they are easily reshapable, not least of all by melting.

High-quality metal recycling is thus a solution for a whole series of sustainability problems, not just with regard to the availability of resources, but also with regard to all the ecological and socio-economic problems, which are inseparably linked with primary metal production. Recycling appears to be the 'ideal solution' for a sustainable metals industry. Nevertheless, metals recycling also has certain specific problems to contend with.

The most significant of these problems include:

- The 'effectiveness' of recycling, i.e. the avoidance of dissipative losses and the guaranteeing of the highest possible return flow of scrap and metallic waste respectively;
- The 'efficiency' of recycling under sustainability aspects, i.e. the relation between the technical, ecological and economic recycling effort expended to the recycling gain;
- The quality of recycling, i.e. the 'quality' of scrap and especially the metal qualities attainable as a result of recycling[43].

The following factors can be listed as particularly relevant factors and problems for achieving the aims of high recycling effectiveness and efficiency as well as high quality of recycled metals:

- The prices for virgin materials and for various scrap qualities;
- The fact that many metals are not used for the most part in a pure form, but rather in alloy form and hence the need to secure the type purity of scrap;
- 'Contamination' of metal flows by tramp elements, which cannot be removed or can only be removed from molten metal with a disproportionately high effort;
- The fact that the use of alloys, materials mixtures and composites is increasing just as much as the degree of integration of these mixtures in products. This is particularly evident in the miniaturisation of electronics – which is otherwise entirely justified from sustainability aspects.

Recycling is an important argument in favour of metals in the sustainability discussion. In comparison with other materials metals are in fact exemplary with regard to both recycling qualities and also recycling volumes. Only for glass and paper are comparable recycling successes noted. At first sight everything therefore appears to be more or less satisfactory in the secondary metals industry. At least in the case of large metal materials flows, as is the case with iron/steel, aluminium and copper, recycling appears to be functioning well. Nevertheless, the negative health and ecological side-effects of recycling in its present form cannot be overlooked. In many areas the problematic side-effects and after-effects of metal recycling appear to reach the level of those of primary production. There are essentially two reasons for this. For the one part, the recycling industry is rather small sized, which means that in most cases comparatively simple technologies are used and that there is frequently an implementation deficit in occupational safety and environmental protection legislation. For the other part, the recycling industry has to contend with a multitude of alloy components, attachments and contaminations. Depending on the scrap quality, almost all elements throughout the entire period system can thus be introduced into the recycling cycles including highly problematic organic substances such as e.g. dioxins, furans and their precursors, i.e. a range of substances that primary metal production does not normally come into contact with in this form. To illustrate at least a relevant part of the inorganic spectrum table 1-3 shows a selection of inorganic emissions from a secondary steel mill (cf. table 1-3).

Table 1-3. Chemical compositions of EAF dusts

Chemical composition of EAF dusts from the production of carbon steel/low alloyed steel and high alloyed steel – based on [IPPC 2001, IISI 2000; Hoffmann, 1997; Strohmeier, 1996]

	Dust from carbon/low alloyed steel production	Dust from high alloyed/ stainless steel production
	[weight %]	[weight %]
Fe_{tot}	25 – 50	30 – 40
SiO_2	1.5 – 5	7 – 10
CaO	4 – 15	5 – 17
Al_2O_3	0.3 – 0.7	1 – 4
MgO	1 – 5	2 – 5
P_2O_5	0.2 – 0.6	0.01 – 0.1
MnO	2.5 – 5.5	3 – 6
Cr_2O_3	0.2 – 1	10 – 20
Na_2O	1.5 – 1.9	n/a
K_2O	1.2 – 1.5	n/a
Zn	10 – 35	2 – 10
Pb	0.8 – 6	0.5 – 2
Cd	0.02 – 0.1	0.01 – 0.08
Cu	0.15 – 0.4	0.01 – 0.3
Ni	0.02 – 0.04	2 – 4
V	0.02 – 0.05	0.1 – 0.3
Co	0.001 – 0.002	n/a
As	0.003 – 0.08	n/a
Hg	0.0001 – 0.001	n/a
Cl	1.5 – 4	n/a
F	0.02 – 0.9	0.01 – 0.05
S	0.5 – 1	0.1 – 0.3
C	0.5 – 2	0.5 – 1

Nevertheless, metal recycling is a success story. The ratio of secondary material in the individual production volumes is already comparatively high in the case of the major metal flows and is even continuing to grow in most cases. The ratio of scrap in global steel production is more than 45% (BDSV 2003). In 1997 37% of aluminium production in Germany and in 1998 approximately 51% of copper production in Germany were based on secondary material[44]. In the USA the proportion of secondary metals in the overall metal production almost doubled from

28% to nearly 53% between 1962 and 1991 (Rogich 1993). Figure 1-7 shows the development in the ratio of secondary to primary metal production for zinc, copper, aluminium, steel and lead in the USA from 1900 to 1991.

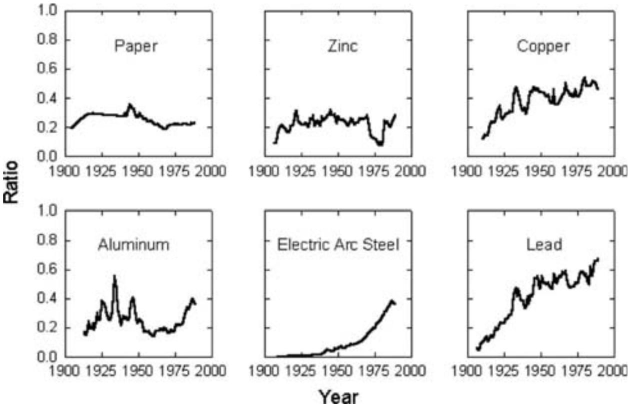


Figure 1-7. Ratio of production from secondary to primary material for paper, zinc, copper, aluminium, steel and lead in the USA in the 20th century[45] (from: Wernick et al 1996).

Nevertheless, a whole series of questions remain unresolved with regard to the objective of a 'sustainable metals industry'. While the proportion of recycling material in the case of steel, copper and lead – despite major fluctuations in the case of copper and lead – still follows a comparatively uniform increasing trend, developments in the case of zinc and aluminium are not so easy to follow. Here the prices for primary and secondary material doubtless play an important role. In order to answer the question that is relevant under sustainability aspects as to how far the demand for metals both at present and in the future can be met using recycled materials, this data is unfortunately not very indicative.

If the proportion of scrap used in metal production is designated as a recycling quota, then a country where only secondary material plants operate would achieve a 100% recycling quota, although the national metals industry is essentially fed by imports, as the case may be. And even if all imports and exports were included, this would still not create a realistic picture. Truly 'effective' recycling quotas should expediently refer to that proportion of a material produced at a time x, which is fed back into the secondary metal production process by a time y[46]. A decisive factor for determining the 'effective recycling quota' is how the volume of metals accumulated in the technosphere behaves, i.e. the domestic stock, as it is known. This volume is available for recycling, at least in principle, even if it is currently only growing and the material does not yet arrive in the secondary metal plants again. Only those volumes, which for various reasons cannot be recovered from this stock for recycling purposes, i.e. true 'dissipative losses'[47] are really lost. Rogich quantifies these total losses to be 18.2%, although he only examines one year[48].

In addition to the volume that is returned, the quality of metals that can be produced on the basis of recycling material is also equally of interest. To avoid confusion when assessing the qualitative 'successes of metals recycling' some further clarifications of concepts need to be made. With regard to the quality and/or value of the recycling material, it is important to make a distinction between 'real recycling on the same order and quality level' and 'downcycling', in which quality loss has to be accepted[49]. In the metals domain recycling is performed successfully on the same quality level, especially if pure and/or well sorted material is recycled, which is easiest to do when processing well defined new scrap (e.g. scrap from metallurgical plants or production scrap). In the case of aluminium and steel recycling mixed old scrap (i.e. materials that have gone through a product service phase) generally result in a loss in quality. This is due to the contaminants introduced in this way and admixed alloy components (in the case of steel contaminants are particularly Cu and Sn, in the case of aluminium they are Fe, Mn, Si, Cu and Zn). Such tramp elements cannot be removed from the melting bath with a realistic effort, for which reason e.g. secondary aluminium from old scrap is no longer processed into wrought alloys, but rather into casting alloys[50]. One example of the downwards cascade in aluminium recycling from aluminium foil via aluminium window-frames to aluminium castings in engines, which is forced by this, is shown in figure 10-9 in the text by Rombach contained in this volume (p. 303).

The VDI (Verein Deutscher Ingenieure – Association of Engineers) has taken into account the quality discrepancies in recycling in two ways with its definitions relating to the guidelines entitled 'Design for Recycling' that it published (cf. VDI 1993). A distinction is made between the recycling of products and components, in which the product form is retained, and materials recycling, in which the product form is broken down and only the material is recycled. Within these two types another distinction is made between *re-use* (product and component recycling at the same quality level) and *further use* (lower-grade product and component recycling) and also between *recycling* (material recycling at the same quality level) and *further utilisation* (lower-grade materials recycling).

The differentiation of value between these two types of recycling is specifically stressed in the differentiation between 'product and component recycling' and 'materials recycling' and the two stages within these strategies. Strategies towards a sustainable metals industry cannot and should not concentrate solely on materials recycling. In many instances the much more extensive sustainability potential is to be found in intensification and, if need be, also extension of product usage.

However, let us stay with materials recycling for the time being and examine again its quantitative aspects, or recycling quotas as they are known. In this context too the question arises as to how these can best be calculated? What is meant by 'secondary material'? Does this refer to production scrap (so called 'new scrap') or post-consumer scrap (so called old scrap), whose product service phase is over? Or if the two types of scrap are mixed (as in most cases), what is the ratio? It is naturally easy to recycle plant scrap at the same metallurgical plant. If the metallurgical plant operates inefficiently, i.e. producing considerable amounts of metallurgical scrap, it even contributes to a high recycling quota. This also holds true for production scrap, such as e.g. scrap from punching machines. The real challenges for a sustainable metals industry are thus to be found in high-quality recycling of old scrap.

It is impossible to make statements about recycling quotas only on the base of amounts of scrap occurring at any place (in a region or in a nation) at a specific time. Recycling quotas should relate to a certain amount of materials facing the whole product life cycle. Insofar the following questions are just as important: How do metal stocks in the technosphere grow or decrease over time? How is the import-export balance of metallic commodities and how is the scrap balance? How much are these figures influenced by temporal production fluctuations and/or by specific production structures and/or competition situations in the different countries? Do these figures state anything at all about possible stretching of resource availability through recycling? The last question must be answered unequivocally in the negative. If we wish to find answers to these questions, further differentiations between certain concepts have to be made, i.e. the above stated differentiation between recycling effectiveness and recycling efficiency. Recycling effectiveness refers to the question as to how much of a specific material can actually be stored in a cycle. Recycling effectiveness has to contend with losses in the service phase and in the recycling phase. Recycling effectiveness refers also to the question as to what proportion of the returning material can actually be recovered in the recycling process (comparable with the ‘yield rate’ in metals extraction from ores). Recycling efficiency refers to the ratio of effort and yield in the recycling process. Recycling effectiveness thus has to contend with losses. Recycling efficiency has to contend with the efforts for recycling, which include efforts to minimize losses. The most important variables for recycling efficiency (in relation to the yield rate) are thus rather ‘technical progress’ in the recycling industry and for recycling effectiveness the type of product design, product utilisation and especially also the success of collecting and sorting after product utilisation. To differentiate ‘effectiveness’ of recycling under aspects of resource consumption and resource availability, Rombach coined the phrases ‘resource-oriented recycling quota’ and ‘technical recycling quota’ (cf. Rombach in this volume). ‘Technical recycling quota’ refers to the effectiveness with which recyclable metals are produced from scrap and waste. The focus is on the losses at the end of product life. The technical recycling quota for various application areas of aluminium in 1997 fluctuated in Germany between 92.2% for construction scrap and mixed scrap, 79.1% for electronics scrap, 75.8% for used cars and 12.2% for aluminium in domestic waste (cf. Rombach in this volume). The ‘resource-oriented recycling quota’, however, refers to the entire materials cycle. It targets what we referred to as one of the decisive issues in the ‘sustainable metals industry’, i.e. to what extent the industry is able to recycle metals in a truly sustainable way.

Regrettably information on ‘resource-oriented recycling quotas’ (recycling effectiveness in a broad sense) is still missing in most cases. Nevertheless, Rombach and Wolf were able to compile some information relating to the aluminium materials flow in Germany. As the ‘resource-oriented recycling quota’ refers to the successful return flow of material from certain application areas (or from a region respectively), until it is re-used as a metal, the areas of application, the duration of application and possible further ‘technical intermediate stocks’ for (used) products and scrap have in some cases to be considered for very long periods. Determining this ‘reservoir’ and its filling level (i.e. the differentiated domestic stock) naturally gives rise to significant problems. According to Rombach, the ‘resource-oriented recycling quota' for aluminium in Germany fluctuated between 92.2% for aluminium usage in buildings, 66.5% for use in electrical and electronic equipment, 31.4% for use in cars and merely 2.9% for use of aluminium in products, which often end up in domestic waste. With the exception of construction scrap, which is evidently very well tracked, the greatest losses occur in insufficient gathering after the service phase. Additionally processing losses play an important role with focus on domestic waste[51].

Such information on recycling effectiveness, as prepared for aluminium flows by Rombach, are still rare, as stated. Only estimates are available for the global steel flow. These estimates state that within a period of 20 years approximately 70% of the material will flow back into recycling processes. The majority of the 30% losses is attributed to corrosion (cf. Willeke et al. 1994).

Copper cycles were examined intensively by a working group led by T. Graedel of Yale University. This group is also pursuing the objective of making statements about dissipative losses. However, dissipative losses of copper into the environment must no longer be solely criticised as material losses with regard to the resource situation, but rather due to the phytotoxicity of copper also with regard to any problematic environmental effects as the result of copper emissions into the biosphere[52]. European copper usage and/or the European copper cycle were itemised and modelled by the group i.a. in accordance with the most important copper application areas. In this respect their average return times (RT years) were estimated as well as those portions of copper that are recovered from these areas as scrap or are sent to the waste flow respectively. Using S/W the ratio of scrap to waste was indicated (cf. table 1-4 from Graedel et al 2002).

Table 1-4. Principal uses of copper 1990 (from: Graedel et al 2002)

#	Category	Use %	RT (years)	S/W
1	Building wire	14	45	50/50
2	Tube	12	60	45/55
3	Alloy rod	11	20	10/90
4	Magnet wire	9	15	50/50
5	Telecommunication wire	8	50	25/75
6	Power cable	8	40	60/40
7	Copper sheet and strip	8	50	60/40
8	Alloy sheet and strip	7	25	20/80
9	Casting alloys	6	30	50/50
10	Motor vehicle wire	4	10	80/20
11	Appliance wire	4	20	50/50
12	Bare wire	3	10	0/100
13	Copper rod	2	40	60/40
14	Alloy tube	2	35	95/5
15	Wire (other)	1	5	0/100
16	Alloy wire	1	5	5/95
17	Chemical and powder	< 1	1	5/95

If these estimates are correct with regard to the considerable volumes of copper that reach the waste flow from some applications, there is still a great deal to be done in the case of copper also. The recycling of copper, which is an especially valuable metal, can anyway be considered as exemplary in many respects. The static model of the European copper cycle drawn up by the group indicates a copper input of 3.43 m. tonnes into the service phase (technosphere) in 1994 (which is equivalent to approximately 8 kg per capita). At the same time 0.92 m. tonnes of copper reach the waste flow every year. This means that the ‘domestic stock’ in technical reservoirs has increased by 2.6 m. tonnes per annum, which is equivalent to 6 kg per capita (cf. Figure 1-8). Of the 0.92 m. tonnes of copper that were introduced into the waste flow in 1994, only about 60% was able to be re-used for recycling purposes[53]. The dissipative losses into the environment via the waste flow thus amounted to 0.485 m. tonnes in 1994. Of this figure, 0.48 m. tonnes ended up on waste dumps and almost 5000 tonnes were expelled in the form of sewage sludge and direct emissions into the soil, the atmosphere and the hydrosphere. On the basis of related work in Scandinavia[54], the Graedel group carried out pioneering work with regard to the detection and modelling of metal flows. Therefore, we have to be content with such selective records for the time being. As no utilisation periods (and thus earlier inputs) could be compared with the dissipative losses demonstrated in the model for 1994, a ‘resource-oriented recycling quota’ cannot be determined for the European copper cycle at this stage. Despite this, much more relevant information can already be deduced from this analysis of waste flows for the purpose of assessing sustainability than from the ratio of secondary materials in primary production. The fact that only 60% of the copper volume reaching the waste flow could be recovered from it does demonstrate that we still have a long way to go to achieve a sustainable metals industry even in the case of a material such as copper, for which recycling efforts are in any case already traditionally very high due to its high value.

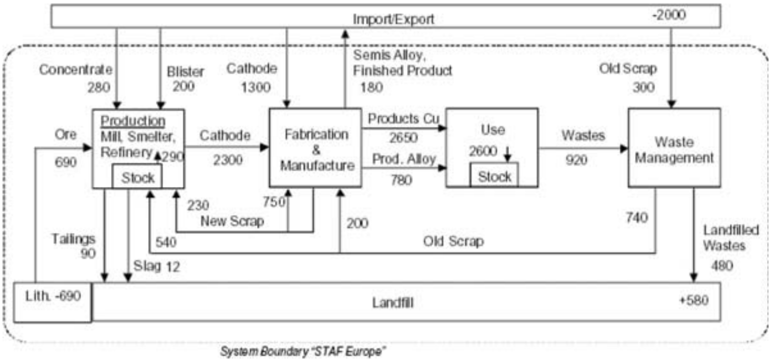


Figure 1-8. Copper cycle in Europe 1994 (from: Spatari et al 2002)

If the resource-oriented recycling quota can be increased significantly as part of targeted sustainability strategies, the consequences of another (dissipation) problem, which has been evident for some time, will increase dramatically, i.e. the contamination of secondary metal flows by tramp elements, in most cases metals that cannot be removed from the metals melting baths using the methods that are economically viable – e.g. copper and tin in steel and aluminium (cf. Marique 1997, Karlsson in this volume, Savov; Janke 1998; Janke, Savov, Vogel in this volume). At present this problem does not appear to be too pressing. Secondary steel plants achieve the requisite maximum contents of contaminants by diluting with primary metals or they supply 'contaminant-tolerant' products such as structural steel[55]. The secondary aluminium plants currently produce in particular cast aluminium qualities, which have lower purity requirements than wrought alloys. Both solutions for the problem of contaminants are, however, anything but sustainable. Once high-quality, low-contaminant metals have been included in products and received by customers – despite all advertising claims to the contrary – as far as the state-of-the-art currently permits, a car body cannot be recycled into a new car body or aluminium foil cannot be recycled into new aluminium foil[56]. And tin cans also cannot be made into new tin cans. If a batch of older tin can scrap that has not been chemically de-tinned in advance is melted down, this would produce e.g. a tin content of 0.3% in the steel[57], however a maximum of only 0.1% is tolerated in unalloyed deep drawing steel. In addition, products with lower requirements with regard to metal qualities (and/or with higher contaminant values) are returned after the service phase with the result that the contaminant content builds up gradually in this way. It would indeed be a strange inherent necessity if, as part of the process towards a sustainable metals industry, the demand for primary metal were no longer to be driven primarily by a still growing demand for metal, as is currently the case, but rather by the 'technical' requirement to 'dilute' contaminants. But the other perspective that we will one day be forced to stop feeding certain scrap fractions back into the metals cycle, but rather to dispose of them because they contain too many contaminants, also seems no less strange from a current viewpoint.

Avoiding the accumulation of tramp elements can and must begin especially at two points, firstly product design (the design and choice of material should be suitable for recycling) and, secondly, separate collecting and processing technologies for scrap[58].

6. AVOIDING DISSIPATIVE LOSSES – A STRATEGY WITH A 'DUAL DIVIDEND'

The following can be stated by way of summary: the most far-reaching problems on the path towards a more sustainable metals industry appear to occur at the boundaries between the ecosphere and the technosphere, as problems of resource availability on the one hand and problems of emissions and waste on the other. The decisive boundaries of 'resource availability', however, do not lie in the mere physical 'existence or non-existence' of resources, but rather in the effort involved, in particular the costs and the ecologically negative accompanying phenomena of their extraction: not all metal resources can and should become reserves, as the increasing effort expended on extraction of poorer and more problematic ores goes to the limits of the intake capacity of sinks. We are thus faced with a similar problem as in the case of fossil energy sources, whose usage will supposedly be restricted much faster by restricting the CO_2 discharge than by 'exhausting' the primary deposits.

Reducing the dissipative losses of metals into the ecosphere has a double benefit especially for metals, which also have problematic environmental effects: firstly preservation of resources and secondly precautionary environmental protection, preservation of the ecological and bioproductive natural capital and precautionary health protection.

Reducing the dissipative losses of metals within the technosphere also has a double benefit, especially for those metals, which are included in other material flows as problematic impurities and/or contaminants. This is concerned with the high quality of recycling, especially keeping separate different flows of metals and alloys. Only by separation and by avoiding contaminants can a high-quality recycling material be produced, thus reducing subsequent efforts expended on cleaning and creating a high-quality metal stock in the technosphere (domestic stock).

Even if the problems appear at the interfaces between the ecosphere and the technosphere, the decisive adjustment factors for reducing dissipative losses both into the ecosphere and within the technosphere are to be found less in resource or waste policies, but rather in the way metals are treated within the technosphere, i.e. especially in product design and product utilisation, and on the basis of that, also in dismantling and recycling. Only a materials flow management that essentially concentrates on product design and production utilisation and which aims to increase not only resource productivity, but also especially to reduce dissipative losses and to maintain the quality of cycles (and/or to increase it if possible), can truly bring us closer to the objective of a sustainable metals industry. Vital information and instruments to this end are, however, still missing. This doubtless includes on the one hand materials flow models, with which not only input-output relations between the ecosphere and the technosphere can be demonstrated at certain points in time, but with which the path of materials flows through the technosphere can be tracked dynamically. On the other hand, a measure for cycle quality is required. The present attempts at exergy and especially entropy audits are important contributions in this respect (cf. Ayres in this volume, Rechberger 2002 a and b, Gößling-Reisemann 2001 and in this volume).

NOTES

[1] The use of gold jewellery can be substantiated by finds dating back some 20,000 years and copper jewellery by finds dating back some 6000 years (cf. Wellmer; Wagner in this volume).

[2] Metallurgical extraction of copper from copper ores has been in evidence since around 3500 B.C. Finds of bronze tools date back to at least 3000 B.C. Finds of iron tools date back to 1400 B.C. (cf. Wellmer; Wagner in this volume).

[3] The volumes extracted for the most important non-regenerable primary materials can be taken from Figure 2-5a/b in the text by Wellmer; Wagner in this volume, pp. 50/51.

[4] The term ‘ecological rucksack’ is taken from works by Schmidt-Bleek of the Wuppertalinstitut. It is defined as the mass that has to be ‘moved’ as a whole in order to produce a certain mass of a product - in this case metal. With reference to the relevant ‘service unit’ the concept of the ‘material input per service unit’ (MIPS) was developed on

the basis of this. In an international context the terms 'material input' or 'material intensity' (MI) appear to be used most commonly at present for such an integrating view of material flows, cf. Schmidt-Bleek 1993a and 1993b and also 1994.

[5] Schmidt-Bleek 1994

[6] If the expenditure alone is considered, this ratio should actually be even considerably smaller. In this example other market factors (e.g. the cartel-like structure of OPEC) do in fact play a more important role.

[7] Cf. the authors quoted in the following. For a critical survey cf. Cleveland; Ruth 1999

[8] Any statements referring to such a lengthy period must doubtless involve major data problems.

[9] Cf. Karlsson in this volume. An explanation of the terms reserves, reserve base and resources is given below.

[10] It was also problems of this nature, such as climate, biodiversity and resource problems, which became highly visible as the result of scientific research, that essentially determined the theme of the Rio conference in 1992.

[11] Regarding the phenomenon of 'Dutch Disease' cf. Messner in this volume.

[12] Cf. the extensive contribution by Müller-Plantenberg and Baumgardt in this volume.

[13] Cf. Müller-Plantenberg in this volume.

[14] Cf. e.g. Merian 1984, Nriagu 1990, Guinée et al. 1999, van der Voet et al. 2000

[15] Cf. von Gleich et al. in this volume

[16] Sulphur hexafluoride SF_6, which is used as an inert gas in the aluminium and magnesium industry, also makes a considerable contribution to the greenhouse effect.

[17] The German steel industry has undertaken, for example, to reduce its energy consumption by 22% in relation to 1990 levels by 2012. From 1990 to 2000 it was already able to achieve a reduction of 14.5%.

[18] Cf. Daly 1990 and 1991, Enquete Commission 1998, p. 46

[19] At the same time this is also an attempt to define the model (concept) of a 'sustainable metals industry' at least in an elementary way.

[20] In view of the effort that (has) had to be expended to date to obtain somewhat reasonable statements relating to carbon flows in the atmosphere, it is evident that more is required in this area than some 'explorative' research projects. Questions relating to the corridor for a sustainable metals industry have been raised. They can be treated and, as demonstrated by the example of carbon cycles, they can in principle also be 'answered' up to a certain point.

[21] In comparison with these geological periods, the entire human history so far is equivalent only to a proverbial 'blinking of an eye'.

[22] The latter could be referred to as 'chemical losses', as opposed to purely dissipative losses.

[23] Cf. Krüger in this volume

[24] Cf. Petrascheck/Pohl 1992, pp. 4-111 concerning the elementary processes of deposit formation.

[25] Ore formation is nature's way of doing the 'preliminary work' for us, so to speak. And the more preliminary work is done, the higher the concentration and the more usable the form is in which ores are present, the lower the effort we have to expend in metal extraction on the basis of this 'natural preliminary work'.

[26] Subsequent generations may only see this differently if they have much more efficient methods of metal extraction, e.g. much higher yields (with which it may be profitable for them to sift through our heaps of excavated materials again) or also using more eco-friendly methods of metal extraction.

[27] In this respect the most feared aspect is contamination of major metal flows by radioactive elements. But also extreme contamination with other metals (so-called contaminants or tramp elements) can mean that contaminated scraps can be better 'disposed of', instead of contaminating more and larger metal flows with them.

[28] In the case of aluminium it can best be assumed that appropriate refining processes (e.g. selective crystallisation) can be applied in due course (Krüger memorandum 2004).

[29] Cf. Petrascheck/Pohl 1992, p. 1, Craig et al. 1996, 2001. The basis for such stipulations of the frequency of a metal in the earth's crust is formed by extrapolations based on the distribution of the most frequent minerals and their average metal content.

[30] Cf. Evans 1997, p. 25

[31] Data as per Petrascheck/Pohl 1992, p. 1, and respectively Craig et al. 1996, 2001, in part including updated minimum contents of extractable ores. Here again an important factor is the indication that the extractability of ores is not at all determined solely by the metal content. Much more important aspects of extractability may be e.g. the qualitative (compound) forms in which the ores are present in the ore, the accompanying minerals, the accessibility of deposits etc.

[32] This could be done e.g. using a cost-benefit analysis augmented by external costs and also using a life cycle analysis, toxicological analysis and risk analysis.

[33] USGS 2001, p. 191 Further differentiations are offered by the Institute of Materials, Minerals and Mining 2002 http://www.imm.org.uk/immres.htm

[34] Cf. BMWi 1999, p. 30. Cf. also Institute of Materials, Minerals and Mining 2002 http://www.imm.org.uk/immres.htm

[35] USGS 2001; BGR 1995; Craig 1996, 2001

[36] The factor can be determined against the background of the natural enhancement factors present to date (cf. Table 1-1) solely for specific metals.

[37] Cf. Taylor; McLennan 1985, 1996, Skinner 1986, Craig et al 1996, Craig et al 2001

[38] Oral discussion contribution for lecture on 'Sustainable metals industry'.

[39] Cf. Wellmer, Wagner in this volume

[40] This does not mean that the availability of resources does not create any impulses for the metals industry. However, what is uncertain is whether a signal of this type can be detected today directly from the declining concentrations of ores extracted in the course of the past decades.

[41] There are no quality losses in the case of metals, which are in any case subject to extensive 'refining', i.e. precious metals, copper, zinc and lead.

[42] Cf. Rombach in this volume.

[43] US Bureau of the Census 1975; US Bureau of the Census 1991

[44] The merely current proportion of recycling material contained in the entire production volume of certain metals should thus not be referred to as 'recycling quota'. This does not mean that figures referring to this are completely irrelevant, especially if they refer to larger spatial units or at best even global production. Wernick and Ausubel suggest the term 'virginity index' referring to the proportion of materials extracted directly from natural primary materials in the entire materials consumption (cf. Wernick, Ausubel 1999).

[45] Even the material that ended up at waste disposal sites could perhaps be recovered, if need be.

[46] He breaks down these losses even further in accordance with losses in post-consumer waste 13%, processing waste 5% and (real) dissipative use 0.2%, cf. Rogich 1993.

[47] In some cases 'upcycling' is also possible, i.e. quality improvement in the recycling process.

[48] The material flow of copper forms an exception in this case for various reasons. In most cases copper is used in a highly pure form (e.g. for electrical cabling). On the other hand, the recycling process, in so far as it entails another electrolytic passage, contains the possibility to remove almost all contaminants.

[49] Cf Rombach. Figure 10-6 p. 300 in this volume 'Technical and resource-oriented recycling quotas for aluminium products' in the text by Rombach contained in this volume, (as per Wolf 2000)

[50] Cf. on this subject and also regarding other dissipative flows of heavy metals into the environment, van der Voet et al 2000.

[51] Cf. Bertram et al. 2002 and Spatari et al. 2002. A model of the Swedish copper cycle in the early 1990s drafted by Nilarp assumes that 37% of the copper content entering the waste management system (10,000 t.p.a.) ends up on landfill sites (cf. Nilarp 1994, model quoted in Karlsson in this volume).

[52] Cf. Landner; Lindström 1999; Bergbäck; Johansson; Mohlander 2001

[53] Structural steel 'wins' initially due to the contaminants – at least with regard to its strength.

[54] As is generally known, scrap is also employed in the production of new steel, albeit in lower quantities and with as low as possible contaminant content. The production of deep drawing quality steel from 100% scrap is only successful if solely new scrap is used – i.e. generally absolutely pure production waste. A wrought alloy could also be extracted from a batch of pure aluminium can scrap, of which all aluminium cans comprise 100% aluminium.

[55] Over the past years the applied tin volume has, however, been able to be reduced significantly. Corrosion protection is now performed by varnish. Tin is used as a 'lubricant' in deep drawing applications (Krüger memorandum 2004).

[56] At present the appropriate measures still concentrate on the (recycling) processing technology.

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Chapter 2

METALLIC RAW MATERIALS – CONSTITUENTS OF OUR ECONOMY

From the Early Beginnings to the Concept of Sustainable Development

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1. HISTORICAL DEVELOPMENT OF METAL USE

A natural resources economy consists in two basic elements. The first is the extraction of anomalous concentrations of raw materials at often more or less remote sites. The second involves the distribution of these commodities by transport and trade among consumers who in general do not settle in the vicinity of the deposits. These two elements were already present during the Stone Age.

1.1 Technological Development

Essentially, today's working methods and fashioning techniques like cutting, sawing, rasping, scraping and drilling could already be carried out with stone tools. However, only the introduction of metal tools permitted working with reasonable precision and effectiveness. There are many other advantages of metal over stone. The most important are better workability, reduced brittleness and recyclability. Yet, in order to reach the desired results in the application of metal tools, materials as hard as their stone equivalents had to be created. One milestone on the path to metal's success was the invention of bronze, another the discovery of the technique of forging iron into steel. Bronze tools are known from around 3000 B.C., the first use of iron dates back to around 1400 B.C. These events initiated the triumph of metals, which accompanied the explosive cultural development of humankind. From then on, metals and evolution appeared to be synonymous. For a long time, the possession and use of metal deposits have been critical to the flowering and the course of nations. The periods of human development that followed the Stone Age

A. von Gleich et al.(eds.), Sustainable Metals Management, 41-68.

are named after the metals or alloys which dominated them – the Bronze Age and the Iron Age.

However, already during the Stone Age man made use of certain metals, e.g., the precious metals like gold and the "semi-precious" metals like copper. These commodities were among the first to be valued by civilisation, and they have retained their attraction for millennia. They are labelled "precious" as they occur in nature in their pure state. Like stones, they can be collected and directly used without further processing. Due to their softness, however, they could not serve as tools but only for decorative and ornamental purposes. The best example is gold, which was already being fashioned for jewellery 20,000 years ago. Copper also was used in a similar way in the Middle East from 6000 B.C. (Bednarik, 1995). Due to its ductility, it could easily be treated by hammering.

Later, around 3500 B.C., a metallurgical way was found to extract pure copper from copper ores. Therefore, the late Neolithic Age is also called the Copper Age. One of the oldest smelting furnaces was discovered near Timna in Israel, a region where copper oxides and siliceous ore were still mined between 1953 and 1984 (Rothenberg, 1990).

However, the essential step forward into the Metal Age was the discovery that an alloy combining copper and tin was harder and tougher than either of the two metals in their pure form. This alloy was bronze and had an enormous impact on manufacture and art in its universal use for tools, weapons, statuary, equipment, ornaments and jewellery. The Bronze Age, a period of some 1,500 years, ended around 1200 B.C. with the introduction of iron technology. The first iron products were simply made of hammered or wrought metal but soon primitive steels came into use. Tools and weapons of iron and steel were a vast improvement over those of bronze and gave a remarkable innovative push to civilisation. This rapid development was caused by the excellent workability of iron and steel in combination with their exceptional hardness, such that they are essential construction materials up to the present day. Moreover, iron ore deposits are relatively widespread.

The transitions from the Stone to the Bronze Age and from the Bronze to the Iron Age were slow and arduous processes covering around 1,000 years. The terms refer to particular locations, for bronze came into use and was in turn replaced by iron at different times in different parts of the world. Most likely, the techniques of mining and metallurgy were passed on via trading routes and warfare. Although, on the other hand, mining and metallurgical skills most likely developed in various regions simultaneously. At least for iron, the coinciding emergence in several civilisations can be reconstructed. The use of smelted iron ornaments and ceremonial weapons became common during the period extending from 1400 to 800 B.C. At about this time, the invention of tempering was made by the Chalybes of the Hittite empire. The oldest known item of iron shaped by hammering is a dagger found in Egypt that was manufactured before 1350 B.C. This dagger is believed not to have been made in Egypt but to be of Hittite craftsmanship. It is likely that the Hittite kings kept ironworking techniques secret and restricted the export of iron weapons. Steel was produced by using a spongy iron bloom, which can be extracted at fairly low temperatures. Next, it was repeatedly forged over a charcoal fire that provided a source for the required carbon content. The Chinese, on the other hand, had optimised the bellows technique around the same time and were able to generate temperatures high enough to produce steel by pyrometallurgical means (Raymond, 1984). Until today, a steady growth of the technical quality can be observed in the process of steel production. The enhancement in precision of machine tools is depicted in figure 2-1, showing the development of the feasible finishing accuracy.

Nature was of assistance to the early metallurgists. Primary sulfide ores, which require an intricate treatment, are often secondarily altered by weathering processes close to the surface, resulting in the so-called supergene enrichment. These altered minerals are mainly oxides and hydroxides, raw materials which may be treated in a less complex way. During weathering, even native copper, silver and gold might develop in so-called cementation zones, commonly resulting in manifold enrichment. Perhaps the evolution of civilisation would have taken another direction if supergene enrichment had not facilitated metallurgical processing of high grade ores in areas close to the surface and hence easy to access (Wellmer & Lorenz, 1999).

Therefore, these weathered blankets which developed above a sulphide deposit were – besides rock salt (in Hallstadt, Austria since ~1000 B.C.) and gemstone deposits – the targets of the earliest miners. Today, supergene enrichment is often still important when assessing an ore deposit. To optimise the economy of a mine, it is advantageous to extract and process the highly mineralised parts of a deposit during the first years of the project's lifetime. The interest formula reflects the time-value of money as the critical influential factor with dynamic economic evaluation methods. Near surface supergene enrichment zones support this management concept, commonly known as the "best-first rule", especially in open pit mines.

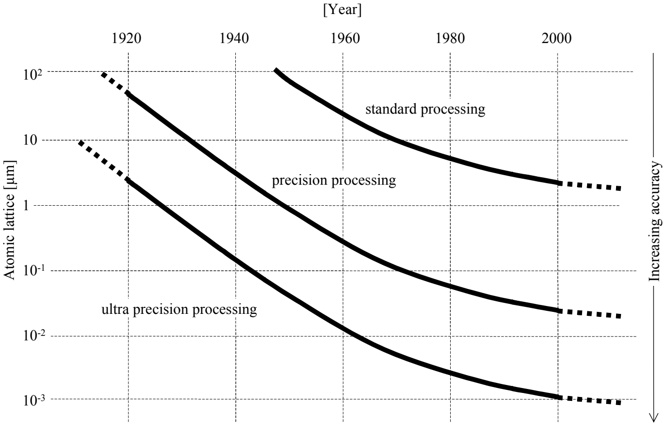

Figure 2-1. Development of feasible finishing accuracy since 1920 (after Spur 1992).

1.2 Historical Consumption

However, even though access to metals considerably improved the conditions for human development, it is obvious that compared to the present, for centuries metal consumption was very low. Throughout millennia, metals have been highly priced goods of limited availability as the following examples demonstrate:

- The best statistics and estimates on mineral production dating back to the early beginnings exist for gold. Today's annual gold production of 2,450 tonnes corresponds to the amount of gold mined in a period of 1,000 years between 500 A.D. and the discovery of the Americas by Columbus in 1492 (Mullen, 1998).
- The Steirische Erzberg, an iron ore deposit in Austria, has been mined since 700 A.D. However, until the beginning of the industrial revolution in the middle of the 19th century, not more than 8,500 tonnes of iron were extracted on a yearly basis. The nearby steel mill of Donawitz, north of Leoben, which ranks among the smaller steel producers worldwide, produces 1.2 million tonnes of steel per year, using 50% secondary scrap. Its annual production corresponds to the cumulated historic production of the adjacent deposit for a period of one and a half centuries.

These are vivid examples of the fact that consumption of minerals has exploded within the last decades. Since the end of World War II, humankind has consumed more raw materials than in the entire history before. The huge opencast copper mines are impressive monuments to our society's appetite for raw materials. Bingham Canyon in Utah is one of the largest of these giant pits. It was the first project to mine low grade ore, which required large-scale mining methods for profitable operation. The "biggest hole in the world" already made use of the concept of economics of scale at the beginning of the 20th century. Its diameter today is 4 km, its depth 1.2 km. 145,000 t of ore per day are produced. To ensure ground control and slope stability, unmineralised country rock has to be removed as well. At Bingham Canyon 263,000 t of waste are removed daily. Although the mine has been in production since 1905, the remaining ore amounts to 929 Mt at grades of 0.6% Cu, 0.03% Mo, as well as 0.36 g/t Au. At present production rates, these reserves ensure a further lifetime of the mine of more than 25 years. The operation still ranks among the twenty largest copper deposits in the world.

Obviously, there are a lot of small mines in operation, with a scale of production comparable to medieval times. However, their share in world mineral supplies is overall comparatively small and limited to certain high-value minerals. In South America only some 120 t of gold are produced by artisanal miners per year. Between 1987 and 1991, the average annual contribution of small-scale mining to African mineral production was estimated to be 40% for diamonds and 20% for gold. But virtually the whole production of semi-precious and heavy minerals within Africa, e.g. gemstones, cassiterite, colombo-tantalite – the so-called "coltan" – could be attributed to small-scale mining. (International Labour Office, 1999).

Especially in many developing nations small-scale mining is a significant factor for employment. Today, an estimated 13 million people in about 30 countries all over the world are artisanal miners, with about 80 million to 100 million people depending on such mining for their livelihood. Small-scale mining can generate substantial local purchasing power and lead to a demand for locally sourced inputs such as food, equipment, tools and housing as far they are available, or encourage their production. At the national level, the export of high-value metals and minerals from small-scale mines can make a major contribution to foreign exchange earnings.

Nonetheless, the bulk of the minerals consumed today are produced by the large-scale mining operations. Among 350 copper mines operating worldwide in 1999, the 20 largest accounted for more than 50%, the top three delivering almost 20% of the annual world copper production (figure 2-2).

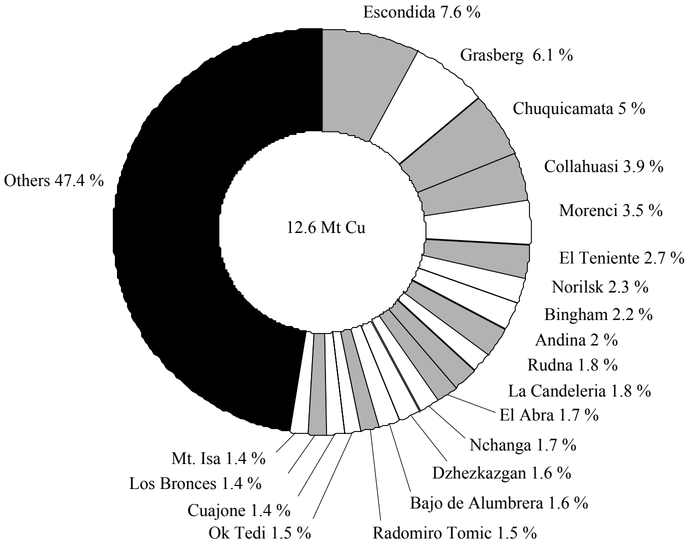

Figure2- 2. Worldwide copper production in 1999 by mining operation. In 1999, the 20 largest copper deposits accounted for more than 50% of world copper production. Chilean mines (sections in grey) produced 35% of world copper (Datasource: Metals Economic Group).

It is tempting to correlate the increase in mineral resources consumption with the increase in world population, which topped 6 billion in October 1999. Certainly, the dramatic upsurge in population during the second half of the last century (1900: 1.6 billion – 1950: 2.4 billion – 1965: 3.2 billion) coincides with the rise in mineral consumption. It is well known that the key mineral consumers are the industrialised countries, which only experienced a modest increase in population. World population growth takes place in the developing nations. However, there has been a shift in mineral consumption. Although the consumption of minerals in the third world is low in absolute terms, there has been a relative increase compared to the situation some fifty years ago (figure 2-3).

This uneven consumption pattern offers a chance to secure the future supply of raw materials: the efficiency of production and utilisation of raw materials will necessarily have to be increased. In a market economy this takes place within supply-and-demand cycles, which are controlled by the commodity prices and nourished by human creativity. Increases in efficiency require investments in research and development, which will have to be made by the industrialised nations rather than by poor third world countries. Subsequently, more economical technologies might be adopted by developing nations to meet the natural resources needs of their growing populations. This implies that developing nations might get the chance to start much higher on the learning curve of rational use of natural resources than did the industrialised world, an aspect to be picked up in chapter 4.

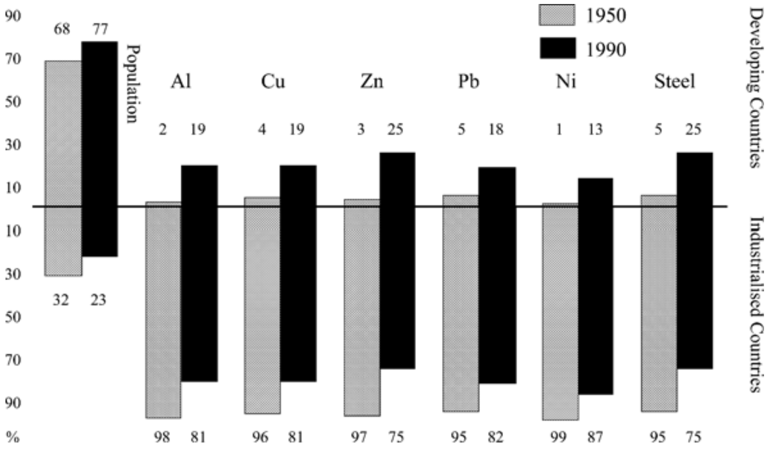

Figure 2-3. Distribution of world population and mineral consumption in the years 1965 and 1990 (Datasource: BGR – DataBank).

1.3 Early Markets and Trade

Metal ores and products were traded over long distances since they appeared in civilisation and historic trade routes can be reconstructed from finds of these products. Egyptian craftsmen relied on copper and tin ores from the Sinai to cast bronze, while the Romans purchased Cornish tin from Phoenician traders (Engels & Wübbenhorst, 1994). A speciality metal product from India was Damascene steel, which sold virtually across the entire ancient world from the first millennium B.C. until the middle ages. Due to its elasticity and hardness, it had the reputation of being the raw material for the best blades of the time. The Indians succeeded in keeping their technique a secret until the 17th century, after which the Syrians in Damascus and the Spaniards near Toledo came up with their own forging methods (Hummel, 1998).

There are early examples that illustrate the law of supply and demand on mineral markets. The West African gold boom of the early 1990s, initiated by the re-discovery of the world-class Sadiola Hill deposit in western Mali in the late 1980s, received a historical dimension when historians brought to mind the legendary king of Ghana, the western part of today's Mali, Mansa Moussa, who had gold deposits to be exploited in the nearby Bambuk region. Since his famous pilgrimage to Mecca in 1324, Mansa Moussa was renowned throughout the continent and the Middle East for his immeasurable wealth. The amount of gold of about 11 tonnes he carried with him as gifts and means of payment was huge enough in those historic times that the gold/silver ratio in Egypt fell to 1:8.5 and the gold prices in Cairo remained severely depressed for twelve years (Green, 1999).

However, in the early days, the usual way was to consume metals in the area they were produced. With the beginning of industrialisation, markets for higher value commodities, like copper, started to develop on a global scale. Copper was shipped from the copper belt in Central Africa or from Chile and Peru to Europe. The momentous step towards the globalisation of metal markets took place after World War II, however, when the size of the vessels made it possible to ship even low-value bulk commodities, like iron ore, all around the world.

In 1960, the industrialised countries of Europe and the United States mined 200 Mt of iron ore per year, equal to almost 60% of the western world's production. At the end of the millennium, iron ore production in industrialised countries was largely limited to the United States which today only produces a 6% share of the almost 1 billion tonnes of iron ore mined worldwide.

A look at the figures of iron ore imports for Germany (figure 2-4) reveals that at the beginning of the 1960s more than 50% of domestic consumption was covered by production from operations in Germany or within the adjacent French province of Lorraine. Today, this situation has completely changed. At present, Brazilian ores hold a 53% share in German iron ore consumption. The iron ore imports are far less diversified than even twenty years ago. Besides Brazil, Australia, Canada and Sweden account for more than 90% of German iron ore imports. Worldwide overseas trading in iron ore has risen from the modest volume of 123 Mt in 1960 to a total of 401 Mt in 1995. One single vessel, the 360,000 DWT "Berge Stahl", the largest ore carrier in the world, delivers almost 4 million tonnes of Brazilian iron ore to the German steel industry each year, which equals approximately the total volume of Brazil's iron ore exports in 1960.

2. CONSUMPTION OF ENERGY, METALS AND NON-METALLIC RESOURCES

Present annual world consumption of mineral and energy resources amounts to 32 billion tonnes, worth about 820 billion euros. Global mineral consumption may be presented in the form of a pyramid. The pyramid can be viewed in terms of value, tonnage, or volume (figure 2-5a and b). The base of the value pyramid (figure 2-5b) comprises the fossil fuels, whereas the construction raw materials sit at the bottom of the tonnage pyramid (figure 2-5a). The pyramids reflect the basic needs of humankind. In both pyramids, aggregates or energy resources required to meet our daily needs for housing, heating and transportation form the base.

In future, these basic needs may be met more efficiently by reducing the consumption per capita, but in principle, people's basic needs will not change.

Most of the non-metallic resources form the lower part of the pyramid, whereas metals are encountered mainly in the upper half. It is obvious that iron forms the unchallenged base of the metals within the tonnage pyramid, which justifies the idea to include our era in the Iron Age. It should be noted that with regard to value, gold ranks even above iron, which implies that the annual production of almost 2,500 t of gold bullion and jewellery have a higher value than the 500 Mt of iron which are consumed every year to maintain our living standards.

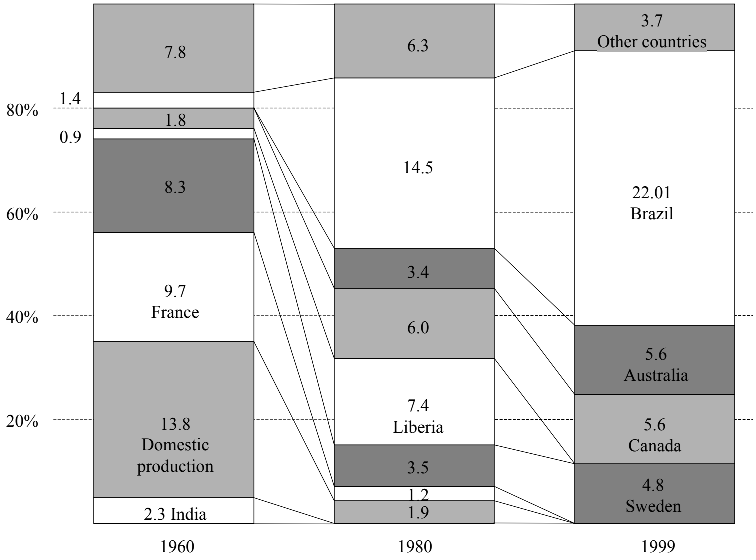

Figure 2-4. German Iron ore production and imports in 1960, 1980 and 1999 (Data source: BGR – DataBank).

As expected, the very top of the tonnage pyramid (figure 2-5a) is occupied by the precious metals and gemstones. Lately, another group of raw materials, the so-called electronic metals, are sharing their company. However, as these materials are at present indispensable in the high-tech end of the industrial process, one may argue that they govern all material flows of mineral raw materials of the pyramid below, basically all minerals that are produced and consumed. Since electronic metals are required by information technology, they are part of the key tools to achieve a higher efficiency in the use of natural resources – the only possibility to face up to global sustainable development.

3. RESERVE LIFETIME, A DYNAMIC ISSUE

Since all metallic raw materials are non-renewable resources, a reflection on consumption is generally coupled with the question of future availability. The issue of future availability is usually quantified on the basis of reserve lifetime, which is the ratio of the reserves known at present to the current annual rate of production. However, this quantification reflects only a momentary situation within a system subjected to dynamic processes. Dynamic development not only applies to mineral production but also to our knowledge about the resources.

Factors that influence reserves comprise the types of economic deposits, the distribution pattern of reserves according to the size of the deposits, mining costs, commodity price levels, the cumulative exploration efforts, developments in technology, and last but not least, human creativity. Hence, the figure of reserve lifetime is a mere statistical “snapshot” of a dynamic system, which only inadequately characterizes true future availability. Still, certain conclusions concerning the need for innovation might be drawn from this ratio (figure 2-6).

Commodities occurring in seams like potash, coal or bauxite frequently cover a considerable area. Typically, the reserve lifetime of these commodities is very high, as it is much easier to calculate and extrapolate reserves of these minerals than it is for commodities occurring in more concentrated localities. Typical examples for the latter are base metals like copper, lead and zinc, with reserve lifetimes of between 20 to 50 years only. This figure, however, has remained almost unchanged for 50 years although annual production has since then constantly risen and meanwhile is a multiple of the original estimated volume (figure 2-7).

What is the background? It is certainly not within the obligation of mining companies to determine the worldwide potential of a commodity. Instead, in order to remain on the scene, they merely have to replenish the reserves they have mined. This can be achieved by additional ore finds, new discoveries or acquisitions. Up to now, there has been no case in which a major mining company has failed to accomplish this task.

One method to replace mined out reserves is exploration. Mineral exploration is a sequential process that starts with an idea and, in case an economic deposit is discovered, ends with conducting a feasibility study. There is an economic reason to break up exploration into a number of consecutive steps. Mineral exploration is fraught with a huge variety of risks. Since exploration is a risky activity, the phased structure helps to reduce the costs of carrying out the many uneconomic steps in the sequential process by rejecting them as soon as they are perceived to be unattractive.

There is a strong connection between geology and the location of certain types of ore deposits. For instance the intrusive systems in the Pacific Rim, especially in the South American Cordillera, are prime hunting grounds for certain types of copper and gold deposits, the so-called porphyries and epithermal systems.

On the other hand, primary diamond deposits tend to occur in areas like southern Africa or the Canadian shield, which have been tectonically stable in Earth’s history for a long time and are most commonly hosted by certain rock types called kimberlite or lamproite. In consequence, geological knowledge is essential at every stage of exploration.

A project that starts in an area with a favourable geological setting but with no other indication for an ore deposit, is called a "grass-root project". The purpose of this stage of exploration is to weed out unprospective ground in favour of more promising areas. On average, 800 grass-root projects have to be professionally conducted in order to find one economically viable ore deposit (table 2-1).

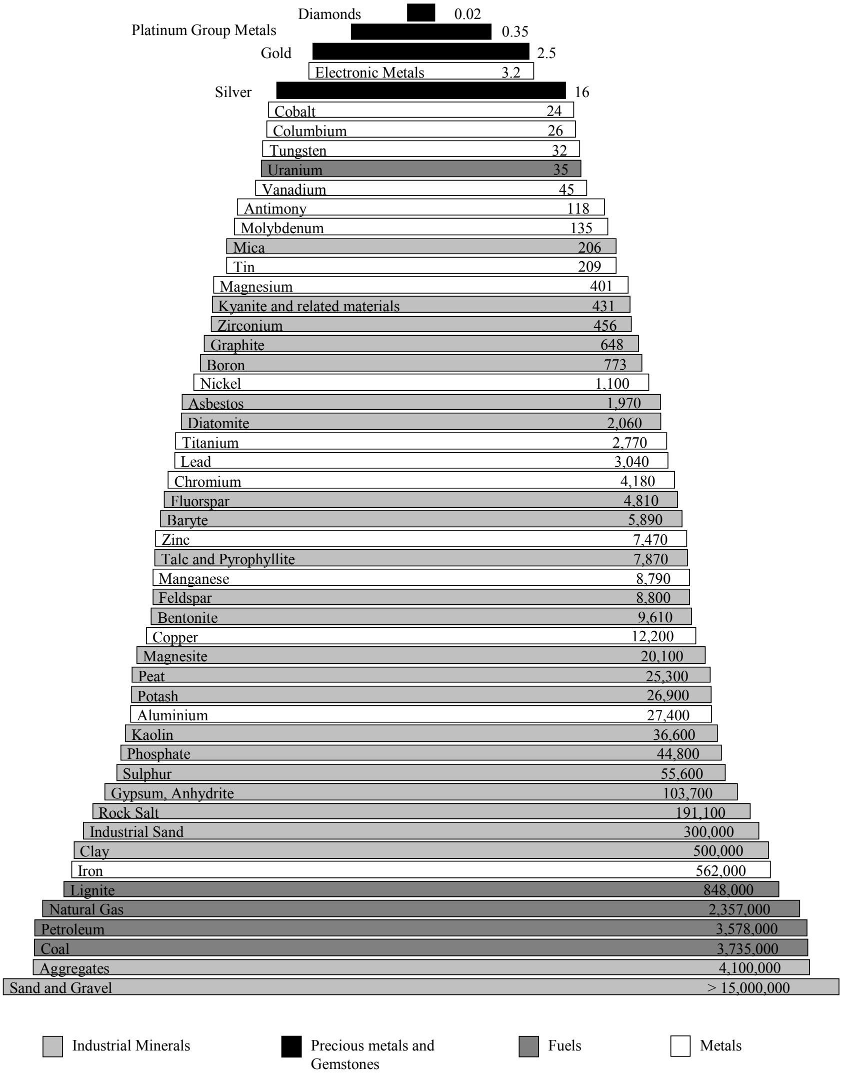

Figure 2-5a. The raw materials pyramid based on tonnage (in 1000 tonnes), reference year 1998 (Datasource: BGR – DataBank).

At each new stage in the exploration process, the focus of the search narrows, the probability of success increases and the exploration costs escalate. However, the process of learning, as described in chapter 7, is of great importance to the success of mineral exploration.

One now may ask, how many average-sized deposits have to be discovered and brought into production every year to keep the worldwide reserves and consumption balance in equilibrium, assuming consumption to be limited to a single deposit? Just considering German consumption, this is shown in figure 2-8 for typical deposit types (see, e.g., Evans 1993). As outlined above, the majority of mineral resources come from a few giant deposits. One may therefore also consider the upper 10% of these populations of a certain deposit type with regard to size (figure 2-9).

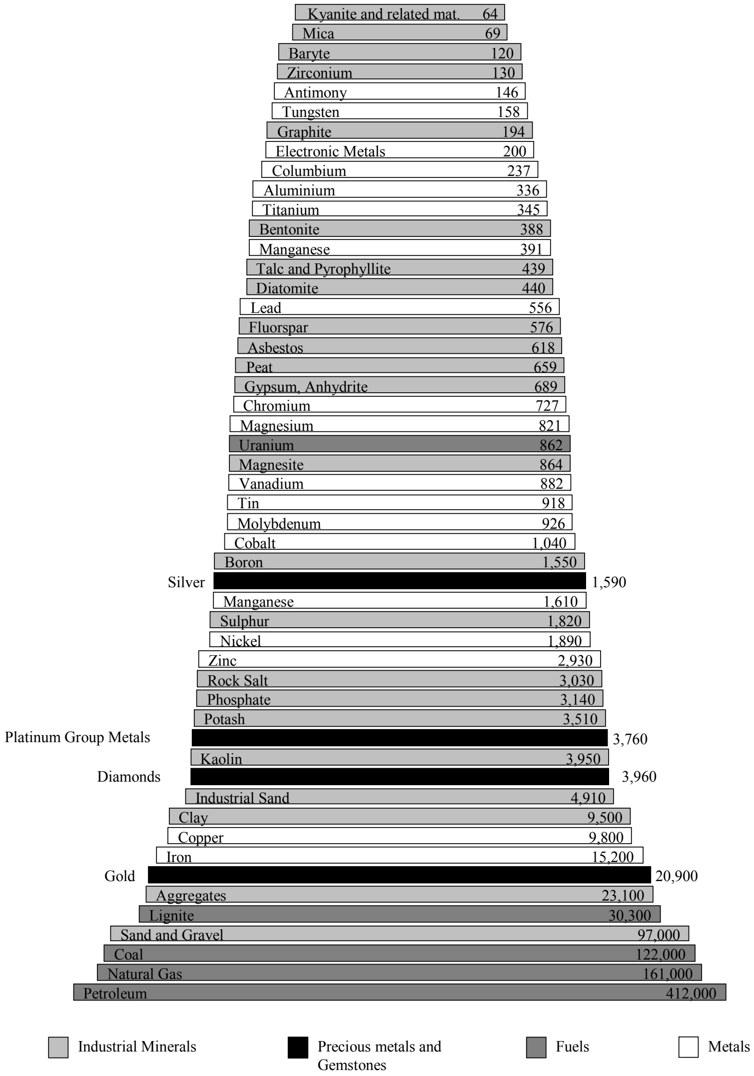

Figure 2-5b. The raw materials pyramid based on value (in million €), reference year 1998 (Datasource: BGR – DataBank).

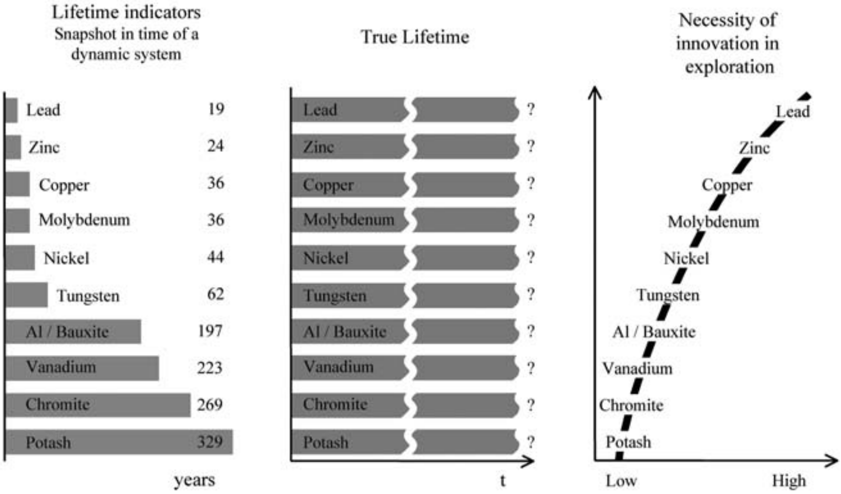

Figure 2-6. Static lifetime of reserves, true lifetime and the necessity for innovation in exploration.

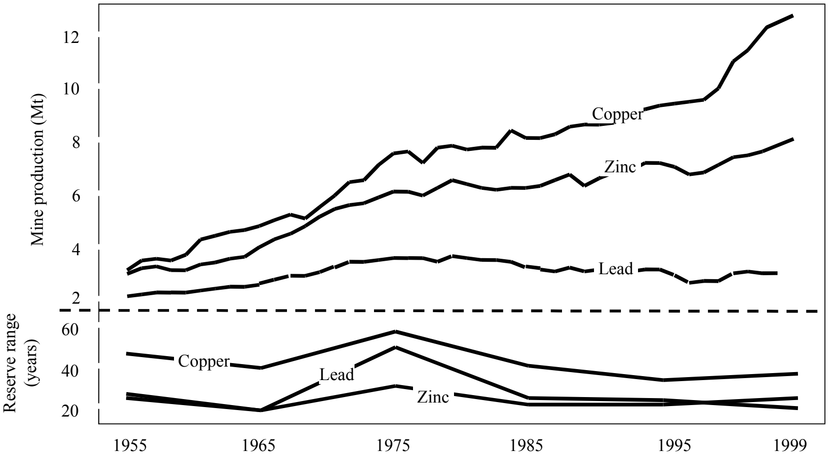

Figure 2-7. Mine Production and lifetime of reserves for copper, lead and zinc from 1955 to 1999 (Datasource: BGR – DataBank).

The figures 2-8 and 2-9 illustrate that the task of explorationists to keep the balance between reserves and consumption translates into a mission to find more than one significant copper deposit every year. Only lateritic nickel deposits which expand as weathered covers over vast areas last for almost half a century at present consumption.

Table 2-1. Average success rates for Canadian metal exploration projects guided by the state and the private industry (Sames & Wellmer 1981, MacKenzie 1989).

	PROSPECTING			EXPLORATION			
	Recon-naissance	Field-work	Samp-ling	Discovery of mineralization	Reserve calculations	New ore body	New mineable deposit
∅ all projects	2,600	1,350	750	100	35	5	1
∅ private projects	800	700	90	16	3	2	1
Base metal exploration only		>500		20	4	2	1

A common belief prevails that one has to mine lower and lower grades to supply the necessary raw materials. This opinion is only partially true. In general, it can be observed that metal grades in ores being mined are presently stagnant. The lower limit of metal grades has been reached on a worldwide scale. Even in the case of copper, for which due to economics of scale ever larger deposits could be mined at declining grades, stable ore grades can be observed today (figure 2-10). The worldwide downshift in copper grades since the mid 1980s is largely due to an innovative method of processing low grade ores: Solvent Extraction/Electro Winning (SX/EW)(figure 2-10). Rather than send low grade material to the tailings dump where its copper content would be lost, the ores are leached with sulphuric acid and an electrical current is then passed through the high grade solution in order to accumulate on cathodes copper of 99.99% purity. This process was pioneered in a developing country (Zambia) and has since been applied in well over forty mines worldwide.

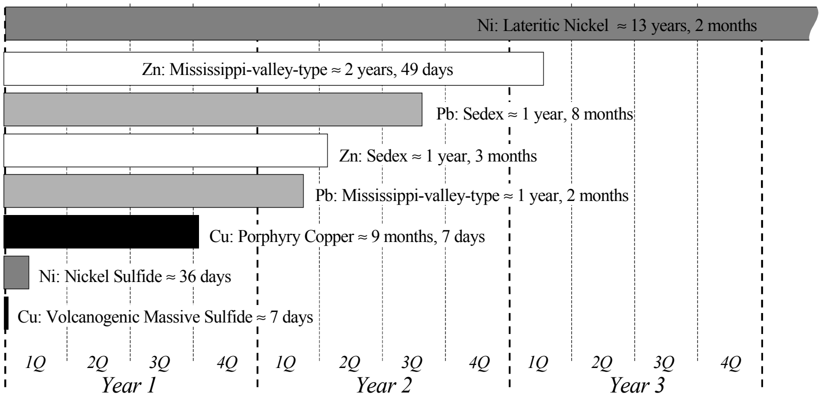

Figure 2-8. How long does a typical ore deposit last ? Hypothetical lifetime of metal deposits in relation to the annual German primary consumption in 1999. The calculations are based on the modal value of metal content of the various deposit types. Data are based on deposit models by Cox & Singer 1986.

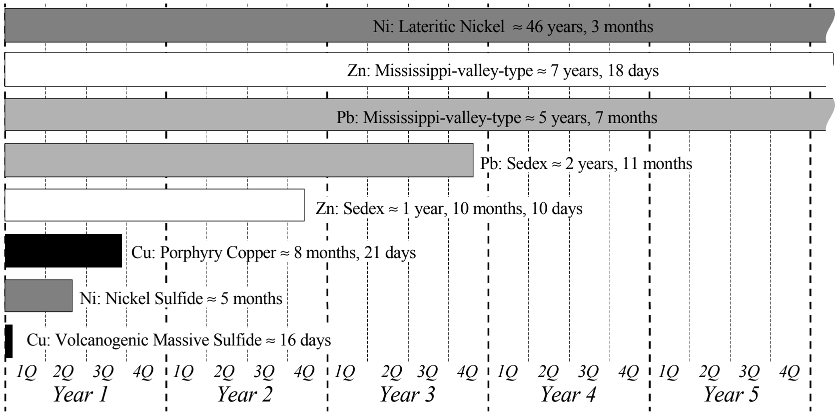

Figure 2-9. Hypothetical lifetime of metal deposits in relation to the worldwide annual primary consumption in 1999. The calculations are based on the upper 10% of metal content of the various deposit types. Data are based on deposit models by Cox & Singer 1986.

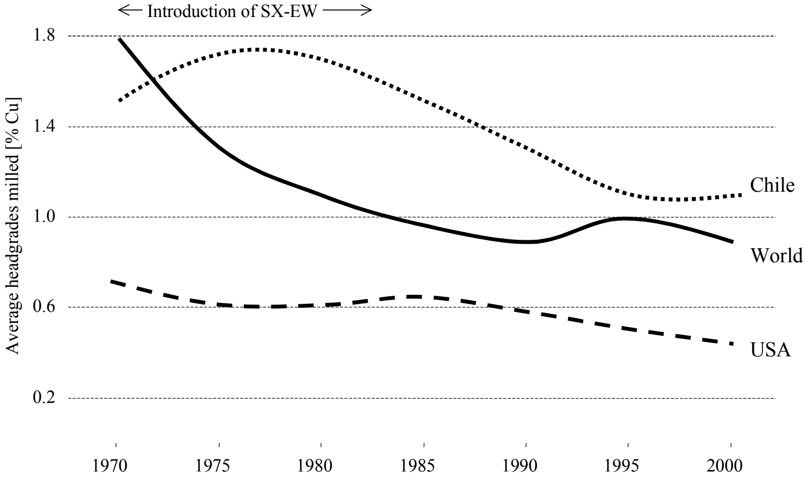

Figure 2-10. Average mill-head grades of copper production on a world-wide scale, in the U.S. and Chile. Note the decline in mill-head grades with the introduction of solvent extraction – electro winning (SX-EW) during the 1970s and early 1980s (Data source: BGR – DataBank).

From this short glance at the exploration industry it can be deduced that figures of reserve lifetime are indicators of the need for innovation in exploration. It is obvious that a far greater effort is needed to keep a dynamic balance for commodities with a short range than for those exposing very high values for reserve lifetime.

4. THE CONCEPT OF SUSTAINABILITY

By keeping a balance between resources and consumption, we are caring for the future. Within this context, the concept of sustainability has to be considered. Sustainable development is a normative term – like liberty and equality according to the philosopher Immanuel Kant. The UN Report "Our Common Future", generally called the "Brundtlandt Report", defines sustainable development as 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). This interpretation has become the widely accepted international definition. It has been complemented in the Montreal Protocol of 1989 by adding that this concept also requires maintenance, rational use and enhancement of the natural resource base. These additions underpin ecological resilience and economic growth, which imply progress towards international equality (United Nations Environment Programme, 2000).

The next step was the Rio Declaration at the UN Conference on Environment and Development in Rio de Janeiro 1992 and Agenda 21, which stresses the three objectives of sustainable development: to conserve the basic needs of life, to enable all people to achieve economic prosperity and to strive towards social justice. All three aspects should initially be considered to have the same priority. Whereas the Brundtlandt definition deals with "intergenerational fairness", the Agenda 21 stresses the "intragenerational fairness". These objectives of sustainable development based on normative terms have to be translated into practical guidelines:

In 1993, the Enquete Commission on "Protection of Man and the Environment", set up by the German Federal Parliament, formulated four general guidelines to implement sustainable development with regard to natural resources that are applicable on a world-wide scale (Enquete Kommission, 1993):

Guideline No. 1 applies to renewable resources like fishery and forestry products, guideline No. 2 refers to the use of non-renewable resources like metals. This guideline states: "The consumption of non-renewable resources should not exceed the amount that can be substituted by functionally equivalent renewable resources or by attaining a higher efficiency in the use of renewable or non-renewable resources." The interpretation is as follows: The use of non-renewable resources should not be larger than the replacement of its functions.

If one considers why humankind needs natural resources, it becomes obvious that in most cases it is not the raw material itself which is important, but the specific function it can fulfil. Exceptions might be agricultural fertilisers like potassium and phosphates, where the particular element is indispensable to the growth of plants. However, for instance regarding the electrical conductivity of copper, the above certainly holds true. This function can be performed by other commodities, sometimes using a completely different technology. For example, copper telephone wires are used to transmit information. These have been extensively replaced by optical fibre glass cables made of silica, a ubiquitous resource. Another solution to the problem of transmitting information followed with wireless transmission by using directional radio antennae or satellites. In this case the use of raw materials has been effectively reduced. Each of the three solutions to one single problem requires different materials.

The guidelines No. 3 and No. 4 of the Enquete Commission concerned with the resilience of the environment have applications to metallic resources as well.

Guideline No. 3 states that "material and energy input to the environment should not exceed the capacity of the environment to absorb them with minimal detrimental effects." Guideline 4 continues: "The rate of anthropogenic input and environmental interference should be measured against time required for natural processes to react to and cope with environmental damage."

The enhanced intensity-of-use of natural resources by recycling as much as is ecologically sound and using materials formerly considered waste products is a step in this direction. Supply and demand for mineral resources are also influenced by the tendency to use less and less raw materials for the same output, thus maintaining the level of the gross national product, a tendency which can be observed in all highly industrialised countries. Savings are not only achieved by a higher intensity-of-use of commodities but also by establishing better supply networks, as examples from the field of utilities demonstrate.

Intensity-of-use factors are defined as the ratio between unit of commodity consumed divided by unit gross national product (GNP) per capita (Malenbaum, 1978). If plotted against the GNP of various countries, this figure shows a typical bell-shaped curve. It increases with augmenting wealth of the developing countries, and reaches a peak for newly industrialised countries (NICs). Thereafter, the curve declines towards the cluster of developed nations. This tendency is not only caused by the growth of the tertiary sector but is also due to the fact that highly developed nations have learned to use raw materials more efficiently. This can be demonstrated when intensity-of-use factors are plotted for a single nation. Again, a bell-shaped curve develops for every specific commodity. However, all commodities show distinct peaks in their intensity-of-use at different times, which indicates that effects of rationalisation, and not the dominance of the service sector, are the reason for this pattern. Otherwise, the peaks should occur simultaneously (Wellmer & Berner, 1997).

In accordance with the goals of agenda 21 it has to be achieved that developing countries learn to optimise their use of mineral resources in order to avoid the inefficiencies that industrialised countries have gone through during their own development processes. If technological transfer is successful, the amplitude of the bell-shaped path should decrease, the curve should flatten. Formerly, new technological achievements always implicated an increasing consumption of primary commodities. Today, as information technology sets the pace, economic growth often coincides with a decrease in specific mineral consumption. In the light of sustainable development, it would be necessary to incorporate developing nations into this trend.

Unfortunately, the contrary can be observed: As figure 2-11 depicts, the peak of the bell-shaped curve has considerably increased, which reflects a progressively more inefficient use of resources. While among the least developed nations the situation has not changed, even a shrinking mineral consumption coupled with a decrease in GDP occurs in some cases. On the other hand, dynamically developing nations and newly industrialised countries, especially within the South East Asian region, show a strong increase in mineral consumption while the GDP per capita reveals only a modest growth. Only in industrialised countries the growth of the GDP has been decoupled from the growth of energy and mineral consumption in the long term, since the oil crises in the 1970s (figure 2-11).

Steel is mainly used for construction purposes. The heavy industries, such as shipyards, have experienced a period of strong growth within newly industrialised countries. At the same time, population has increased dramatically. This causes the peak in figure 2-11 to augment along the x-axis. On the other hand, the stagnant or even decreasing growth rates of population in industrialised countries, combined with a more rational use of construction materials and the growing importance of the tertiary sector, leads the curve to develop in an inverse sense.

5. SUPPLY AND DEMAND CYCLES OF MINERAL RESOURCES

Above, exploration was discussed as an appropriate means to keep a dynamic balance between reserves and consumption. If we apply Guideline No. 2 of the Enquete Commission, which implies that functional equivalents must be continuously found for exhausted resources, the discovery of new reserves will be only one of many possible solutions.

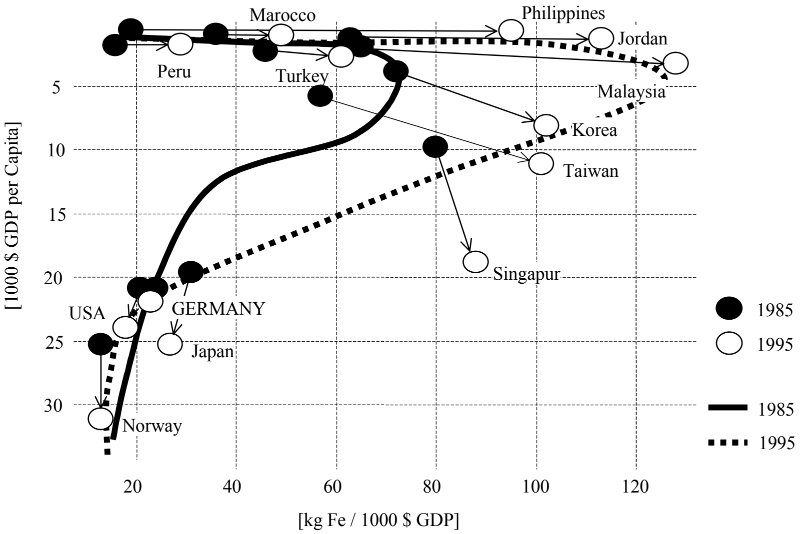

Figure 2-11. Intensity-of-use factors for steel in the years 1985 and 1995; GDP in 1990 US-$ (Wellmer & Wagner, 2000).

Others comprise:

- Enhancement of mineral recovery during mining, beneficiation, smelting and refining
- Substitution
- Improvement of recycling rates and processes
- Reduction of consumption by more efficient use and application
- New solutions as demonstrated in the case of various possibilities to transmit information in telecommunications.

The solutions to provide a replacement of the functions of resources listed above are part of a general supply-and-demand cycle. However, it is essential to consider them in connection with a further resource, human creativity. The supply-and-demand cycles for mineral resources are primarily driven by the price of the commodity, although it should be noted that psychological aspects, such as an increased environmental awareness, have an impact too. Two examples from the world metal commodity markets are given where the effect of price was the driving force towards a new equilibrium:

1.) The cobalt crisis of the late 1970s was triggered by the political crisis in the province of Shaba, formerly Zaire, now reinstated as Democratic Republic of the Congo. The province's main industrial plant is largely related to the production of minerals. Copper has been mined in and exported from the region for centuries. As for the important by-product cobalt, Zaire used to be the world's largest producer until the early nineties. The years following independence experienced a strong secessionist movement in the province of Shaba, that once again culminated in 1978 with a rebel invasion. Although the mines temporarily halted production, there was no physical shortage on the market. However, the prices for cobalt rallied from 6.40 $/lb to 45 $/lb in January 1979. Despite an increase in cobalt reserves within the U.S. National Defense Stockpile, the quotes plummeted back to 4.34 $ by November 1982.

What had happened? Formerly, little possibilities for substitution were known for cobalt in its main applications, particularly permanent magnets. In 1976, the German government commissioned a study to analyse what effect a 30% shortfall of a commodity would have on the processing industry. As for chromium and cobalt, which were considered difficult to replace, it was found that about six million jobs would be affected. This survey totally underestimated the ability of the industry to react to surging prices. Shortly after the cobalt price peaked, new materials, ferrites, were invented, replacing cobalt in permanent magnets and thereby totally changing the consumption pattern (figure 2-12).

2.) A more recent example of the industry's reaction towards price changes is the market for palladium. The platinum group metals in general have become the centre of attention in the precious metals markets. Platinum and rhodium prices have soared to multi-year highs, while during 2000 and going into 2001 palladium traded at record levels, more than doubling the 1980 peak. The supply of the metal from Russia is the main factor in the price volatility. During the last decade, a substantial gap between consumption and mine production was compensated by sales from the Russian stockpile. Palladium's main use in autocatalysts fitted to cars and trucks has strongly increased during recent years as the legislation controlling emissions from vehicles has been tightened worldwide.

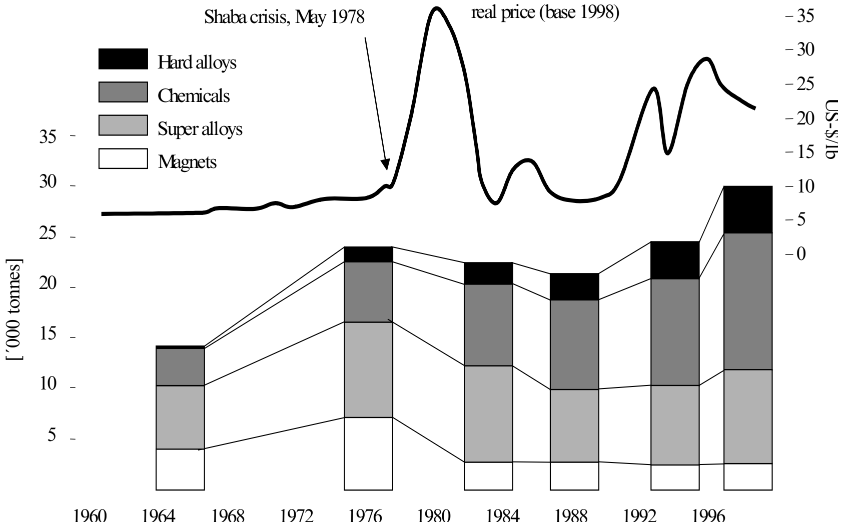

Figure 2-12. Development of cobalt prices and cobalt consumption by end-use (modified after Wellmer & Dalheimer, 1999).

However, during 2000 the rising price of palladium began to have a negative impact on demand for the metal. Substitution with other materials gained ground in electronics and the dental sector and many automotive companies publicly stated their intention to reduce their dependence on the metal, which at times had been introduced as a cheap substitute for platinum. The amount used in catalytic converters is about to be reduced by almost 50% by 2003. Supplies from western mines are strongly increasing, as project expansions in South Africa and North America come on stream. Exploration for platinum group metals, especially in North America, experienced a boom. Hence, the mismatch between consumption and mine production is likely to close. Non-automotive applications have already seen significant substitution of palladium. The rate at which substitution by other metals and ceramics proceeds in the automotive sector will have a major impact on the long-term outlook of the palladium market.

In a materials flow study of worldwide coverage recovery rates for eight commodities (iron, aluminium, copper, nickel, chromium, manganese, phosphate, coal) during mining, beneficiation and smelting were examined (Kippenberger, 1999). Table 2-2 summarises the recovery losses for these commodities during the various stages of processing, which indicate that considerable potentials for the enhancement of raw materials recovery still exist. For manganese these recovery losses are above 50%. However for chromium, phosphate and even copper, if SX/EW is taken into account, these losses lie around 30%. This is a clear indication of the need for further technical rationalisation.

Among the commodities table 2-2 deals with, only coal is completely incinerated when used. Concerning the metals the study deals with, a remarkable amount is being recycled, not to forget the energy savings that are achieved in secondary production.

Table 2-2. Losses in mining, beneficiation and metallurgy for various commodities (after Kippenberger, 1999)

	Share of world production recorded [%]	Mining losses (estimate) [%]	Beneficiation losses [%]	Smelting and refining losses [%]	**Total losses [%]**
Aluminium	Mining (79%) Metallurgy (96%)	5	4.0	5.0	**13**
Chromium	Mining (77%) Metallurgy (100%)	15	18.0	7.0	**35**
Iron	Mining (65%) Metallurgy (90%)	7	16.0	2.1	**23**
Copper	Mining (75%) Metallurgy (94%)	12	14.7	5.9	**29**
Manganese	Mining (51%) Metallurgy (97%)	10	30.7	24.0	**53**
Nickel	Mining (70%) Metallurgy (70%)	8	10.2	8.4	**24**
Phosphate	Mining (61%)	5	33.0	-	**36**
Coal	Mining (91%)	18	6 (estimate)	-	**23**

6. RECYCLING, SUBSTITUTION AND THE CONCEPT OF THE NATURAL RESOURCES HIERARCHY

Concerning the use of secondary materials the question arises: what is the principal aim of recycling? Is it to make maximum use of the secondary material, or is the main objective to minimise environmental impact by reducing energy consumption and thus CO_2-emissions to a minimum? There is a consensus that it should be the latter. Therefore, the optimum is not to recycle raw materials to 100% but to diminish overall energy consumption (Wellmer & Becker-Platen, 2001). A product can be characterised by whether the metal it contains is concentrated or whether it occurs in a highly disseminated form. An example of the use of pure and massive metal in a product is lead in car batteries. Obviously, this metal content is easily recoverable. Combined with the comparably short life-cycle of car batteries, the particular strong concentration of the metal in a specific product is the reason why such a high recycling rate of more than 50% can be achieved for total lead consumption.

On the contrary, zinc in cosmetic products or lead and titanium in paints constitute the other end of the scale. No one would ever reflect on recovering metals from these products. However, metal production from secondary raw materials, as long as they are reasonably concentrated, requires less energy than the mining, smelting and refining of primary ores. Recycled aluminium for example requires only 5% of the energy needed to extract the metal from bauxite, the primary ore. This figure accounts for 20% in the case of copper, 50% in the case of lead. The more disseminated the distribution of a metal in a secondary raw material is, the higher the energy requirements for its purification.

Figure 2-13 compares the total German consumption of lead in batteries with the calculated balance of demand for primary metal, taking recycling into account. It becomes obvious that during the last five years, due to more efficient treatment, almost all lead needed in batteries could be provided by recycling. In certain years, e.g., 1997, even a surplus could be recovered, which is available for other uses without the need to mine primary reserves.

Substituting one material for another may have more than one driving force. Costs, quality, superior properties, availability, necessity and compliance with environmental standards can each play a part, although economic advantage is often the predominant reason. Within the metal sector, constant innovation and research produces new alloys and improved metal specifications. The variety of available materials increased greatly in the 20th century. This is an ongoing process.

Driven by economics and rationalisation, substitution of one raw material for another, like plastics and concrete for metals, is constantly occurring in industry. Substitution can, however, also be looked at from the point of view of a natural resources hierarchy with respect to sustainable development (figure 2-14). Following the concept of sustainability, higher value resources should always be substituted by lower value resources, where value is determined by long-term availability. The top of the hierarchy is occupied by the most valuable resources, i.e., the energy resources. These are followed by mineral resources whose deposits are created by natural enrichment, e.g., the metalliferous deposits and industrial minerals like phosphate and barite.

At the base of the hierarchy are the waste products and residues from beneficiation, smelting and refining or the burning of higher-value resources. For example, slags from copper smelting can be processed into iron-silica stone, which due to its high specific weight and resistance, may be used for hydraulic construction purposes to secure river embankments, levees in ports and coastal fortifications, thus saving primary resources (Example 1 in figure 2-14).

The next level consists in resources, such as construction raw materials, which are almost ubiquitously present in the Earth's crust and those like magnesium or potassium, which from a geochemical point of view, occur in practically unlimited quantities in the oceans. Therefore, in some respect they might be even considered as renewable resources.

Another example (number 2 in figure 2-14) of substitution within the hierarchy are energy savings achieved by triple glazing. Glass consists of quartz-sand, dolomite, calcium and sodium carbonate. All of these are bulk raw materials with a practically unlimited availability. Of course, an additional energy input is required to manufacture triple-glazed windows. However, in time, considerable savings of fossil fuels may be realised due to enhanced insulation (figure 2-15).

The aim of mineral policy in the sense of sustainable development must be to utilise, whenever possible, the resources at the base in order to conserve resources at the top. This may be politically achieved, for example, by means as the German Waste Avoidance, Recovery and Disposal Act, which penalises waste disposal.

Instead, the law promotes maximum utilisation of waste products combined with a minimised disposal of waste, as illustrated above for slags from metallurgical plants.

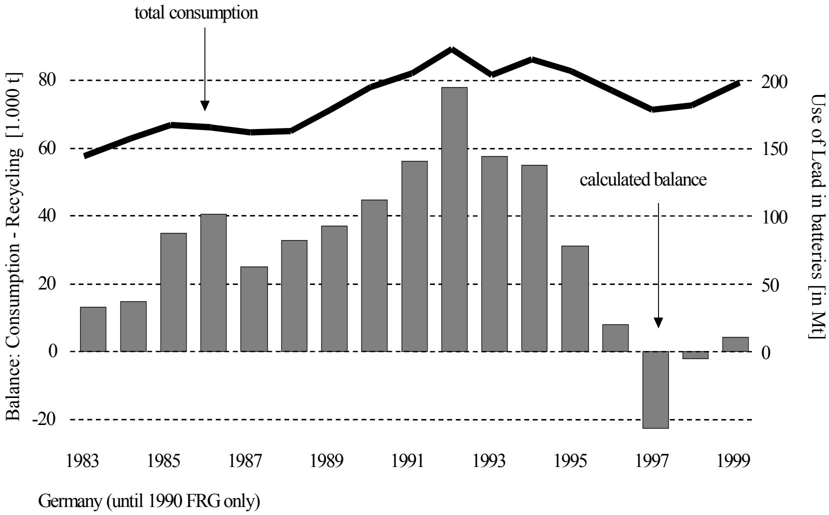

Figure 2-13. German consumption of lead in batteries and calculated balance of demand for primary metal (Datasource: BGR – DataBank).

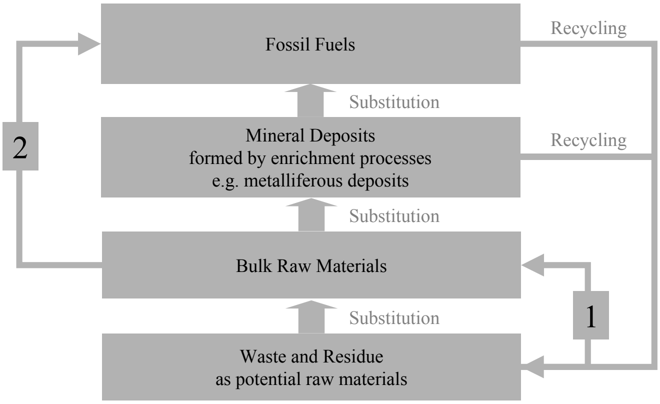

Figure 2-14. The concept of the natural resources hierarchy (Wellmer & Stein 1998).

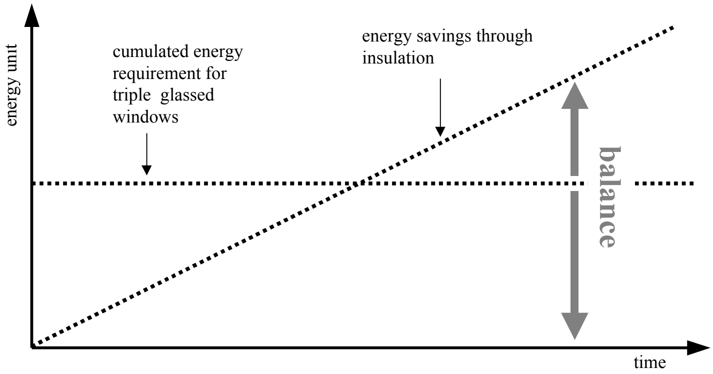

Figure 2-15. Energy savings by triple glazing.

7. THE IMPORTANCE OF LEARNING

Learning is a process that in many cases can be modelled by a sigmoidal curve. At the beginning there is very little curvature, the start-up difficulties are reflected by a low gradient. Then, the slope increases until it reaches a plateau. By then, a saturation stage has been reached and very little or no further learning occurs.

This learning curve has become a central concept in corporate strategic planning. It provides a theoretical rationale for measuring and predicting productivity improvements and growth processes. Its use has been documented in most major industrial sectors after the first observation of this kind was presented to the aircraft industry in 1936 (Wright, 1936). From various empirical approaches, a set of models was developed. The basic idea that combines the approaches to a concept can be formulated in the following two statements:

- Under certain conditions in industrial production a productivity gain is reached
- This phenomenon can be interpreted as the effect of learning

All the examples given above for methods of replacing non-renewable resources by functional equivalents, as required by the rules of the Enquete Commission, follow a learning curve. The experience shows that learning is not a process confined to a certain time interval but the phenomenon may start anew with a technological breakthrough or radical innovation.

Occasionally, in science, existing knowledge in a specific field is suddenly augmented so that it acquires a new unity and value recognised thenceforth as the established principle. Today, this phenomenon is commonly addressed as a shift in paradigm (Kuhn, 1996). In 1939, the Swedish geologist Waldemar Lindgren was already attributed as being responsible for such a shift concerning the formation of ore deposits long before the term "shift in paradigm" existed (Graton, 1939). The phenomenon can be exemplified by a learning curve describing the productivity of Canadian nickel mines (figure 2-16).

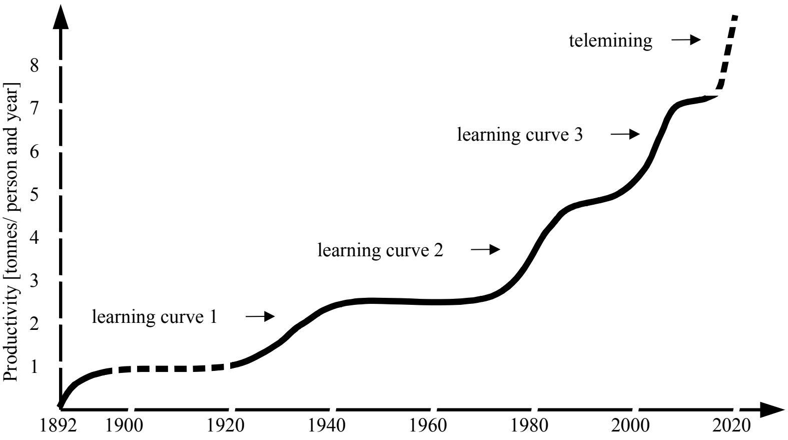

Figure 2-16. Productivity growth in Canadian nickel mines describes a multi-phase learning curve.

Learning and human creativity is a critical factor for improving the efficiency of production and the use of natural resources on the one hand and for the constant discovery of additional resources through exploration on the other.

When looking at isolated mining districts, it can be observed that meaningful discoveries of additional reserves generally do not occur during the first operational years. One explanation is that it requires time to conceive an appropriate conceptual model and to develop a customised exploration strategy. Using year-by-year production data and reserve statements, the discovery of additional reserves can be calculated and plotted representing the exploration success as a function of time. For certain deposit types, distinct curve patterns develop. The analogies within deposit groups are due to the particular spatial characteristics of orebodies as well as to their geometrical and morphological features, referred to as geological continuity (Wagner, 1999).

As an example, the Falconbridge nickel operations at Sudbury, Canada, were able to multiply their initial reserves through on-site exploration and development many times over (figure 2-17). It is interesting to note that there is an almost linear correlation between additional ore discoveries and the lifetime of the on-going operation. This coherence reflects the deposit's geometry along a steeply plunging structure, the Sudbury astrobleme. As the mining operation develops to further depths, additional parts of the deposit are discovered and classified as ore.

However, there are distinct discontinuities within this story of success. A first steep rise in reserves occurred during the Korean war in the early 1950s. A far more prominent discontinuity was caused by a mining strike during the years 1968 to 1970. An imminent physical shortage of nickel on the world markets had led to a revaluation of ore reserves at Sudbury in combination with the application of a lower cut-off. Yet, after the situation had stabilised these recalculations were not revised. Instead, the operations had learned to process the lower grade material – an example of how operational learning can influence the availability of resources.

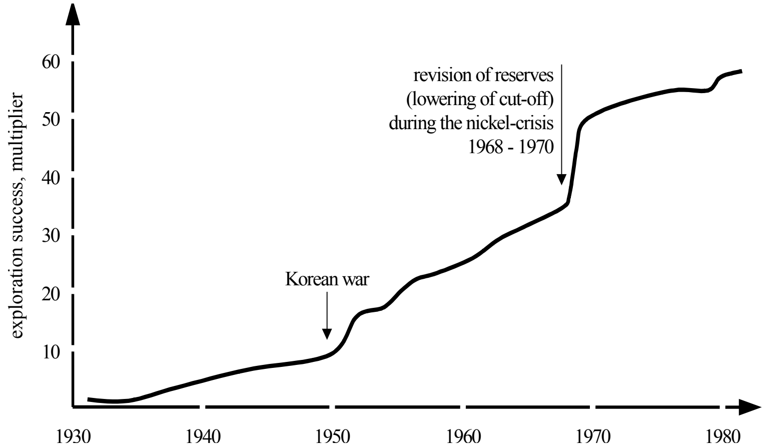

Figure 2-17. Cumulative ore discoveries of Falconbridge's Sudbury Division mines (Datasource: Canadian Mines Handbook).

8. THE SINK PROBLEM OF NATURAL RESOURCES AND ENVIRONMENTAL RESILIENCE

Rules 3 and 4 of the Enquete Commission state that the amount and rate of material and energy input into the environment should not exceed nature's capacity to absorb them with minimal detrimental effects. In the context of these rules, the problems of soils acting as a sink for anthropogenic substances has to be examined. We have to realise that man's activities have considerably increased the heavy-metal concentrations in the soil in and around urban industrial areas (Birke & Rauch 1997). Urban settings are a focal point for environmental contamination due to emissions from industrial and municipal activities and the widespread use of motor vehicles. A common example is the growing lead content in human bones in correlation with the steady growth of lead consumption (Friege et al. 1985). Soils, like all rocks, contain most elements in the periodic table, including heavy metals. Most of them naturally occur in very small quantities, the geogenic or natural background.

Therefore, increased effort has to be made to devise improved methods of reducing emissions, thereby protecting our soil so that the capacity to function as a sink is not diminished. Significant advances have been made in industrialised countries in the last decade. Nevertheless, efforts have to be continued. Again, lead may be taken as an example. A survey by Thomas et al. (1999) demonstrated that the phasing out of lead in petrol has led to a considerable reduction of lead concentrations in the environment. A recent study by the U.S. Geological Survey has also shown that lead concentrations in sediments have declined as much as 70% since the 1970s and 1980s (Calendar & Rice, 2000).

9. CONCLUDING REMARKS

The mechanism of continuously discovering new solutions for the replacement of non-renewable resources like metals is primarily driven by the commodity prices, which in turn are affected by the supply-and-demand cycles for mineral resources and the effects of learning and innovation. This mechanism has been proven to work so far in our market economy to keep a dynamic balance between supply and demand of mineral resources. There is no reason to believe that this mechanism will not function in the future. With regard to the environmental aspects and the sink issue, one can be optimistic that improved technologies will find the necessary solutions.

The more pressing problems of humankind are part of another domain: ever increasing world population and food. Fresh water and soil are needed for agriculture. In many arid and semi-arid areas fossil water is used today for irrigation. These limited reservoirs have to be considered as a non-renewable resource in the medium term. Huge quantities of soil, which also has to be considered a non-renewable resource in the face of population growth, are lost every year due to erosion and desertification, thus reducing the amount of arable land per capita on a world-wide scale (figure 2-18). It may seem paradoxical at the first glance but with regard to its future, at the beginning of the third millennium humankind should be more concerned with renewable resources than – with the exception of soil – with the availability of non-renewable resources.

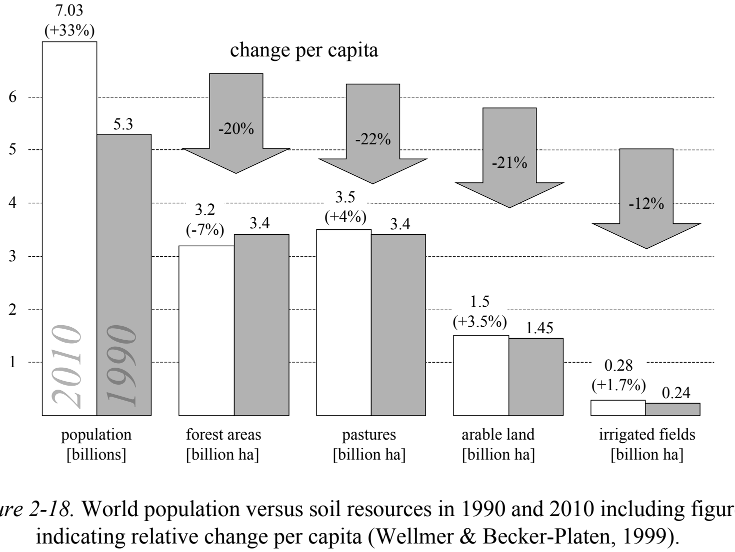

Figure 2-18. World population versus soil resources in 1990 and 2010 including figures indicating relative change per capita (Wellmer & Becker-Platen, 1999).

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2

ECONOMY, THERMODYNAMICS, AND SUSTAINABILITY

Chapter 3

ALUMINIUM

Supply and international trade

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1. INTRODUCTION

Primary aluminium processing is characterised by multi-stage processing in production locations, which are predominantly geographically distant from demand centres. While, for example, large primary aluminium production facilities are located in Canada or Australia, the main demand regions are the USA, EU-15, and the Far East. The principal production processes consist in bauxite mining, alumina refining and primary aluminium smelting. Consequently, at each processing stage international trade is important to link demand and supply.

The importance of trade differs not only between each processing stage. Because of its low added value, the share of internationally traded bauxite in world bauxite mining is rather low, compared to that of traded primary aluminium: in 1995 30% compared to 45%. Also, the importance of international trade varied in the last century and will presumably change in the future. In 1960 one fifth of world primary aluminium production was internationally traded; in 1999 slightly less than 50%.

The relevance of international trade is influenced firstly by the ability of exporting regions to competitively supply their output. The capacity to do so depends on several determinants, which can be influenced either by firms (e.g., management of chosen technology) or by government (e.g., taxation). Moreover, the resources of a region (e.g., bauxite deposits) are essential. On the demand side, preferences and politics in demand regions also affect the importance of international trade.

The aim of the paper is to analyse the determinants influencing the production of and trade in bauxite, alumina and primary aluminium. The considered factors are beyond the control of firms. In the discussion we differ between determinants that are given for firms but are not set by the government and those which are set by policy-makers, either on a local or national level. The former include the availability of bauxite and energy carriers. The latter consist in trade, tax and environmental

A. von Gleich et al.(eds.), Sustainable Metals Management, 71-96.

policy. Using a simulation technique, the presumable development of production and trade in the current decade is analysed, although not all the determinants mentioned are considered.

The paper is organised as follows: In Section 2 a short overview of the main inputs and the costs of processing of primary aluminium is given. Section 3 outlines the main trends in production, demand and international trade in primary aluminium. Section 4 deals with the incentives for trade. In the first part of the section theoretical considerations are presented. In the second part relevant determinants of competitiveness are analysed. Section 5 explores a demand-driven scenario and discusses resulting production and trade in the current decade. In Section 6 a summary is given.

2. COSTS AND INPUTS OF PRIMARY ALUMINIUM

In 1995 worldwide operating costs of mining one tonne of bauxite were US$ 15, of which 43% were labour costs and 11% energy costs. To refine one tonne of alumina in that period cost a firm US$ 150. The main cost factors were bauxite, with 34% of total operating costs, thermal energy (22%), labour and caustic soda (each accounting for 12% of operating costs). Production of one tonne of primary aluminium gave rise to costs of US$ 1350. The main cost component was alumina with a share of 33%. In 1995 electricity and labour had a share of 24% and 10% respectively (Schwarz 2000).

3. TRENDS IN PRIMARY ALUMINIUM SUPPLY AND TRADE SINCE 1900

The world production of primary aluminium amounted to just 6700 t in 1900. Today, one of the smallest European smelters could produce this volume. In 1995 the Hoyanger 1B smelter in Norway fabricated 7000 t (CRU, 1997).[1] By 1999 world production had risen to 23.6m t.

With rising output. the geography of production has changed. Not only did the number of countries increase from five in 1900 (USA, Switzerland, France, Germany and the United Kingdom) to more than 40 in 1999, but the centres of production also shifted away from these five countries (figure 3-1).

The trend in the variation of production geography began quite early in the first half of the last century. However, in 1940 more than 80% of primary aluminium was still produced in North America (now including Canada) and Central Europe. At the end of World War II, with the rise of socialism and decolonisation, the change in production geography sped up dramatically.

Following the example of the Soviet Union in the period before World War II, a broad industrialisation of the economy was the main development strategy in many newly established countries in Africa and Asia as well as in the, until then mainly agrarian countries in Latin America and also in Australia. Another motive, predominantly in socialist economies, was to become independent of the supply of industry products from "capitalist" countries. As a part of these strategies and motives these countries began to build, more or less systematically, new production facilities, thus reducing the importance of the five "original" producing countries. In 1999 these five economies shared about one fifth of total output.

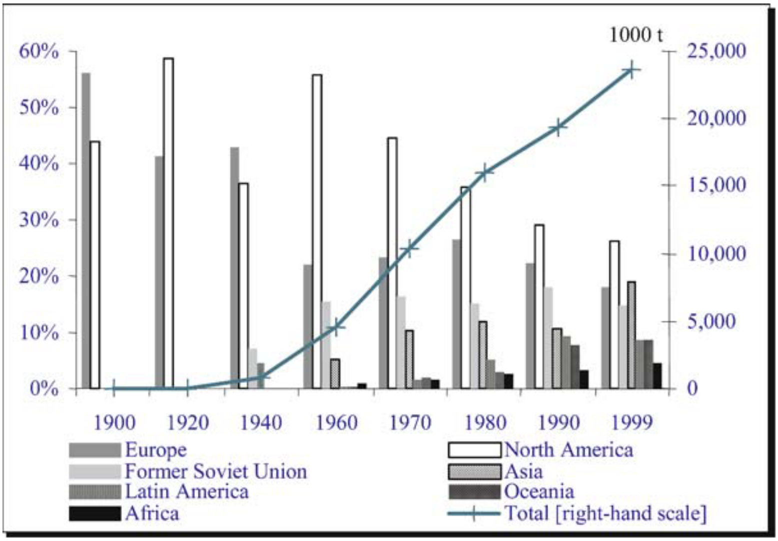

Figure 3-1. Production of primary aluminium, 1900-1999. Sources: Own calculations based on Metal Statistics and Aluminium-Taschenbuch.

Looking at production geography in 1999, the most important regions were North America (26% of total output), Asia (19%) and Europe (18%).

In the longer run, the world supply and demand of primary aluminium are balanced. Consequently, the consumption of primary aluminium developed in a manner comparable to production, reaching about 23.6m t in 1999.

In the pre-war period, no important centres of industrialisation existed outside North America, Europe, and Soviet Union. Therefore, consumption of primary aluminium was centred in these regions. In keeping with production geography, with the end of World War II the distribution of demand to different regions changed. In the following, only the period after 1960 is discussed, as from that year onwards detailed data were available. Since 1960 the old centres of consumption (Europe and North America) have lost their importance as main demanders and they have been mainly replaced by Asian countries.

In 1960 North America consumed about 40% of world production. By 1990 this share had dropped to just 25%. However, due to a long-lasting economic boom in the USA, until 1999 an edging up of the share to 30% can be observed (figure 3-2).

The development in Europe is apparently comparable to the one in North America. Europe's share dropped to 27% in 1999 from 36% in 1960. But the decline is not as dramatic as in North America. And no recovery of the share is observable.

One reason for this is the collapse in demand in the transition countries. A drastic decline of demand is evident in the Former Soviet Union (FSU) as well (figure 3-2).

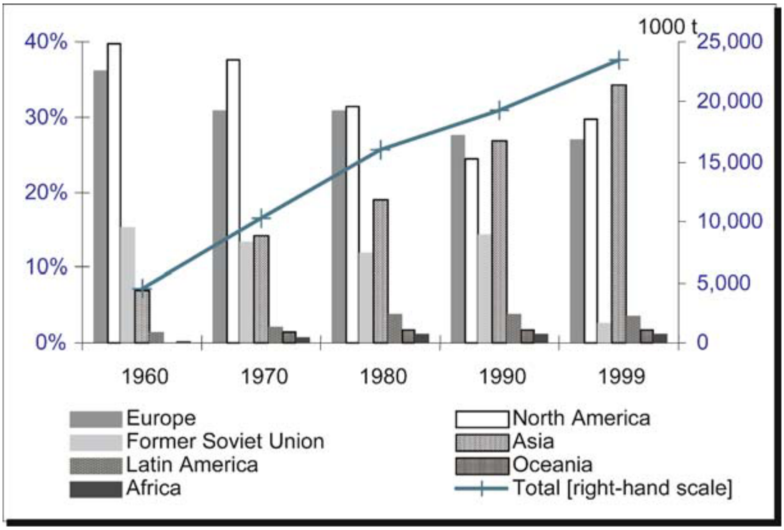

Figure 3-2. Demand for primary aluminium, 1960-1999. Source: Own calculations based on Metal Statistics.

Asia is the only region where demand has increased above the world average. In 1960 only 7% of primary aluminium was consumed in that region, in contrast to more than 37% of world production in 1999. The driving "forces" of that development were Japan (since the 60s), the newly industrialised countries in Southeast Asia (in the 80s and 90s) and China (since the 80s). The consumption in the other regions, Latin America, Australia, and Africa, did not change much (figure 3-2).

Trade volume also increased in keeping with production and demand. However, in the last 40 years growth in trade volume has been more than twice as high as in production. Since 1960 trade volume has grown on average by 30% annually, and production by 13.3% (figure 3-3).

Although trade volume has grown continuously since 1960, the importance of trade, measured by the share of trade volume in production, has not. Until 1980 the share dropped from 23% to 20%. That means until 1980 production increase occurred mainly in those countries where demand escalated. This changed in the 80s and 90s. In the two decades, the trade share exploded from 20% to more than 44.5%. Thus, in that period regional production and regional demand grew apart.

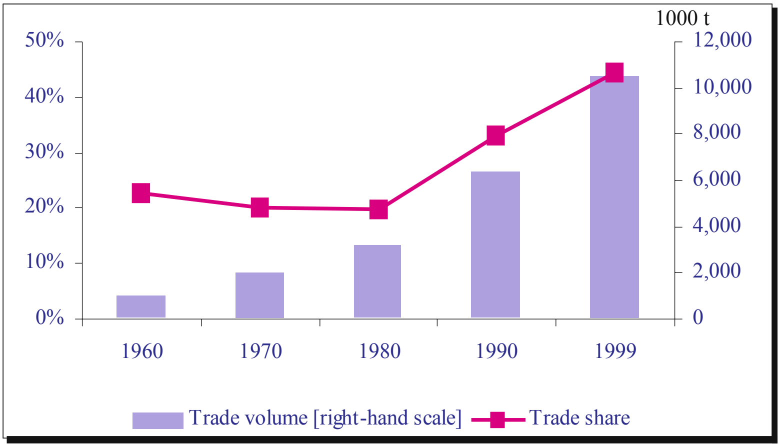

Figure 3-3. Trade in primary aluminium, 1960-1999. Source: Own calculations based on Metal Statistics. As trade data were not available, the difference between domestic production and domestic consumption was used as a proxy for trade volume. Trade volume is defined as half of the sum of import and export of all countries. Trade share is the share of world trade volume in world production.

Looking at the changing pattern of trade relationships, two developments seem to emphasise the increasing importance of trade:

– Exploitation of comparative advantages in exporting and importing regions. A typical example is the development of the Australian primary aluminium industry. Australia has comparative advantages (the underlying theory will be discussed in the following section) in producing primary aluminium. Bauxite is abundant in Australia. As since the 60s demand in Southeast and Far East Asia has grown considerably and smelters in that region could not satisfy the demand, in the 80s the Australian aluminium industry became an important exporting industry. Today, Australia produces mainly for the world market and not for domestic consumption which, in relation to the output, is almost negligible. Another example is the USA. Until the 80s American industry exported primary aluminium. This changed in the 80s. Since then supply conditions in the USA in relation to those abroad have worsened. Consequently, production capacity has dropped even though demand, especially in the 90s, increased considerably. In 1999 nearly 40% of domestic demand was imported.

– Collapse of the FSU. In the aftermath of the collapse of the FSU and the following economic decline in that region, domestic demand for primary aluminium slumped completely. Since production did not change considerably compared to 1990, a rising gap between production and domestic demand emerged. The excess supply was exported. In 1999 domestic production outstripped domestic demand by nearly 2.8m t. The respective figures for 1980 and 1990 were 570,000 t and 730,000 t.

In 1999 the main exporting countries were Russia (24.6% share of world export volume in 1999), Canada (15.4%), and Australia (12.9%). The main importing countries, or regions, respectively, were the EU (27.3% of world import volume in 1999), USA (23.1%), and Japan (19.9%).

4. INCENTIVES TO TRADE ALUMINIUM GLOBALLY

4.1 Driving forces for trade: Theoretical considerations

The figures presented above reveal the increasing and now overwhelming importance of trade. Our in-house simulation for the current decade confirms this trend (cf. Section 5), even though the change of trade volume will be not as drastic as in the last twenty years. In the section above, two suggestions were offered explaining the rising relevance of trade, at least in primary aluminium. As the second one – the collapse of the FSU – is rather intuitive, the sources on which the first one is based are derived from the theory of international trade.

From the theoretical point of view countries[2] engage in international trade for two basic reasons:

- Countries trade because they differ in supply conditions,[3] and
- Countries trade in order to achieve economies of scale in production.

4.1.1 Comparative advantage

Nations, like individuals, can benefit from trade by reaching an arrangement in which each supplies the things it produces relatively well, as long as they differ in supply conditions. The outcome is traded between participating countries. All economies can gain from such an agreement even if one of them can produce all the goods more efficiently than all the others. It is sufficient that a country produces predominantly those goods with which it has a comparative advantage over foreign competitors. The main reason why all economies benefit from such an arrangement is that economies are constrained by resources, factors, and time. However, such a deal will not ensure that all economic agents in an economy will necessarily profit from trade.

A country has a comparative advantage in supplying a good if the comparative costs of producing that specific good are lower than abroad. Comparative costs are the costs of one domestically produced good with respect to the costs of other domestically produced goods. Due to the concept of comparative advantage, each country should produce at least one good with a comparative advantage.

A simple numerical example will clarify the concept of comparative advantage. The world is divided into two countries, which produce with one factor – labour – two goods, cheese and wine.[4] The home country has lower unit labour requirements, i.e., higher labour productivity, in both industries. The home country needs 1 unit of labour to produce one pound of cheese and 2 units to produce one gallon of wine. The corresponding figures for the foreign country are 6 and 3. Thus, the comparative costs of cheese production are at home ½, abroad 2. But the comparative costs of wine production at home are 2, abroad ½. The home country has a comparative advantage in cheese production in the same way as the foreign country has one in wine production. This means a worker at home would earn only half as much producing wine as he does producing cheese, while the reverse is true for a worker abroad. Following the theory, trade should progress along this comparative cost pattern.

In accordance with the traditional theory of international economics, we assume perfect competition in all markets. Thus, the market price of cheese in terms of wine is determined by the opportunity costs of cheese. The opportunity costs are determined by the unit labour requirements in cheese production per unit labour requirement in wine production. Due to this, in case of no trade, the relative market price of cheese at home is ½, abroad 2. Since in a trade situation the relative price of cheese should be identical in both countries, the world price must lie between these values. For the sake of argumentation, the world price is set at one: a pound of cheese trades for a gallon of wine on world markets.

Both countries gain from trade as both countries can use labour more efficiently than without trade. At home one hour's labour produces only ½ gallon of wine. The same hour could be used to produce one pound of cheese, which can be traded for 1 gallon of wine. It is obvious that the home country would not profit if it exported wine, i.e., the product with which the foreign economy has a comparative advantage. The reverse is true for the foreign country.

The so-called Ricardian world is far too simple to give a complete analysis of either the causes or the effects of international trade. It was just used to explain the essential concept of comparative advantage. Although differences in labour productivity explain the existence of foreign trade, divergences in countries' resources is seen in traditional international economics as a main push factor for international trade. This is emphasised in the Heckscher-Ohlin-Samuelson approach. The main finding does not contradict the concept of comparative advantage. A country should tend to export those goods whose production is intensive in factors with which they are abundantly endowed, compared to the foreign country. The relative price of a factor will be lower in that country in which it is plentiful, compared to the foreign country.

The development in primary aluminium trade in the second half of the last century could be explained according to the Heckscher-Ohlin-Samuelson approach. Canada and Australia are abundantly endowed with intermediate goods and factors (Australia: bauxite and consequently of alumina and cheap coal; Canada: hydropower). Thus, their becoming leading suppliers of aluminium worldwide follows the logic of the model.

4.1.2 Economies of scale

Traditional theory centres on divergences in production conditions. But a great deal of trade worldwide is carried out between countries with rather small divergences in resource and factor endowments. This is inter alia a consequence of the increasing opening of economies and continuous flow of knowledge in research and development of products and processes at least among industrialised countries. The latter is a result of the former. And the former was a starting point for the "internationalisation" of firms, i.e., the willingness of enterprises to trade and, in a second step, to produce goods internationally.

Modern production of important final and intermediate goods is characterised by firm specific economies of scale.[5] Rising production leads to decreasing average costs. If a supplier has an innovative edge, he can expand his monopolistic profits. If a firm has to compete in a market with almost identical products, decreasing average costs permit it to reduce prices and to improve competitiveness.

On the assumption that a producer wants to expand his profit, notwithstanding that in economic theory profit maximising behaviour is generally assumed, he will expand his production level up to the point that the average costs are minimised. If the produced amount is larger than domestic demand, the producer has to supply part of the production abroad, generating international trade.

In a changing world with integrating economies, comparative advantages of regions can and will change. For this reason, firms that are engaged in international production will make use of the comparative advantage of distinct regions by focusing new production centres in such regions. A consequence could be that production in countries with high demand will migrate to regions with comparative advantage but low demand, for example in the case of primary aluminium from the USA to countries like Canada. Consequently, trade between economies will increase.

4.2 Determinants of competitiveness of processing primary aluminium

The theoretical considerations as well as the examples have shown the relevance of supply conditions for the development of production in a country and the pattern of international trade. As the argumentation was rather theoretical, in the following Section some conditions will be discussed that are relevant for the competitiveness of primary aluminium processing. The section focuses on the availability of natural resources such as bauxite and energy carriers for electricity production.

The world depicted in the traditional theory of international trade is characterised by the assumption of perfectly functioning markets. This assumption implicitly assumes that all firms compete in an identical political framework, since only the supply conditions differ between regions. Looking at the "real world" this is an idealistic assumption. Without going into detail, policy-makers heavily influence the economic environment of a firm by e.g., raising import duties. In Section 4.2.2 some of the most important features for the primary aluminium industry will be analysed. These aspects comprise electricity prices, import tariffs, taxation regimes, internalisation of external effects as part of environmental policy and export dumping policies.

Although the chapter cannot supply a fully detailed discussion of this wide range of aspects and their relevance for specific countries, it serves to give a picture of the present aluminium industry and its forces for structural change and adaptation of global trade.

4.2.1 Factors determined by natural environment and market organisation

Although factor endowment with respect to natural resources was not the focal point in trade theory, obviously bauxite must be available to be traded. For 1999 world bauxite reserves[6] are estimated to be 25bn t. There are numerous bauxite deposits mainly in tropical and subtropical areas, but also in Europe and elsewhere (figure 3-4). Reserves are unevenly distributed throughout the world with Guinea, Brazil, Australia, Jamaica and India ranking as the five richest countries, possessing 75% of worldwide reserves. Average static lifetime (ratio between present reserves and annual production) indicates an adequate bauxite supply for nearly 200 years. Country-specific lifetime is unevenly distributed, with Greece, Brazil, Guinea and India as countries with static lifetimes of more than 200 years (Hausberg et al. 2001).

Global bauxite resources are estimated to be 55-75bn t (U.S. Geological Survey 2000) mainly located in Latin America (33%), Africa (27%), Asia (17%) and Oceania (13%).

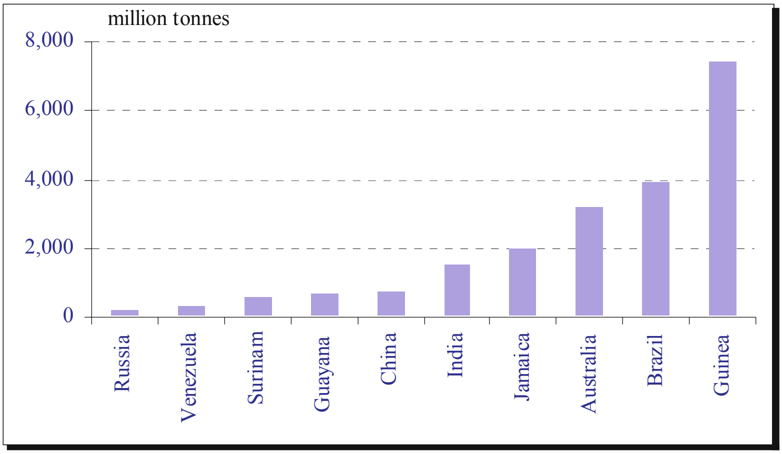

Figure 3-4. World bauxite reserves, 1999. Source: U.S. Geological Survey (2000).

To produce aluminium, large amounts of energy, particularly electricity, are necessary. As electricity transport over long distances is not profitable, investment in smelters requires sufficiently cheap local energy sources. According to IPAI statistics, 53% of smelters worldwide are supplied by hydropower and 31% by coal-based power. Gas-based power, nuclear electricity, and oil-based power contribute 9%, 6% and 1% (IPAI 1999).

Hydropower is regarded worldwide as the cheapest among the alternatives. Therefore, new smelter capacities very often result in combination with sufficient availability of hydropower, e.g., in Canada, Latin America, Norway and Iceland. However, other countries with sufficient availability of cheap fossil-based electricity show an increase in capacity too, e.g., Australia, India and China.

As figure 3-5 indicates, for Asia (India), Oceania (Australia) and Africa, fossil-based sources of electricity are dominant. Only Europe (Germany, France) shows a high share of nuclear energy. In North America, Latin America (Venezuela, Brazil) and partly in Europe (Norway) hydropower dominates. Although some countries did not report to IPAI (e.g., China, Poland, Russian Federation). Figure 3-5 gives instructive information on the structure of the electricity supply world wide.

Due to the high specific electricity demand per tonne of primary aluminium, the price of power is a very sensitive parameter. High-electricity-price aluminium producers pay twice as much as low-electricity-price producers. In 1997 the aluminium industry average worldwide was US$ 20.7/MWh. Canada had the lowest tariffs and Asia and Eastern Europe the highest (CRU 1997).

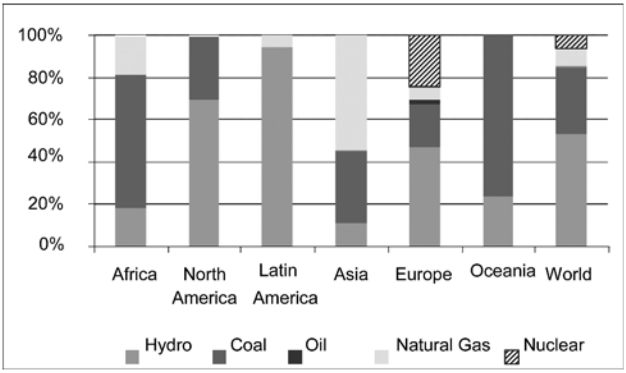

Figure 3-5. Electrical power used in primary aluminium production, 1998. Source: IPAI (1999).

Of the electricity supply in 1996, 61% was based on contracts with fixed prices and 39% on contracts with metal-linked variable electricity prices (CRU 1997). Contracts with variable electricity prices are orientated towards the price of aluminium on the London Metal Exchange.

The two price regimes differ in risk sharing between the aluminium industry and electricity suppliers (Craul 2000). Aluminium companies with fixed electricity prices take the full risk of falling metal prices but also take full advantage of rising prices. In the case of metal-linked electricity prices, the aluminium industry and energy industry share the risks and advantages, since with falling aluminium prices the price of electricity drops as well and vice versa. Analysts interpret this price regime as offering competitive advantages to parts of the aluminium industry. Canada, Latin America and Australia are the regions with the highest share of metal-linked electricity prices.

4.2.2 Policy-induced determinants

Subsidies

Very often, low and variable electricity prices are considered to reflect a special kind of subsidy (Kirchner 1988, Adams 1990). This assessment requires a subtle analysis. For example, price differentiation with low prices for aluminium processors or risk-sharing based on metal-linked variable electricity prices could be means of securing markets for the energy suppliers (Spies 1990). In these cases, the assessment of subsidies is not tenable. In certain cases, e.g., Venezuela in 1998, due to high metal prices the aluminium industry pays even higher electricity prices than private consumers (Pinto 1998).

A local or governmental body can affect the electricity prices for aluminium processing firms directly, by subsidising the price, or indirectly, inclining the policy of a power-generating enterprise. A specific influence of local or governmental policy can be assumed if either a power-generating enterprise has monopolistic power or the existence of that firm is politically guaranteed. In both cases, policy-makers additionally have to have the capability to directly or indirectly influence decisions by that firm. Monopolistic power is crucial for having the opportunity to offer different prices to different groups of consumers (Kirchner 1988). If the existence of a company is guaranteed, it is not pressured to set prices according to the constraint of profit making. Hence, the appointed prices can follow other, e.g., social or political, considerations. Certainly, these conditions are not generally fulfilled. Worldwide, the electricity sector is structured very differently, ranging from government controlled and monopolistic to private and competitive power supply. In the course of the deregularisation of electricity markets in several countries, e.g., the EU, the power supply is organised more and more privately and competitively. Hence, affected power suppliers lose their ability to vary prices among consumer groups. Additionally, governmental ability to control the power supply is diminishing.

Deregularisation and privatisation is, however, no obstacle for policy authorities to arrange price schemes for selective industries and lessen the effects of these policies on electricity prices paid by these industries. For example, in the Australian state of Victoria, a long range contract – running from 1984 to 2016 – between smelters located in Victoria and the then state-owned electricity provider was fixed, leading to a decoupling of electricity prices paid by smelters from market prices for electricity. In the year 2001, the state agency in charge made losses of about \$17.50/MWh of power demanded by smelters, filling the gap between the electricity price paid by smelters of \$13.50-15.50/MWh and the market price of \$31-33/MWh. Another way of subsiding the price is used in the Northwest of the USA. In that region an agency of the US Department of Energy provides to smelters situated there power for a price of about US$ 8/MWh below market price (Turton 2002).

Import tariffs

In general, import tariffs serve to protect domestic industries against foreign competition. Whether they result in gains for the totality of domestic industries depends on some conditions not discussed here.

A lot of countries charge tariffs on imports of bauxite, alumina and aluminium. Before the Uruguay Round, the only alumina-producing countries levying tariffs on bauxite imports were India (45%) and Venezuela (5%). Alumina imports were taxed by India (65%), China (20%), Poland (10%), EU (5.5%), Argentina (5%) and the Russian Federation (5%).

With 4.4% to 9% generally low, although significant, tariffs on unwrought aluminium were levied by China, the European Union and others. For India, the tariffs were 60%. Tariffs on waste and scrap were normally zero (with a few exceptions), while tariffs on powders were generally higher than on unwrought aluminium. Tariffs on semi-fabricates were significant in most countries (for details cf. UNCTAD 1996).

Except for India, tariff concessions, negotiated during the Uruguay Round, were generally small. For bauxite and alumina Indian tariffs were reduced to 25% and 40%. However, compared to other countries, Indian tariffs remained high. In total the Uruguay Round tariff concessions are unlikely in themselves to lead to major changes in trade patterns (UNCTAD 1996). For the tariffs themselves, this conclusion cannot be drawn. At present, the discussion on the necessity and efficiency of tariffs for aluminium products, or rather on further concessions, is still ongoing.

Mining taxation policy

Taxation is the main source of income for any government. Unlike other industries, natural-resource-based industries, such as bauxite mining, are affected not only by capital taxes but by royalty taxes as well. Raising royalty taxes expresses the government's desire to benefit from the presence of bauxite deposits on its territory and resulting scarcity rents.

There are quite a number of mining taxation regimes (Mining Journal 2000). They are structured differently with respect to income taxation and royalty taxation, optimally reflecting a kind of balance between stakeholders' needs, as expressed by the government and the mining industry.

In some cases, analysts agree that tax regimes reduce the comparative advantage countries once enjoyed over their competitors. Jamaican mining tax policy is an example (Nappi 1992). The government raised a uniform royalty tax on each tonne of bauxite mined on its territory and a production levy on bauxite mined linked to the average world market price of aluminium ingots. Fiscal reforms in the seventies raised the total taxes collected by the government on each tonne of bauxite mined from US$ 1.77 to US$ 15.08 in 1977. A further fiscal reform in 1979 introduced a two-tiered system of tax on bauxite production, differing between a basic production of 13m t and incremental production with a lower tax rate.

This rapid increase of specific taxes accompanied a development where Jamaican producers were confronted with competitors supplying higher quality but cheaply processed bauxites, e.g., Guyana and Australia. To some extent, the unequal fiscal treatment of mining activities explains the decline in competitiveness of Caribbean countries like Jamaica in favour of countries like Brazil or Venezuela (Nappi 1992).

Environmental policy: Internalisation of external effects

The phenomenon of external effects is theoretically well understood and documented and well accepted in practical terms. Modern environmental economics and policy offer a number of instruments to deal with this phenomenon and to internalise external effects, ranging from negotiations, the property-rights approach to Pigou taxes. More practical approaches comprise the price-standard-approach and specific environmental regulations.

From a theoretical point of view, it is important to define the Pareto-efficient level of external effects and level of internalisation and vice versa. The Pareto-efficient level of external effects is determined by a situation where the sum of all agents' profits (or utilities) is maximised. In practice, it is clear that due to the lack of information and the number of agents involved and for several other reasons, it is very difficult to determine Pareto efficiency. Therefore, practical solutions reflect a stakeholder's ability to impose his interests (including governmental interests).

In any case the internalisation of external effects – whether negative or positive – has an influence on comparative advantage, as it influences production costs. Selected external effects have been studied for aluminium production in Venezuela (Pinto 1998), and for bauxite mining in Bintan, Indonesia, (Kölfen 1999) and Jamaica (Happel et al. 1999). Although a clear picture of external effects on the aluminium industry and of the level of internalisation does not exist, it is agreed that the present situation is in favour of countries which do not have far-reaching environmental standards and therefore no sufficient internalisation of external effects. From the viewpoint of foreign trade, the lack of environmental legislation might be regarded as an advantage over competitors.

Export dumping

Export dumping is seen as a situation where a domestic firm supplies a product on a foreign market at a price below its own production costs. Hence, the chances of a firm penetrating a market or at least staying in a market will be enhanced. A profit-maximising firm will run this strategy if the losses are either directly or indirectly financed by the government or to crowd out competitors. In the latter case, this will generally happen only for a short time. A badly functioning internal auditing system can lead to the same situation, i.e., that goods are sold below cost. Irrespective of the reasons for export dumping, economies with competing enterprises will try to hinder such imports.

In the course of the transformation of centrally planned economies, the aluminium industry in the FSU was confronted with a lot of problems (McDonald 1994). Traditionally, there was hardly any foreign trade with Western countries. However, domestic markets collapsed in the early nineties. In total, demand for the FSU aluminium industry had dropped by 82% by 1995 (Dobozi 1996). As a result of inflation and price control policy for nonferrous metals, the domestic price fell below export prices for aluminium.

As a consequence, the FSU aluminium industry raised its exports to Western markets from 0.7m t in 1990 to 2.4m t in 1995. An increase in exports cannot necessarily be qualified as export dumping. In this case, the reproach of dumping was based on the aspect that FSU export prices did not reflect real production costs. As a consequence, Western producers cut their production and shut down capacities. The EU imposed an import quota of 15,000 t per month on unwrought aluminium from the states of the FSU from August 1993 to February 1994. The quota was abolished as a result of the memorandum of understanding concluded in January 1994 between Australia, Canada, Norway, the Russian Federation, the USA and the EU. Under the memorandum of understanding, the Russian Federation undertook to reduce its output of primary aluminium by 500,000 tonnes by July 31, 1994.

5. MODEL-BASED PROJECTION OF GLOBAL PRIMARY ALUMINIUM TRADE IN 2010

Considering some of the determinants discussed above, in the following the longer-run trend of production of and trade in bauxite, alumina and primary aluminium will be analysed. Using a simulation technique, the research is based on the partial equilibrium world trade model GlobAl, which contains the complete production process for primary aluminium.[7] The version used is a slightly revised variant of the model developed by Schwarz (2000; cf. Schwarz et al. 2000). The model is based on work by Brown et al. (1983), Nichols et al. (1992) and Manne et al. (1994).

The motivation for developing a world trade model is to give an insight into the longer-run trends in trade, considering the main determinants of competitiveness. But since a model cannot handle all features, some simplifications are generally made. Bearing this in mind, the GlobAl model takes into account policy-induced determinants of trade tariffs. Additionally, bauxite availability in the countries and the diverging mix of energy carriers and prices between the regions are modelled.

5.1 The model GlobAl

GlobAl belongs to the group of partial equilibrium world trade models and is linear in nature. The model gives a simplified picture of the processing of primary aluminium. Primary aluminium is processed in three steps, beginning with the mining of bauxite. Mined bauxite is processed to alumina and the latter to primary aluminium.

Technologies simulated in the model follow the one used in reality in a stylised way. For mining, only one technology is modelled, which is not altered until 2010. However, due to technical progress, requirements for all input goods decrease by 20% between 1995 and 2010. Alumina is refined in the model by six types of processing: three types of digestion – low- and high-temperature autoclaves and tube reactors – are combined with two types of calcination – rotary kiln and fluidised bed processes. Four technologies are distinguished for smelting – Söderberg (VSS&HSS), side-worked pre-baked (SWPB), centre-worked pre-baked (CWPB) and point-feeder pre-baked (PFPB) technology. Installing new equipment, which generates higher energy efficiency, reveals technical progress in refining alumina and smelting aluminium.

Demand for and production of all goods are separated geographically. Recognising this, the world is divided into 15 regions.

On the basis of minimising the total costs of production, investment and transport, the model calculates the production of the different goods in each region as well as trade flows between regions. Irrespective of this, since in all markets perfect competition is implemented, the model is demand-driven. That means total output of each good is determined by demand for this good. Demand for primary aluminium is exogenously given. Demand for alumina and bauxite is derived from the demand for primary aluminium and alumina, respectively. The assumption of perfect competition ensures that the bauxite, alumina and primary aluminium produced in a region is completely distributed domestically and abroad. The chosen objective function implies profit-maximising economic agents. The model is static and depicts the development between 1995 and 2010 in one period.

The data in the base year refer to 1995 (cf. Schwarz 2000). Prices of various input factors – i.e., labour, electricity, thermal energy carrier, caustic soda, lime – converge between regions until 2010, leaving the world price of each input good constant. Relative world prices of input factors are constant throughout the period. Nevertheless, relative prices in the regions as well as between the regions will change. Transport tariffs will decrease by 10% (cf. Schwarz 2000).

Tariffs for bauxite, alumina and primary aluminium differ regarding traded good and region. In general, more highly processed goods are taxed more highly than less processed ones. In 1995, tariffs for bauxite were spread between 0% and 10%, for alumina and aluminium between 0 and 25%. For the model, it is assumed that tariff rates in each region will decline by 20%.

The above projections are based on considerations discussed in literature or put forward by experts. In contrast to this, the possible future macroeconomic and microeconomic environment is seldom discussed in a way that could be implemented into the model. Thus, additional changes of the macroeconomic and microeconomic environment are not modelled. In particular, no variation of tax rates is considered.

5.2 Scenario: Cases and results

The model is used to analyse the effects of changed demand for primary aluminium on production and trade of all demanded goods. Using the scenario technique, three cases are analysed which differ regarding the demand level for primary aluminium in the regions in 2010:

- Base case (or case 1): on the basis of projections regarding the development of income, the final aluminium intensity of the entire output of an economy as well as of the primary aluminium intensity of final aluminium products for each region, demand for primary aluminium was calculated,

- Case 2: in this case a higher income growth than in case 1 is predicted, leading to a higher demand for primary aluminium compared to case 1,
- Case 3: in this case development of income is identical to case 2. However, because of increasing innovation rate and structural change in aluminium production, a lower final aluminium intensity of the entire output of the economy and of primary aluminium compared to that in case 1 and 2 is predicted. Consequently, the world demand for primary aluminium is below that in the other cases. The world demand for primary aluminium, alumina and bauxite was calculated on the basis of the estimations. The figures are shown in the following table.

The importance of foreign markets to meet domestic demand differs among the three goods. As the value added by processing steps increases, the share of foreign trade rises too. That means the share of externally traded bauxite in world production is the lowest: in 1995 it was 19.8%; the share of alumina at that time was 37.3%, that of aluminium 40.5%.[8] A main reason is the low value added to bauxite, thus reducing the incentive to trade outside the region (figure 3-6).

Table 3-1. World demand for bauxite, alumina and primary aluminium, in million tonnes

	1995	2010		
		Case 1	Case 2	Case 3
Bauxite	115.57	167.25	183.02	152.82
Alumina	42.99	60.93	67.73	54.39
Aluminium	20.22	27.94	31.08	24.95

Demand for primary aluminium in 2010 is estimated according to the assumptions presented in the text. Demand for alumina and bauxite is derived from demand for primary aluminium.
Source: own calculations.

Until 2010 the “hierarchy” of relevance of trade with bauxite at the top, i.e., the lowest share, and aluminium at the bottom, i.e., the highest share, will not change; but the shape of the hierarchy will. That means the importance of trade on different process levels will alter as well as between the cases (figure 3-6).

Irrespective of the assumed case, the openness of domestic bauxite markets declines considerably. The largest shrinkage will be in case 3, the smallest in case 2. The deterioration of the share in case 3 is accompanied by a decline of total volume of trade by 11.8%.

This is due to a shift of alumina production to bauxite mining regions. In the four most important mining regions alumina output will grow more quickly than bauxite mining, irrespective of the assumed case (table 3-2). In these regions, alumina output in relation to bauxite mining will increase at least by four per cent (case 2). In cases 1 and 3 the relative growth rate is more than twice as high compared to case 2.

To meet rising demand for alumina, new capacities have to be installed. Due to cost considerations this will be done first in the main bauxite mining regions. If demand for alumina surpasses a particular level, costs in non-mining regions will exceed investment costs in mining regions. The particular demand level seems to be beyond that calculated in case 1. In contrast to the mining regions, on the world level, alumina production decreases compared to bauxite. Given the conditions in the markets, investments in alumina in bauxite mining regions are profitable, with a weak linkage to demand for primary aluminium.

Table 3-2. Development of alumina production relative to bauxite mining[1]

	Share[2]	Case 1	Case 2	Case 3
Four most important mining regions[3]	79.6%	9.4%	3.9%	10.6%
World	100.0%	-4.4%	-2.9%	-6.6%

[1]The change of output of alumina between 2010 and 1995 is set in relation to output change of bauxite mining between 1995 and 2010. / [2]Share of world bauxite mining / .[3]Africa, Australia, Brazil and rest of Latin America. Source: own calculations.

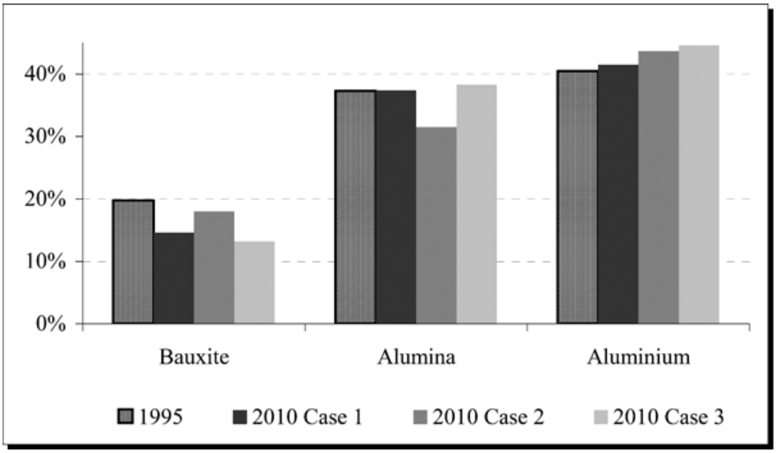

Figure 3-6. Share of net trade balance in domestic demand. Source: own calculations.

A quite different picture is given in the alumina market. Irrespective of the fact that the share of traded alumina is about twice as high as that of bauxite, the specific trend contrasts with that of bauxite. With increasing output of alumina, the share of traded alumina decreases. In case 3, with the lowest output increase, the share is 38.3%; in case 2 only 31.5% of alumina is traded externally. Thus, as long as the demand increase of alumina is quite low, capacities of smelters are mainly expanded in importing regions or – to a lesser degree – new ones are constructed. If the demand level is high, i.e., in case 2, additional capacities are installed mainly in exporting regions.

The "openness" of primary aluminium markets is greatest. In 1995 about 40.5% of aluminium produced was traded externally. Irrespective of the assumed case, the relevance of foreign trade will increase. The trend, however, has an interesting pattern. The highest figure is realised in case 3, the lowest in the base case. As demand for aluminium rises to the level assumed in case 3, new smelting capacities are mainly built up in the most important exporting regions, such as Canada and rest of Western Europe. When demand increases to the level of case 1, additional capacity will be installed to a greater extent in importing regions like the USA, compared to case 3. In this case, investment volume in importing regions slightly exceeds that in exporting regions. Demand above the level of case 1 is met mainly by new capacity in minor exporting regions, like the Middle East. This pattern results from the diverging costs in production among the regions.

5.2.1 Regional trends in bauxite mining, demand and trade

Irrespective of the chosen case, Australia and rest of Latin America will keep their position as the world's leading bauxite miners; although they will lose market shares in some of the cases (table 3-3). The importance of both regions is due to large deposits of bauxite in the respective regions combined with low costs of mining. The total costs will reach in 2010 US$ 7.70/t (Australia) and US$ 8.10/t (Rest of Latin America) per mined tonne of bauxite on the average of all cases. The costs are denominated in US dollars for the base year 1995.

Table 3-3. Supply of and demand for bauxite, in million tonnes

	Supply				Demand			
	1995	2010			1995	2010		
		Case 1	Case 2	Case 3		Case 1	Case 2	Case 3
N America	*0.00*	*0.00*	*0.00*	*0.00*	*11.72*	*15.19*	*20.84*	*13.78*
USA	0.00	0.00	0.00	0.00	9.36	11.75	15.94	10.33
Canada	0.00	0.00	0.00	0.00	2.36	3.44	4.90	3.44
Latin America	*32.20*	*43.85*	*45.95*	*42.59*	*27.55*	*39.99*	*39.99*	*37.31*
Brazil	10.20	11.76	11.76	11.76	7.93	11.59	11.59	8.91
Rest of L America	22.00	32.09	34.19	30.83	19.62	28.40	28.40	28.40
Europe	*9.70*	*21.05*	*23.13*	*18.44*	*20.95*	*29.29*	*35.28*	*24.63*
EU-15	2.20	6.25	6.25	6.25	9.68	10.76	11.76	8.72
Germany	0.00	0.00	0.00	0.00	1.72	2.47	2.22	2.47
Rest of W Europe	0.00	0.00	0.00	0.00	0.00	0.00	1.46	0.00
FSU	6.10	10.40	10.40	10.40	8.13	14.13	15.58	14.13
CEEC	1.40	4.40	6.48	1.79	3.15	4.40	6.48	1.79
Africa	*14.90*	*17.11*	*25.21*	*8.52*	*1.74*	*2.54*	*4.25*	*2.54*
Asia	*13.40*	*21.47*	*22.79*	*19.57*	*13.12*	*22.49*	*22.79*	*19.60*
Middle East	0.60	1.36	1.36	0.80	0.40	1.36	1.36	0.58
India	5.20	8.16	8.16	7.42	5.03	8.16	8.16	7.42
China	6.50	9.75	9.75	9.15	5.30	9.75	9.75	9.15
Rest of Asia	1.10	2.20	3.52	2.20	2.38	3.22	3.52	2.45
Australia	*42.70*	*63.77*	*65.94*	*63.70*	*40.49*	*57.75*	*59.86*	*54.96*
World	112.90	167.25	183.02	152.82	115.57	167.25	183.02	152.82

Source: own calculations.

Even though both regions were major mining regions in 1995 and will be in 2010, they were not the world's leading exporting regions in 1995. Only in case 3 will Australia have the largest market share. Both regions have the world's largest alumina industry, which will satisfy the rising demand for alumina by the primary aluminium industry until 2010. Thus, in neither case will more than 15% (Australia) and 18% (rest of Latin America) of mined bauxite be exported.

The world's leading export region in 1995 was Africa and will be in 2010, at least in cases 1 and 2. In both cases, about 60% of exported bauxite worldwide will be supplied by Africa's mines (table 3-3). Some mines in Africa operate on the competitive fringe. As companies operating in Africa do not have the endowment to extend refining capacities, thus exceeding the growth of world demand for bauxite, they have to supply the resource worldwide. However, as mining costs in Africa are on average rather high – in 2010 they will be at US$ 20 per mined tonne of bauxite – they can only satisfy the "residual" world demand. That means the demand which other bauxite exporting regions are not willing to meet. Consequently, as worldwide demand for bauxite is rather low, i.e., in case 1, the market share drops below 30% from 61% in 1995. The drop will be accompanied by a drastic decline of exported bauxite by 54.6%, compared to 1995.

In 2010 about half of traded bauxite will be shipped to the USA, irrespective of the assumed case. Thus further increasing its importance as a leading bauxite market. In 1995 firms located in the USA imported 38.6%.

In 1995 EU-15 was the other main importing region involving 30.8% of worldwide imported bauxite. This will change dramatically by 2010. In case 1 and 2 the share decreases to about 17%, in case 3 to 12.2%. This development is a consequence of new mining capacities in Greece, which will nearly triple between 1995 and 2010. The additional capacities in Greece will be mainly used within the EU-15, replacing foreign imports. Consequently, the total volume of bauxite imported by the EU-15 will be lower, compared to 1995, irrespective of the assumed case.

- **Australia will remain the world's leading bauxite mining and demanding region.**
- Africa's mines, in 1995 an important exporting region, on the competitive fringe, satisfy the "residual" world demand for bauxite. Thus, in the low demand case it will lose its position.
- The USA will remain the world's leading bauxite importing region.

5.2.2 Regional trends in alumina refining, demand and trade

Comparable to bauxite, in 1995 Australia and the rest of Latin America were leading producers of alumina; and this will not change until 2010, according to the results of the calculations. The market share of Australia will not change considerably, varying between 28.9% (case 2) and 32.1% (case 3), compared to 30.5% in 1995. In 1995 the rest of Latin America produced about 15% of world alumina. The share will vary between 14.5% and 18.1% (table 3-4).

Both regions profit from low refining costs, compared to the world average and large capacities, established before 1995. In the model, the capacities in 1995 predetermine the maximum possible enlargement of new production facilities. In 2010 average refining costs in Australia will amount to US$ 126 per tonne of alumina, in the rest of Latin America US$ 118/t. The world average costs will be about US$ 130/t. Because of low capacities, regions with lower costs like Africa or Brazil could not displace the two leading regions. In each region firms will incur costs for refining of US$ 114 per refined tonne of alumina.

As the USA, FSU, Canada and the EU-15 are leading primary aluminium producers, about half of the alumina produced worldwide was used in these regions in 1995. This will not change until 2010 (table 3-4).

The main producers of alumina were and will be the main exporters, as their primary aluminium industries cannot absorb the domestic alumina production. Australia's market shares in world export vary between 62.5% (case 3) and 63.3% (case 2), compared to 60.0% in 1995. In 1995 the rest of Latin America supplied 29.1% outside the region. In 2010 this will alter between 24.7% (case 2) and 34.4% (case 3) (table 3-4).

Table 3-4. Supply of and demand for alumina, in million tonnes

	Supply				Demand			
	1995	2010			1995	2010		
		Case 1	Case 2	Case 3		Case 1	Case 2	Case 3
N America	*5.60*	*7.14*	*9.70*	*6.16*	*12.18*	*18.01*	*18.01*	*16.29*
USA	4.50	5.49	7.35	4.51	7.38	10.39	10.39	8.67
Canada	1.10	1.65	2.35	1.65	4.80	7.62	7.62	7.62
Latin America	*8.50*	*13.99*	*13.99*	*13.00*	*4.36*	*6.34*	*7.73*	*5.83*
Brazil	2.10	4.16	4.16	3.17	2.62	3.17	3.17	3.17
Rest of L America	6.40	9.83	9.83	9.83	1.73	3.17	4.56	2.66
Europe	*10.50*	*12.30*	*15.07*	*10.35*	*14.49*	*18.70*	*20.22*	*16.15*
EU-15	5.30	5.04	5.64	4.06	4.77	6.25	6.25	5.99
Germany	1.00	1.06	1.06	1.06	1.30	1.61	1.61	1.34
Rest of W Europe	0.00	0.00	0.70	0.00	2.18	3.88	3.88	3.88
FSU	4.50	5.63	6.33	5.63	6.88	7.75	9.27	6.29
CEEC	0.70	1.62	2.39	0.66	0.65	0.82	0.82	0.00
Africa	*0.60*	*0.94*	*1.64*	*0.94*	*1.30*	*2.75*	*2.75*	*2.75*
Asia	*4.70*	*7.76*	*7.76*	*6.47*	*7.19*	*10.68*	*12.95*	*8.93*
Middle East	0.20	0.65	0.65	0.28	1.95	2.50	3.57	2.50
India	1.70	2.56	2.56	2.30	1.09	2.56	2.93	2.30
China	2.10	3.25	3.25	2.96	3.72	4.17	4.99	2.96
Rest of Asia	0.70	1.30	1.30	0.93	0.43	1.45	1.45	1.18
Australia	*13.10*	*18.80*	*19.58*	*17.47*	*3.47*	*4.45*	*6.07*	*4.45*
World	43.00	60.93	67.73	54.39	42.99	60.93	67.73	54.39

Source: own calculations.

Canada and the USA were the main importing regions, receiving in 1995 23.1% and 17.9% respectively, of net traded alumina worldwide. With the exception of case 3 in the case of the USA, both countries will expand their shares and thus the demand for alumina above the world average. Both regions are important aluminium producers. Canadian smelters will expand their production facilities above the world average, as domestic alumina refineries cannot meet the rising demand for aluminium. US American smelters will grow at a rate below the world average. However, since domestic alumina producers cannot fulfil the demand of domestic smelters, the latter have to expand imports. Necessary investments in extending production capacities beyond those presumably realised in the US alumina industry would lead to prices higher than the one for imported alumina. The only exception is case 2. In that case, firms in the USA expand their production facilities above the world average. Due to a worldwide high demand, the price of domestic alumina will be less than that of imported alumina. Consequently, the share in the world market drops.

In addition to the two North American countries, the FSU, the rest of Western Europe, the Middle East, and China were important importers in 1995, with shares of between 14.8% (FSU) and 10.1% (China) with the rest of Western Europe and the Middle East in between (13.6% and 10.9%, respectively) (table 3-4). According to the calculations, China will lose market share. In case 3 it will almost stop importing alumina. Also in case 1 the fall in market share is accompanied by a decline in import volume. Chinese industry is not competitive with foreign suppliers due to high production costs. Only in case 2 does the import volume increase slightly by 7.4%. A similar pattern can be expected for enterprises in the FSU. The higher the world demand for alumina is, the higher import demand will be, but only exceeding the 1995 level in case 3 by 23.5% (table 3-4). The motives of smelting firms in the rest of Western Europe are apparently the same as in Canada. The companies will expand their smelting capacities above the world average, as they have a comparative advantage in processing aluminium. Since they have no domestic alumina industry, they have to enlarge the import of alumina. Only in case 2 will the establishment of alumina production facilities be profitable. Because the extension of smelting capacities is the same in all cases, the import volume will be the same as well, except in case 2. The share variation is a consequence of changing world trade volume.

The Middle East is a minor aluminium producer. In contrast to Canada and the rest of Western Europe, companies in that region expand their capacities above the world average only in case 2. Since the domestic alumina industry is rather negligible, smelters have to expand their import market share in that case.

- **Neither regional dispersion of producer nor demander will change considerably.**
- **Thus, no significant changes occur in the distribution of exporting and importing regions.**

5.2.3 Regional trends in aluminium smelting, demand and trade

In 1995 regional centres of primary aluminium production were the USA and Canada (17.3% and 11.2% of world production, respectively) and on the Eurasian continent, FSU and EU-15 (15.7% and 11.2% respectively) (table 3-5).

The importance of these four regions will tend to decline by 2010, continuing the trend evident since the 60s of a “de-concentration” of production on the world level.[9] And with increasing demand, “de-concentration” is edging up. The higher demand for primary aluminium is mainly met by increasing output in regions with small market shares in 1995: Africa, India, Middle East, the rest of Asia, and the rest of Latin America. These five regions had a joint market share of 15.2% of world production in 1995. In all three cases the share will be higher: highest in the high demand case 2 (22.6%) compared to 18.3% (case 1) and 21.0% (case 3), respectively (cf. table 3-5). The regions are those where an “aluminisation” of the economy can be stated. With the exception of India, these regions have the lowest production costs, together with Canada. In all these regions the operating costs are below the world average by nine per cent at least. Divergences of production costs are determined by operating costs, since in the model investment costs do not differ among regions. India’s firms produce at high costs on an average of all smelters, irrespective of the fact that some production facilities processing primary aluminium are internationally competitive (cf. Vasudevan 1999). Due to the highest duties worldwide, domestic industry is protected. In the model, Indian tariffs in 2010 will exceed those in the rest of the world on average by 185% (bauxite), 320% (alumina) and 290% (aluminium).

Table 3-5. Supply of and demand for primary aluminium, in million tonnes

	Supply				Demand			
	1995	2010			1995	2010		
		Case 1	Case 2	Case 3		Case 1	Case 2	Case 3
N America	*5.60*	*8.27*	*8.27*	*7.48*	*5.64*	*6.44*	*7.27*	*5.82*
USA	3.40	4.78	4.78	3.98	5.06	5.77	6.56	5.25
Canada	2.20	3.50	3.50	3.50	0.59	0.67	0.71	0.57
Latin America	*2.00*	*2.91*	*3.56*	*2.68*	*0.88*	*1.34*	*1.43*	*1.15*
Brazil	1.20	1.45	1.45	1.45	0.50	0.70	0.74	0.60
Rest of L America	0.80	1.46	2.10	1.22	0.38	0.65	0.69	0.55
Europe	*6.60*	*8.54*	*9.24*	*7.38*	*6.09*	*6.88*	*7.28*	*5.82*
EU-15	2.20	2.88	2.88	2.76	4.87	5.40	5.62	4.49
Germany	0.60	0.74	0.74	0.62	1.50	1.67	1.74	1.39
Rest of W Europe	1.00	1.78	1.78	1.78	0.41	0.45	0.48	0.38
FSU	3.10	3.50	4.20	2.84	0.53	0.60	0.69	0.55
CEEC	0.30	0.38	0.38	0.00	0.29	0.42	0.49	0.39
Africa	*0.60*	*1.26*	*1.26*	*1.26*	*0.26*	*0.37*	*0.48*	*0.39*
Asia	*3.30*	*4.90*	*5.94*	*4.11*	*6.97*	*12.48*	*14.08*	*11.35*
Middle East	0.90	1.15	1.65	1.15	0.45	0.70	0.84	0.67
India	0.50	1.17	1.35	1.05	0.57	1.27	1.41	1.14
China	1.70	1.90	2.28	1.36	1.86	4.15	5.40	4.37
Rest of Asia	0.20	0.67	0.67	0.54	4.09	6.35	6.44	5.17
Australia	*1.60*	*2.05*	*2.80*	*2.05*	*0.38*	*0.42*	*0.53*	*0.42*
World	19.70	27.94	31.08	24.95	20.22	27.94	31.08	24.95

Source: own calculations.

The USA, EU-15, and the rest of Asia (Japan) are the leading users of primary aluminium worldwide, demanding in 1995 about 70%, in 2010 about 60% of aluminium produced worldwide. As the first two have important aluminium industries, the most significant importing region is the rest of Asia. In 1995 this region accounted for 46.1% of net traded primary aluminium; EU-15 had 31.6%, the USA 19.6%. Thus, the three regions accumulated 97.3% of worldwide net traded primary aluminium. This will change in 2010, according to the calculations. Chinese import demand will explode from 0.16m t in 1995 to 2.25m t at least (case 1). China’s market share will vary in 2010 between 19.4% (case 1) and 27.1% (case 3), compared to 1.9% in 1995. The exploding demand of China partly crowds out other demanders from the market, inducing dropping market shares. In case 2 and 3, the rest of Asia share falls to 42.4% and 41.5% respectively. Thus, in 2010 about two thirds of traded aluminium will be shipped to the Far East and Southeast Asia (table 3-5).

The EU-15 share declines by nearly one third. In 2010 in either case 1 or 2 presumably one fifth of net traded aluminium will be imported by EU-15, in case 3 only 15.6%. In case 1 and 3 the drop is accompanied by a decline in imported volume from 2.67m t to 2.52m t and 1.73m t, respectively. In the same way as EU-15, the USA will lose market share. In case 1 and 3 import volume falls considerably to 1m t (case 1) and 1.27m t (case 3) from 1.66m t in 1995 (table 3-5).

One remark should complete the discussion on import demand. Industries in China as well as in the rest of Asia are rather small, compared to the size of demand. In the case of China this is not surprising, taking operating costs into consideration. China has, next to Germany, the highest operating costs. They exceed the world average by 23%.[10] In the case of the rest of Asia, historically low capacities constrain the building up of new capacities, even though the operating costs are 18% below world average.

In 1995 nearly one third of worldwide net traded primary aluminium was supplied by firms operating in the FSU, followed by Canadian (20.4%) and Australian enterprises (15.4%). Companies from the FSU will experience market share losses between 6.6%-points (case 2) and 11.9%-points (case 3). In case 3 the drop is accompanied by a fall in export volume of 10.9%. An insignificantly increasing domestic demand is contrasted by a drop in production. Contrary to the share losses of enterprises in the FSU, Canadian aluminium traders will expand their market share, however, in case 2 only slightly. As mentioned above, Canadian firms will enlarge their production facilities above the world average. Since domestic demand drops in comparison to the world average increase – in case 3 Canadian demand will fall absolutely, compared to 1995 – the additional production has to be supplied to world markets. Australian producers will more or less maintain their 1995 position in the world market.

- **THE TREND OF REGIONAL "DE-CONCENTRATION" OF PRODUCTION PLANTS WILL PRESUMABLY CONTINUE.**
- Far East and Southeast Asia will considerably increase their importance as leading demanding and importing regions, due to exploding import demand by China.

6. SUMMARY

Since 1960 the average growth rates of production and trade volume have been 13.3% and 30%, respectively. Whereas trade volume has grown more or less continuously its growth rate was smaller compared to production until 1980. Therefore, the importance of trade, measured by the share of trade volume in production, did not grow continuously. This share dropped from 23% in 1960 to 20% in 1980. The reason was that until 1980 production increase occurred mainly in those regions where demand had risen. Beginning in the 1980s the situation changed radically. From 1980 to 1999 trade share doubled from 20% to 44.5%. The reason was that regional production and demand diverged. The driving forces behind this development were the realisation of comparative advantages in trading countries and at the beginning of the 1990s the collapse of domestic demand in the FSU.

Supply conditions are particularly important for the development of production in a country and the pattern of international trade. With respect to the competitiveness of primary aluminium processing, natural environmental and market organisation factors as well as policy-induced determinants are discussed. The former comprise availability of bauxite and primary energy sources and the contractual basis of electricity prices, whereas the latter include subsidies, import tariffs, mining taxation, internalisation of external effects and export dumping. Although this wide range of determinants is not discussed in full detail in its relevance for specific countries, the overview serves to give a picture of the present aluminium industry and its forces for structural change and of adaptation of global trade.

Having analysed past trends in production and trade in primary aluminium and its pre-products, a projection of future development is explored. Using a process-based partial equilibrium world trade model of primary aluminium, a demand-driven scenario of production and trade in the current decade is discussed. The analysis shows that the importance of foreign markets for meeting domestic demand differs between primary aluminium and its pre-products bauxite and alumina. In particular, the share of externally traded bauxite in world production is the lowest and the share of primary aluminium the highest. That means as the added value of processing steps increases, the share of foreign trade rises. For the current decade, model results show no dramatic change of existing trends. Australia will remain the leading bauxite mining and demanding region. Africa's mines satisfy the residual world demand for bauxite, acting on the competitive fringe. The USA will remain the leading bauxite importing region. In the case of alumina, neither the regional dispersion of producers nor demanders will change considerably. For primary aluminium, the trend towards a regional de-concentration of production plants will presumably continue. Far East and Southeast Asia will probably considerably increase their importance as leading demanding and importing regions. This is mainly due to projected exploding imports by China.

NOTES

[1] There are smaller smelters in China, which, however, are not considered by CRU.

[2] Countries generally do not act as economic agents deciding directly on the distribution of production to domestic and foreign markets as well as domestic demand, at least in market economies. Since in the theoretical literature the notion of "country" is typically used, we will do the same. However, one should be aware that on the supply side, firms (or the boards of firms) are the ones who decide on production plans and thus, on demand for input goods and factors, as well on output level and the regional distribution of the output. On the demand side, private and public households decide on their own, following their own decision calculus.

[3] Differences in demand conditions are seldom discussed, even though they can generate trade, as supply conditions in countries are much the same.

[4] The example is drawn from Krugman and Obstfeld (1988).

[5] Another variation of economies of scale is sector-wide economies of scale. In this case, on the firm level, the marginal earnings could remain constant as output grows. However activities outside the sector could generate external profits to the sector, with the consequence that the sector as a whole achieves economies of scale. For example, human capital accumulation in a sector of which upstream and downstream sectors can gain.

[6] A resource is simply the identified or probable physical presence of minerals in the earth, which may or may not be exploitable economically with presently available technology. Reserves represent that portion of the resources that has been precisely measured and which is, or might be, available for production over a specified time period.

[7] The whole section draws heavily on Poganietz (2001).

[8] Data consider only net trade of each good in relation to domestic demand. Transit trade is excluded. Data are not comparable with those used in Section 3. In the following, trade between model regions is presented and not trade between all the countries in the world.

[9] This should not be confused with a de-monopolisation of production. The model says nothing about the number of firms and their development. Since most aluminium-producing companies are multi-nationals, a regional "de-concentration" can mean either a monopolisation or a de-monopolisation of production on the company level.

[10] This result reveals a shortcoming of the model. In the model a cost minimising calculus is assumed. Since China is still a country with a strong socialist tradition, decisions regarding the production of important, as well as large-scale, industries are still under the supervision of the ruling party. It is doubtful that this will change completely in the next ten years.

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Chapter 4

PROSPECTS FOR A SUSTAINABLE ALUMINUM INDUSTRY

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1. ALUMINUM AND SUSTAINABLE DEVELOPMENT

Aluminum has proven itself to be a material that is indispensable for the economic development of modern societies. The past several decades have witnessed a significant increase in the annual global production of bauxite, alumina and primary aluminum. In 1997, annual production reached 123 million tonnes, as illustrated in figure 4-1. The main fields of application for this comparatively young metal are in the construction, packaging and transportation industries.

While those countries responsible for the production of bauxite and alumina (the raw materials necessary for primary aluminum production) are mainly found in the southern hemisphere, the majority of aluminum production and further refinement to value-added products continues to take place in the industrialised nations of the northern hemisphere, namely the US, Canada, Japan and Germany. At present, the aluminum industry makes significant contributions to the gross national products of several developing countries, particularly those of Guinea, Guyana and Jamaica. Given the economic dependence of developing countries on the aluminum industry, it can be assumed that primary aluminum production will only continue to increase. Despite increased recycling efforts and resource optimization, the World Bank estimates that global economic growth will lead to a 2.3% average annual increase in demand for primary aluminum for the years 1992 – 2005 (UBA, 1999, p.23).

Bauxite is the main raw material used in aluminum production. Its supply is assured for the next several decades, as there are sufficient known occurrences of high-grade bauxite suitable for exploitation. Based on the ratio of proven bauxite reserves to annual production capacity, the current reserves may be expected to last 202 years (Wellmer, 1998). However, it is possible that sink capacity may be

A. von Gleich et al.(eds.), Sustainable Metals Management, 97-111.

stretched to its limit: "The prevailing argument in the sustainable development debate is that production capacity will be exhausted faster than supply (see above, p. 14)."

In regions where bauxite mining or aluminum production and refining takes place, factors such as the size of the operation, production methods used, and prevailing local conditions will determine the extent of ecological, economic and social impacts experienced. These impacts may be either positive or negative in nature. Primary impacts may generate subsequent secondary and tertiary impacts, some of which may be totally unanticipated. A comprehensive study of resource utilisation and the resulting material flows is required in order to understand and assess these impacts. For this reason, over the past several years, entrepreneurs, politicians and concerned parties have been calling for the implementation of sustainable development policies, which give equal consideration to economic, social and ecological issues.

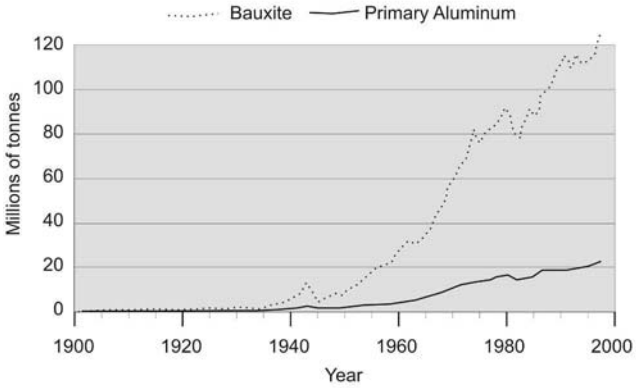

Figure 4-1. Global production of bauxite and primary aluminum (MG, 1997); (USGS, 2000).

The "Minerals and Metals Policy" of the Canadian government is one of the first attempts to address the complex issues within the field of mineral and metal raw materials. According to this document, sustainable development of minerals and metals involves (MMPC, 1999, p. 4):

- "finding, extracting, producing, adding value to, using, re-using, recycling and, when necessary disposing of mineral and metal products in the most efficient, competitive and environmentally responsible manner possible, utilizing best practices;
- respecting the needs and values of all resource users, and considering those needs and values in government decision-making;
- maintaining or enhancing the quality of life and the environment for present and future generations; and
- securing the inclusion and participation of stakeholders, individuals and communities in decision-making."

2. RESOURCE-ORIENTED ANALYSIS

In order to meet the challenges of sustainable development, the aluminum industry must adopt an integrated and interdisciplinary approach, which is easily understandable. This approach should not only be based on co-operation and participatory decision-making using reliable sources of information, but it should also account for the competing interests of various stakeholders, in both present and future generations. The Collaborative Research Centre 525, which is responsible for resource-oriented analysis of the material flows associated with the extraction, processing and refining of metals and minerals, was established at the Technical University of Aachen (RWTH) in 1997 to develop objective methods and tools to take this discussion further. The long-term goal of this project is to identify "cleaner" technology options for the production and processing of metallic raw materials. These options should take advantage of the latest developments in technology while satisfying economic, ecological and social objectives. The purpose of this project is to develop an integrated resource management system for aluminum production and processing based on the principles of sustainable development, which will then be tested for its relevance and applicability (SFB, 2000).

- This research project intends to address the following issues:
- How can the term *sustainable development* be understood in the context of the aluminum industry?
- How can sustainable development in the aluminum industry be measured and evaluated?
- To what extent is the existing system of aluminum production and supply sustainable?
- What cleaner technology options exist and how can they be used to facilitate sustainable development in aluminum production?

Using process chain analysis, economic models and simulations, an attempt will be made to answer the following questions:

- What short-term contributions can technological innovation and development make in terms of resource optimisation?
- What additional long-term benefits may be realized through the implementation of innovative technologies and organizational changes on the supply-side of the industry?
- What effects do changes in the level and nature of the demand have on the material and energy flows derived from primary aluminum production?

The Collaborative Research Centre 525 is divided into nine subprojects. Project participants include twelve institutes and academic chairs at the Technical University of Aachen, as well as the Systems Analysis and Technological Development Group from the Julich Research Centre. The work includes an assessment of deposit development, from extraction to mineral processing and smelting of the primary raw materials, as well as manufacturing and end-use of value-added aluminum products. It also includes an analysis of those processes supplying secondary raw materials, namely: recycling, transportation procedures, and energy supply. Processes that utilise or dispose of the major waste streams generated by the aforementioned activities will also be examined. This methodology makes it possible to analyse the impact of the technical process chain on the environment, as well as on society and the economy.

During the first phase of the project (1997 – 1999) preliminary work was conducted in order to lay the foundation for the development of an integrated resource management system. The second phase of the project (2000 – 2002), built upon this foundation by further developing the ideas through the use of various methods, such as process chain analysis and economic models. Figure 4-2 illustrates both the structure of the proposed resource management system and how it may be used to develop "cleaner technology" options that address technical, as well as economic, environmental and social concerns.

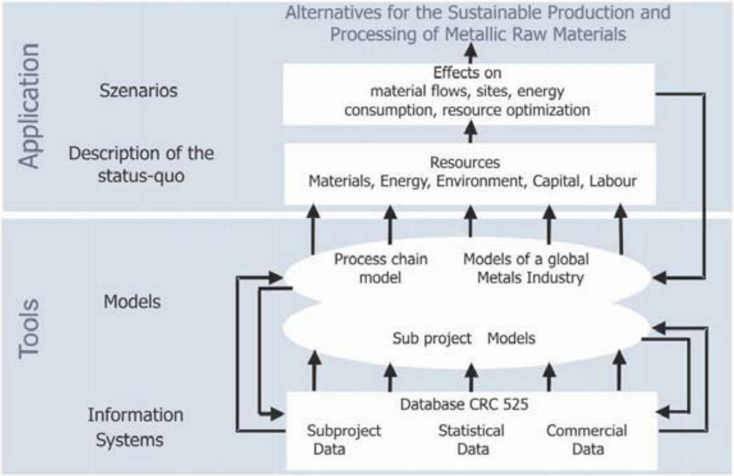

Figure 4-2. Structure of an integrated resource management system for the development of alternate treatment and handling strategies.

The management system developed by the Collaborative Research Centre is based on practical investigations as well as computer models and simulations. These may be divided into the following categories:

- information systems specific to a particular sub-project;
- information systems common to all sub-projects;
- models specific to a particular sub-project; and
- integrated process chain and economic models.

The tools developed in the initial phase of the project may then be used to provide a description of the current state of the industry, which would include:

- processes: e.g., a comparison of the various processes available for electrolytic reduction of alumina;
- products: e.g., a material balance for aluminum foil in the packaging industry;
- systems: e.g., an assessment of the possibility of substituting unalloyed primary aluminum with alloyed secondary aluminum; and
- industry: e.g., investigations of the global commercial material flows of aluminum.

The primary focus of these investigations is “resource utilisation.” This term encompasses energy and materials, as well as the environment, labour and capital.

Using present resource utilisation and the current state of the industry as a starting point, simulations will be used to investigate various scenarios and compare them to desired outcomes. These scenarios will be evaluated based on their impact on material flows, energy consumption, the local environment and efficient use of the resource.

The results of these simulations will then be discussed with representatives from science, industry and other stakeholder groups. This process is seen as a precursor to the creation of a panel of experts from within the field, whose members will include representatives from both the Collaborative Research Centre and external parties. This panel will be responsible for the formulation of policies, practices and alternative approaches for the sustainable development of aluminum. These alternatives may be normative, operational or strategic in nature. The assessment tools developed throughout the course of the research can also be used in the preliminary formulation of goals for sustainable resource use throughout the life cycle of aluminum. These concepts should be practical in nature, appropriate for the given problem and have sufficient consensus from the participants. It is our goal to develop a tool that may be used by the various stakeholders in their efforts to create policies and practices for a more sustainable use of metallic raw materials.

The focus of the work during the first phase of the project (1997 – 1999) was on aluminum, in the second phase (2000 – 2002), it was copper.

3. PROCESS CHAIN OF PRIMARY ALUMINUM PRODUCTION

The following flow sheet (figure 4-3) depicts the various stages of primary aluminum production, from extraction to electrolytic reduction.

3.1 Bauxite Deposits

Worldwide, bauxite is the main raw material used for primary aluminum production. On the basis of their genesis, bauxites are categorised into two main categories: karst bauxites and lateritic bauxites. Lateritic bauxites usually occur as wide, thin deposits located near the surface, whereas karst bauxites occur as pockets, which generally exhibit greater thickness than their lateritic counterparts. The spatial extent of these deposits is limited. One will often find several small deposits within a given region. Figure 4-4 provides an overview of the global distribution of bauxite production for the year 1997.

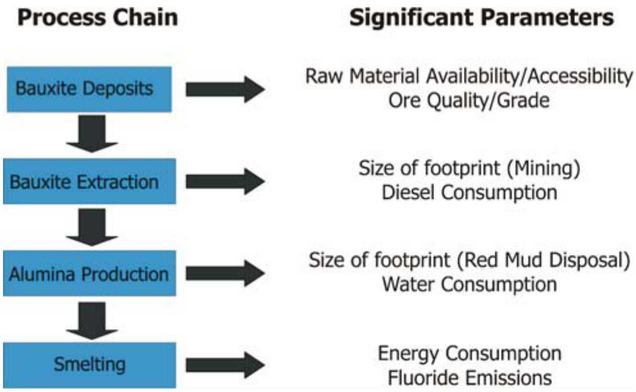

Figure 4-3. Simplified flow sheet for primary aluminum production.

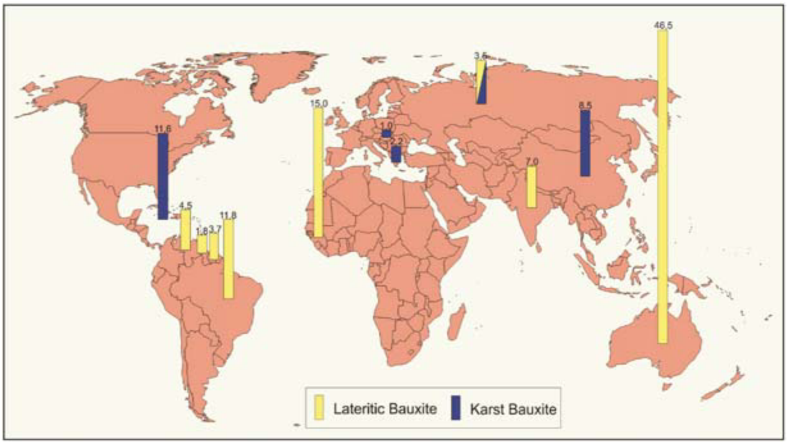

Figure 4-4. Global bauxite production for 1997 (Martens, 1999).

3.2 Bauxite Extraction

The majority of bauxite extraction occurs in open pit operations. Production is generally not continuous. During the initial phases of production, surface soil, or overburden, is selectively removed. The overburden may be used immediately for reclamation, or it may be stockpiled until commencement of reclamation. At that point, the overburden will be placed in those areas where the ore has already been extracted and the soil will be prepared for recultivation.

Open pit bauxite mining operations generally use wheeled loaders and hydraulic excavators, which load haul trucks, as illustrated in figure 4-5. At some locations, consolidated overburden or bauxite must be fragmented prior to loading. This can be achieved through drilling and blasting or with tractor scrapers. Scrapers have increasingly become the method of choice due to low noise emissions and vibrations and technological improvements. The bauxite is then transported to bins or stockpiles in haul trucks. At larger operations conveyors may also be used to transport the bauxite over longer distances. Once an area has been mined out, it may be reclaimed and cultivated. Many operations have reclamation programmes that operate in tandem with production.

Figure 4-5. Loading a haul truck at the bauxite mine in Weipa, Australia.

The most important parameters for bauxite extraction are the extent of the surface area disturbed (i.e., the footprint), which is measured in terms of total pit area and infrastructure, and energy consumption, which is measured in terms of diesel use.

At some operations, the bauxite must be washed to remove gangue material. After washing, it is dewatered in thickeners and filters to minimise moisture content and then dried in ovens. The tailings and slimes produced during washing and dewatering are usually diverted to sedimentation ponds, where the solids can settle to the bottom, allowing the process water to be recycled. The end result of this process is a sellable product.

3.3 Alumina Refining

The alumina necessary for electrolytic reduction in the smelter is produced during digestion and calcination. The most frequently used method is a wet-chemical procedure known as the *Bayer process*. In this process, aluminum oxide is leached from the bauxite using caustic soda, in addition to other chemicals such as lime and flocculants. The process takes place at high pressure and temperatures ranging from 140°C to 280°C, depending upon the mineralogical composition of the bauxite. The tailings from this process consist of undissolved bauxite residues, silicate-bound aluminum oxides and process chemicals (caustic soda, lime and flocculants). This waste material is commonly referred to as “red mud.”

The red mud is separated from the liquor and diverted to settling ponds. The red mud will be stored here indefinitely as there have been no economically viable processes developed yet to make use of this waste material. Final disposal of the waste material may occur using one of five deposition methods (e.g., foundation liners, surface caps or drainage systems), as illustrated in figure 4-6. In some cases, however, no further preventative measures are taken, leading to the introduction of waste materials into the biosphere.

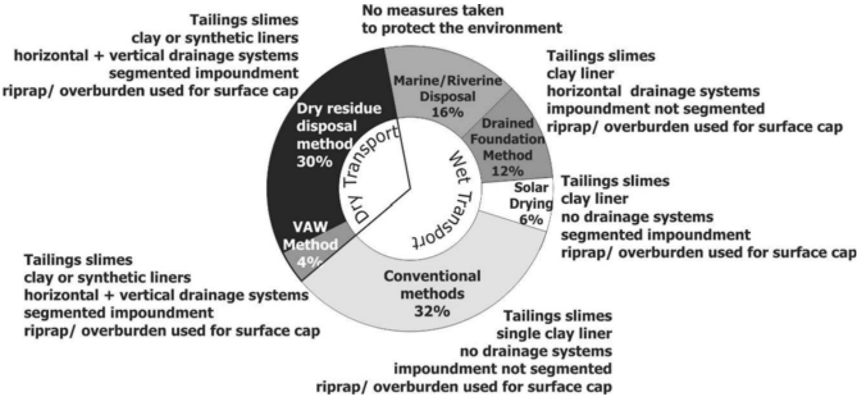

Figure 4-6. Deposition methods used for long-term storage of red mud wastes produced globally in 1997 (Hausberg, 1999).

3.4 Aluminum Smelting

Primary aluminum is produced by the electrolytic reduction of aluminum during the smelting process. This reduction takes place in electrolytic cells, known as pots. After dissolving the refined alumina in molten sodium aluminum fluoride, a current is passed through the flux, reducing the aluminum ions and thereby forming molten aluminum, which is subsequently removed from the pot.

The electrolytic cells used in this process may be distinguished by the type of anode used (Söderberg anodes or pre-bake anodes), the electric current feed and the manner in which the alumina is introduced into the flux. The main difference between the different cell types, based on sustainability criteria, is the specific power consumption per tonne of primary aluminum produced. The electrical current is the main energy carrier in the reduction process, whereby the specific energy expenditure is dependent upon cell potential and current efficiency.

The following sections deal only with bauxite extraction and disposal of red mud generated during alumina refining.

4. PROSPECTS FOR A SUSTAINABLE ALUMINUM INDUSTRY

4.1 Technological Prospects

4.1.1 Bauxite Extraction

Annual global production of bauxite for 1997 was 123 million tonnes, of which Australia produced 35%, Guinea 14%, and Jamaica and Brazil, 10% respectively (USGS, 2000). In order to achieve this level of production 1500 ha of surface area were disturbed and 110 million litres of diesel fuel were consumed.

As most bauxite is mined in open pit operations, the technology selected for the extraction of the ore has very little influence on the amount of land disturbed. The only factor that can be influenced is the rate of reclamation. The time delay between overburden removal and commencement of reclamation is determined to a large extent by the closure plan. The development of a comprehensive closure plan, prior to any mining activity, allows operators to optimise equipment use and minimise reclamation time. Studies have shown that immediate use of the removed overburden for reclamation purposes has distinct advantages over temporarily stockpiling the material. The nutrient content of the stockpiled overburden decreases over time, thereby limiting the success of subsequent reclamation. Two other important factors that determine the extent of the surface area disturbed are the spatial dimensions and orientation of the deposit (i.e., deposit geometry) and the grade of the ore.

Energy use, measured in terms of diesel fuel consumption, is dependent on equipment selection, mass of the material to be transported and transport distance. Energy consumption per tonne-kilometre can be minimised through appropriate equipment selection and use. The main factors to be considered are equipment capacity and the skill of the equipment operators. Technical trends within the industry are towards increases in equipment size and levels of automation. Both of these trends can lead to a reduction in energy consumption.

In addition to the bauxite ore, waste materials, consisting mainly of overburden, must also be handled and transported. The amount of overburden is dependent upon the geometry and depth of the ore deposit. The associated transport distances can be influenced by good production planning and scheduling. If one compares the ratio of overburden-to-bauxite in decommissioned and proposed future mines, as illustrated in figure 4-7, it may be possible to minimise strip ratios by developing only those deposits with favourable ratios. This, however, is unlikely to happen as the selection of deposits for development is more dependent on factors such as bauxite grade, economic viability and proven and probable reserves.

4.1.2 Red Mud Disposal

In 1997, 72 million tonnes of red mud (40 million m^3) were produced. Disposal of this waste material required over 205 ha of land. More than 27 million m^3 of process water was bound within the red mud. Research has shown that the parameters of waste volume, surface area and water consumption are all considerably affected by the deposition method used.

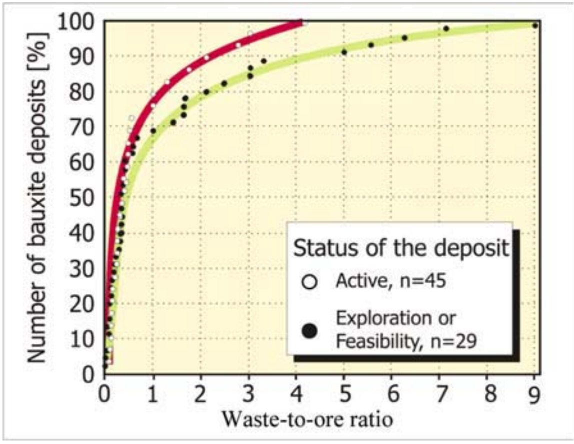

Figure 4-7. Strip ratios at selected active and potential mines (Martens, 1999).

Consequently, these parameters can be significantly reduced through improvements in deposition methods and practices. Careful selection of the bauxite to be mined, along with processing methods, can lower the amount of red mud generated by over 10%. However, it is the deposition method that will have the greatest impact on the aforementioned parameters. The application of more complex and therefore more cost-intensive processes for red mud deposition (such as the VAW method, the dry residue method in humid climates or the solar drying method in arid climates) could lead to a decrease in waste volume, resulting in a reduction of resource use of more than 25% (Hausberg et al., 1999).

4.2 Organisational Prospects

The transition to a sustainable aluminum industry, from extraction to processing and beyond, is leading to dramatic changes within the industry, forever altering the way it sees itself. Several trends have already been identified as parts of this process. During the seventies and the eighties, most companies employed reactive strategies when dealing with ecological and social issues. Instead of minimising waste volume and potential impacts on the environment, “end-of pipe” treatment was used to ensure regulatory compliance. This then gave way to the precautionary approach adopted in the last decade. It involves the use of highly efficient management systems that enable companies and organizations to prevent and minimise potential negative impacts on both the environment and society. Figure 4-8 illustrates these recent developments in management strategy.

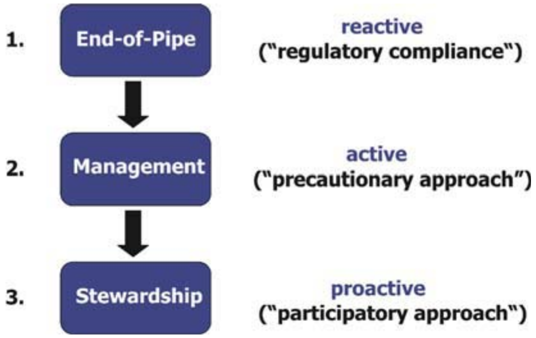

Figure 4-8. Historical development of management strategies

A remarkable number of global players in the bauxite and aluminum market have committed themselves to continuous improvements in their environmental policies and practices. One example of such a player is the multinational company Alcan Aluminum Ltd. (Alcan, 1995). Although the changes have only just begun, the aluminum industry is well on its way to incorporating sustainable development policies into its business strategies. Some companies and organisations have already moved to the next level of management strategy, adopting some of the comprehensive policies and practices of the stewardship approach. To find examples of the increasing drive towards greater transparency in business practices, one only need refer to the social and environmental reports published by Rio Tinto (RioTinto, 2000) and Noranda (Noranda, 2000), in the year 2000 the Second Bauxite Mine Rehabilitation Survey from the International Aluminum Institute (IAI, 2000) as well as the current Environmental Profile Report of the European Aluminum Association (EAA, 2000).

The precautionary approach adopted in the 1990s is increasingly being complemented by a participatory approach. This reflects a conscious attempt to reconcile the short-term needs with long-term interests of the various stakeholders.

The process of integrating principles of stewardship into daily business practices must proceed in discrete stages (figure 4-9), each of which may necessitate substantial investments of time and money.

While conventional management systems address issues such as the creation of corporate policy and business plans, and supervision and monitoring of company activities, stakeholder participation and increased transparency and accountability require the development of more comprehensive tools and strategies (based on practical experience). Some of the steps involved in this process result in significant business risks, as proactive business practices may have unforeseen consequences. Therefore, emphasis should be placed on the need for a widely accepted, transparent and comprehensive outline of indicators that can be used to measure progress. Tools that can aid in the successful management of stakeholder groups and broaden the perspective of material flow analyses to encompass more than just one business or organisation should supplement these key indicators. In conjunction with articulated commitments and clearly defined goals, progress towards sustainable development objectives should be documented through periodic reporting. When putting these initiatives into practice, one must distinguish between two levels of operational implementation: company-wide and industry-wide (i.e., company practice and industry policy).

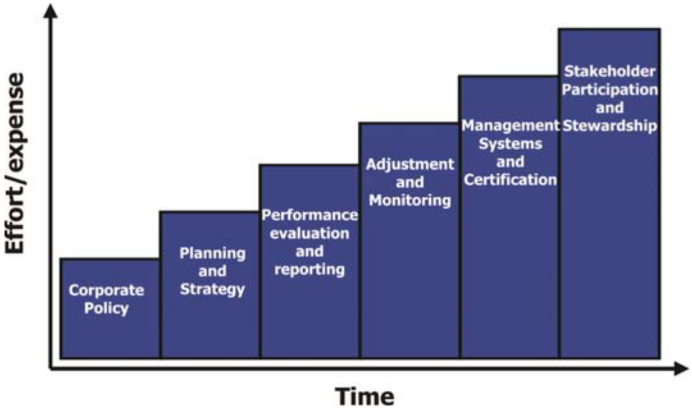

Figure 4-9. Implementation of stewardship principals.

At the operational level within an individual organisation, resource and material flow analyses lead to organisational and technological innovation in the form of new management systems and continuous process optimisation. These can be augmented by the development of:

1. new methodologies (e.g., performance indicators); and
2. organisational tools; these may be used for conducting material flow analyses and participant analyses (e.g., mapping) within the context of the industry and society as a whole.

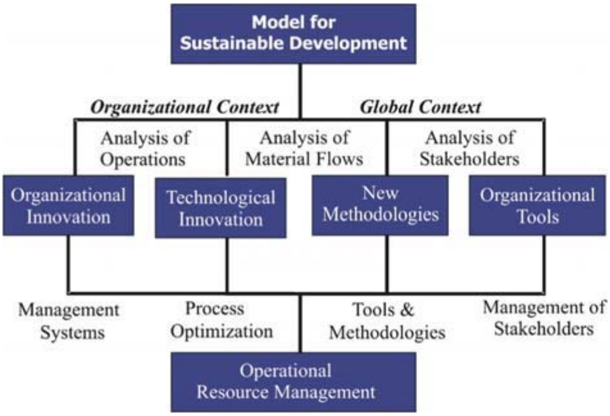

Figure 4-10. Operational resource management of metallic raw materials

Together, these two elements represent the main constituents of future resource management systems (see figure 4-10).

It cannot be expected that the introduction of this new generation of management tools will result in operating cost reductions of the same magnitude as those obtained through the implementation of quality control and environmental management systems. The enormous pressure faced by the aluminum industry from increasing globalisation and opening of markets in recent years has led many to assume that more transparent and efficient business procedures have already cut operational costs to their minimum. Rather, it can be expected that the introduction of proactive, participatory sustainability concepts can contribute to improvements in the company's competitiveness and strategic positioning, within both local and global markets.

To support this view, a number of outcomes from key initiatives addressing the sustainable development (SD) challenges facing mining and metal companies can be stated.

A recent survey assessed perceptions, policies and progress relating to sustainable development of major global players of the mining industry (PWC, 2001). Over 80% of surveyed companies responded that they had taken steps to embed the principles of sustainable development throughout their organisations. As key socio-economic concern the survey identified the issue of how to engage more effectively with stakeholders, including local communities. Also, a large share of respondents indicated that they had refrained from some form of investment due to external stakeholder influence.

Rio Tinto can be cited as an example of a company that has adopted such participatory management practices (in its Australian operations). By encouraging and fostering the participation of various stakeholder groups in exploration and mining projects, from planning and design to development, according to Rio Tinto, the company has managed to secure itself a competitive advantage over its industry rivals (Harvey, 2000).

The most important benefits associated with enhancing community engagement are usually regarded to be:

- Improvement of public reputation and corporate image
- Anticipation of social conflicts prior to projects
- Capitalizing on experiences and social competence of external parties for setting priorities and assessing outcomes.
- Securing of funding from World Bank and Green Investment Funds

Regarding the access to future funding from the World Bank, it has to be mentioned that the World Bank is currently carrying out an "Extractive Industries Review" aimed at discussing the future role of the World Bank in the extractive industries with concerned stakeholders and developing a set of recommendations that will guide involvement of the World Bank Group in the oil, gas and mining sectors. The discussion is taking place within the context of the World Bank Group's overall mission of poverty reduction and the promotion of sustainable development (World Bank, 2002). Another important driver for community engagement arises from the recently celebrated World Summit on Sustainable Development. Paragraph 44 of the Johannesburg Plan of Implementation deals with mining, minerals and metals and places particular emphasis on enhancing the participation of stakeholders, including local and indigenous communities and women, to play an active role in minerals, metals and mining development throughout the life cycles of operations (WSSD, 2002).

However, building the business case for sustainable development remains a key challenge for mining operations. The Non-Ferrous Metals Consultative Forum of Sustainable Development is a multi-stakeholder initiative initiated by the International Commodity Bodies for Non-Ferrous Metals. This multi-stakeholder initiative had established a Working Group on Production that carried out a stock-take and assessment of sustainable development drivers and existing community engagement approaches in metal mining. First outcomes from this stock-take indicated that "studies conducted by "green" investment funds revealed that companies which show a high score on "SD Indicators" tend to outperform the industry averages, indicating a correlation between corporate SD approach and economic performance. However, the enhanced economic performance cannot be related unambiguously to application of SD approaches. It is also possible that the companies that incorporate SD principles in their business strategies are simply better managed" (NFMCF, 2002).

5. OUTLOOK

In addition to the prospects for bauxite mining and red mud disposal outlined in this paper, there are several other developments which could lead to more sustainable practices within the aluminum industry. Optimisation of energy supply and consumption during the various electrolytic reduction processes, as well as optimisation of bauxite cut-off grades, are just two examples. The implementation of currently available technologies and management tools can make a substantial contribution to a more sustainable aluminum industry. However, the use of these techniques does not relieve manufacturers and consumers of their obligations. Sustainability objectives cannot be met without the efficient production and use of recycled aluminum. In order to create a sustainable aluminum industry, from mining to smelting, from manufacturing and use through to recycling and waste disposal, companies must adopt a more holistic perspective, placing company policies and strategies within a broader global context.

The integrated approach followed by the Collaborative Research Centre 525, allows it to address some of the challenges facing the aluminum industry and its consumers. Its work can be applied in many cases, using models and simulations to identify and develop handling and treatment alternatives, leading the way to more sustainable development practices at all stages of the aluminum life cycle.

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Chapter 5

TOWARDS A SUSTAINABLE COPPER INDUSTRY?

Trends in resource use, environmental impacts and substitution in the global copper industry

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1. INTRODUCTION

Copper is a metal that has been used by mankind for thousands of years. Still a vital material for many useful applications, it is nowadays a very scarce raw material owing to its average ore concentration of less than 1%. The sustainability debate begs a number of questions concerning the future of copper. What trends can be observed in the usage of copper compared to other resources? What are the main aspects involved in sustainable copper extraction and usage? What trends have occurred in copper production and usage over the past few decades – and how have they affected (positively or negatively) the environment? What are the environmental and economic effects of the structural transformation of the global copper industry? What are the prospects of substituting copper by other materials? To what extent have the main functions of this quite expensive metal been replaced, and how simple or difficult is the process of substitution – a process which will ultimately determine whether the increasingly scarce deposits of copper will suffice for the functions mankind requires of it? These questions are discussed below in an attempt to discover whether the copper industry is or could become sustainable.

This article will start by describing the main uses of copper, before establishing exactly what we envisage under the term 'sustainable copper industry'. This will be followed by a discussion of first the usage of copper (against the background of the overall consumption of resources) and then of the economic structural changes in the global copper industry and their environmental implications. Finally, the possibilities and limits of replacing copper by other materials will be tackled by studying the example of copper's role as a conductor of electricity. The closing

A. von Gleich et al.(eds.), Sustainable Metals Management, 113-139.

outlook will summarise the main findings and assess the chances of the global copper industry becoming truly sustainable.

2. COPPER AND ITS USES

The use value of copper was originally recognised a few thousand years ago. It was first smelted in the fourth millennium BC, and the invention and spread of bronze (an alloy of copper and tin) had such an impact on human development owing to its numerous uses that an entire technological stage of human history was named after it, the Bronze Age, which in Britain lasted from *c.* 2000 to 500 BC (Cf. Deutsches Kupferinstitut 1987: p. 2 and Metallgesellschaft AG (Ed.) 1993: p. 16.). Since that time, the number of applications for copper has constantly increased. Since listing them would be next to impossible, let us restrict ourselves to the main applications of copper (at least in terms of economic significance) in the final quarter of the 20th century. Fig. 1-1 shows the main uses of copper in the three main copper-processing countries, the USA, Japan and Germany, which in 1995 jointly accounted for processing 42% of the world's refined copper. [1]

Fig. 1-1 shows that the usage of pure refined copper with a concentration of 99.9% in the form of various semi-finished copper products accounts for the majority (70%) of copper usage. Within this category, the most common applications stem from copper's excellent electrical conductivity. In the USA, Japan and Germany, some 50% of processed copper is used in various electrical applications (Cf. Deutsches Kupferinstitut 1990: p. 3; Lyman/ Black 1988: p. 1114 and Metallgesellschaft AG/World Bureau of Metal Statistics (Eds.) 1997: p. 326). Pure copper in the form of wires and cables, as well as metal plate, strip, foils and windings, is used to conduct electricity and electronic signals especially in the electronics, telecoms, electronic data-processing and construction industries (Cf. Deutsches Kupferinstitut 1987: p. 13; Deutsches Kupferinstitut 1990: p. 3; Brodersen 1992: p. 1158–1159 and Lyman/Black 1988: p. 1114–1115). Copper thus plays a key strategic role as an essential material in the infrastructure of power transmission and electronics.

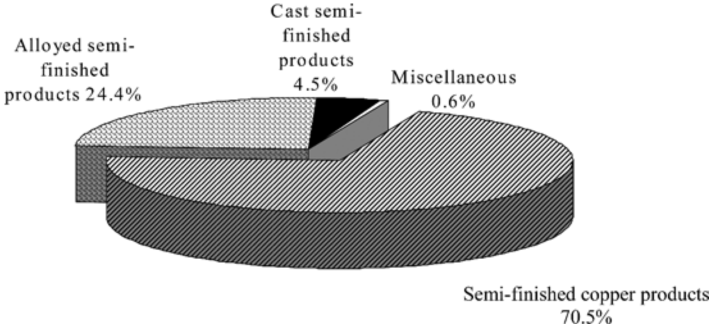

Figure 5-1. Copper usage by products in the main processing countries: the USA, Japan and Germany (1995)*.

* Data are based on aggregate figures for copper usage in Germany, Japan and the USA in 1995. Owing to national differences in statistics, the following principles were applied: *Germany*: total consumption of copper products by usage (usually slightly less than domestic production); *USA*: domestic deliveries of copper products; *Japan*: production of copper and copper-alloy products. Own calculations based on Metallgesellschaft AG/World Bureau of Metal Statistics (Eds.) 1997: pp. 262, 325 and 340.

Semi-finished copper products not used to conduct electricity are mainly employed in areas where its good thermal conductivity and excellent resistance to corrosion are required. Hence copper is used in heating and refrigeration systems, water and gas pipes, and diverse containers, tanks and other equipment used for example in the food, beverages, brewing, paper, metal and chemical industries. Pure copper is also used in the construction of machines, locomotives and vehicles, such as in car radiators (Cf. Deutsches Kupferinstitut 1987: pp. 13–15; Deutsches Kupferinstitut 1990: p. 4; Brodersen 1992: pp. 1158–1159; Lyman/Black 1988: pp. 1117–1118 and Oehler 1992).

About a quarter of the copper used in Germany, Japan and the USA takes the form of various alloys, the metals most frequently used being tin, zinc, iron, aluminium, lead and nickel. These alloys are used for numerous applications ranging from pipes, valves and fittings, turbines, oil tanks and impellers to various components in ship and vehicle construction, seawater desalination plants and of course coins (Cf. Deutsches Kupferinstitut 1987: p. 15; Deutsches Kupferinstitut 1990: pp. 4–5; Arpaci/Vendura 1993: p. 341–342 and Schleicher et al. 1992). About 5% of the copper produced goes to foundries, where individual casting moulds are made from pure copper or copper alloys, mainly for usage in vehicle, machinery and equipment construction (Cf. Deutsches Kupferinstitut 1990: pp. 4–5 and for the importance of casting: Engels 1992). Finally, the relatively small 'miscellaneous' category covers usage in pest control, artificial fertiliser additives, dyeing agents, etching solution for dyeing, stain, additives for pet food and photovoltaic solar cells (Cf. Deutsches Kupferinstitut 1990: pp. 4–5, Deutsches Kupferinstitut 1987: pp. 15–16, Scheinberg 1991: p. 895 and Engels 1992). Given the prevailing trend of tailoring modern materials ever more specifically for their intended usage, the advent of new developments and combinations of copper alloys and compounds is certain, while new areas of copper usage are bound to be opened up by research.

3. THE CONDITIONS FOR A SUSTAINABLE COPPER INDUSTRY

Adopting the definition of sustainability by the Brundtland Commission, according to which the needs of the current generation are to be satisfied without compromising the satisfaction of future generations' needs (WCED, 1987: p. 43), the key management rules for a sustainable copper industry are as follows:[2]

Firstly: The environmental impact of copper usage (pollutant emissions, mechanical intervention in the natural environment) must not be allowed to result in the degradation of higher regional or even global life-preserving functions. By way of precaution, the relevant safety margins must be observed and the environmental impact minimised.

Secondly: Limited, non-renewable resources must be treated sparingly, especially if no economic renewable substitutes are available for important areas involving direct needs satisfaction. Copper reserves must not be allowed to be completely exhausted in order to safeguard important applications in the future (including those yet to be invented).

Thirdly: The applications of copper necessary for the satisfaction of important needs must be secured in the long term without increasing their environmental impact. The depletion of the world's copper deposits for these purposes must be slowed down by greater substitution using renewable materials, copper recycling, and substitution by non-renewable resources, which are less scarce and/or less environmentally harmful.

Fourthly: The economic dependence of individual national economies on the extraction and sale of copper resources must be kept within narrow limits. Diversifying sources of income is especially important for developing countries in order to transform the exploitation of copper reserves into a process that is to be both environmentally and economically sound.[3]

Copper is important to sustain modern societies for current and future generations, especially with respect to its role as a key resource for supplying human society with electricity and heat. Moreover, this is an area in which there is not yet an adequate substitute for copper and in which stretching existing resources by means of careful usage, recycling and substitution are essential if the copper industry is to be made sustainable. It is also essential that the high direct and indirect environmental impact of extracting and using copper (comprising for example the emission of pollutants and mechanical interventions into natural systems) be minimised. The four aspects of sustainable copper usage mentioned above are discussed in Sections 4 and 5 using empirical data and trends.

4. TRENDS IN RESOURCE USE AND THE ENVIRONMENTAL IMPACT OF COPPER USAGE

Below, the trends of global copper usage are discussed in the context of the overall use of resources in the 20th century (4.1). The extent to which structural transformation in the global copper industry has had a positive or negative impact on the environment is then discussed (4.2).

4.1 Development trends in the usage of resources in the 20th century

Figures 5-2 and 5-3 show the development of the global production of important renewable and non-renewable resources since 1870. Not surprisingly, they indicate an enormous increase in the global usage of all resources over the past 120 years. Fig. 1-2 highlights in particular the scale of the global usage of natural resources. Note that it does not include stone, sand or gravel – the natural resources which are most commonly used throughout the world, but which are also the least scarce, occur everywhere in the earth's crust, and play at most a marginal role in international trade owing to their low prices and comparatively high transport costs. In 1991, the global production of stone, sand and gravel was some 20 billion tonnes, easily making them the most significant global mass resources (cf. Young, 1993: pp. 9–10). As figure 5-2 shows, they are followed by hard coal and oil, with annual production exceeding 3 billion tonnes in the 1990s. As the majority of fossil resources are burned to generate energy, these data underline the extraordinary importance of raw materials used for energy production within the context of overall resource use.[4]

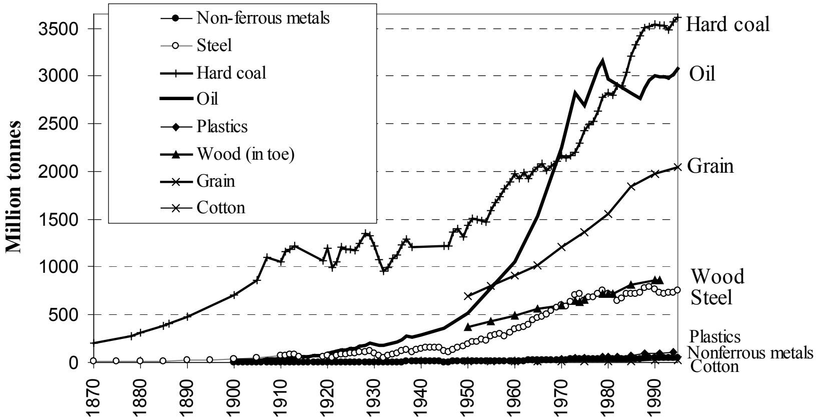

Figure 5-2. Global production of main renewable and non-renewable resources, 1870–1995 (million tonnes).

NB: 'toe' stands for "tons of oil equivalent" and quantifies wood (which is usually measured in cubic metres) in terms of its energy content in equivalent quantities of oil. Data sources for fig. 5-2 and 5-3: Data for iron and steel production and the production of refined non-ferrous metals taken from: Metallgesellschaft AG/World Bureau of Metal Statistics (eds.) 1996, Metallstatistik/Metal Statistics 1985–1995: pp. 60–65. Production data on steel, iron and hard coal taken from: Wirtschaftsvereinigung Stahl (ed.) 1996, Statistisches Jahrbuch der Stahlindustrie 1996: pp. 345, 349–353 and Clark 1990: pp. 104, 251. Oil data taken from: Clark 1990: pp. 30, 110, 246, 264 and Tippee (ed.) 1997, pp. 314–319. Plastics data taken from: Glenz 1989: p. 1238 and anon. 1995: p. 1761. Wood data taken from: Forest Products Society (ed.) 1994: p. 22 and Alexandros (ed.) 1995: pp. 206–230. Data on grain and cotton taken from: FAO (ed.) 1969–1996, Production Yearbook.

In fourth place in global mass resource usage comes grain, the first renewable resource in the list, of which in the mid-1990s about 2 billion tonnes were produced every year. It is followed by steel and timber production, both at about 800 million tonnes annually. The difference is that steel is only used as a material, whereas half the production of timber, a renewable resource, is used as material (e.g. in the construction and paper industries), the other half being used to generate energy (as firewood).[5] These six mass resources are trailed by others produced in quantities about an order of magnitude smaller: plastics used solely as material (113 million tonnes in 1995), non-ferrous metals (altogether 45 million tonnes in 1995) and cotton (20 million tonnes in 1995).

The scale of production of non-ferrous metals, whose development is shown in figure 5-3, indicates they cannot be regarded as a significant *mass* resource.

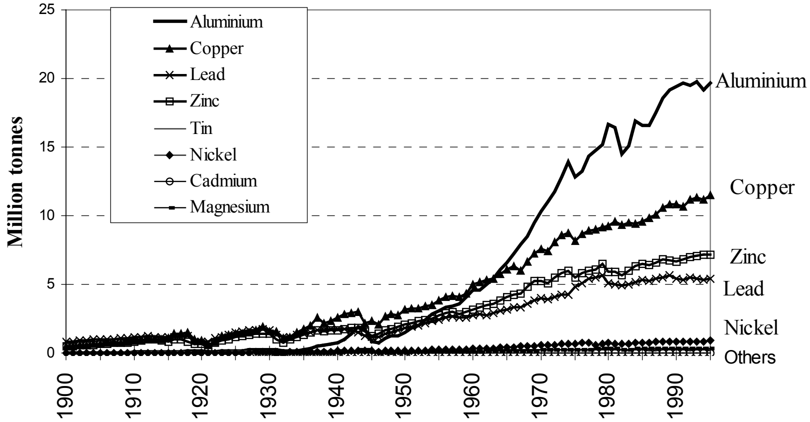

Figure 5-3. Global production of non-ferrous metals 1900–95 (million tonnes). Source: Metallgesellschaft AG/World Bureau of Metal Statistics (Eds.) 1996, pp. 60–65.

One possible exception is aluminium, which has the potential to become a mass resource of growing importance. This still relatively young light metal is available in plentiful reserves throughout the world, and the boom in aluminium use over the last 50 years (including its usage for structural applications as a substitute for concrete and steel) has made aluminium one of the most frequently used non-ferrous metals. Although aluminium dwarfs the significance of the other non-ferrous metals, this is not to say they do not have important functions. Copper, for example, with its relatively low annual production volume of nearly 12 million tonnes in 1995 plays a key functional position throughout the world in the infrastructure of the energy sector and the electronics industry.

Figures 5-2 and 5-3 also reveal another important trend regarding the global use of resources. Apart from plastics, which since the 1960s in particular have undergone incomparable annual growth, the usage of many other mass resources has more or less stagnated since the 1970s or thereabouts. This stagnation trend set in without the need for regulatory national or international policies to this effect. Instead a ‘natural’ saturation appears to have taken place in the global usage of resources. Simultaneously it must be emphasised that resource usage has not been absolutely reduced; the situation is instead characterised by a clear drop in the increase in annual production.[6]

This stagnation trend in the usage of resources is mainly explained by six factors. *Firstly*, the oil crises significantly slowed down economic growth as of the 1970s.[7] *Secondly*, saturation phenomena regarding the consumption of additional raw materials were observed in the industrialised countries as the service sector gained in importance and manufacturing industry declined (MacMillan/Norton, 1992: p. 490). *Thirdly*, contrary to the expectations of many mining companies, saturation in the industrialised countries was not compensated for by the growing consumption of resources in the newly industrialising developing countries, as only a few developing countries embarked upon a successful course of industrialisation

(Warhurst, 1994: p. 40). *Fourthly*, the emerging environmental policies in the industrialised countries in the 1980s were accompanied by technological developments which helped reduce the consumption of traditional raw materials (such as increased miniaturisation and light weight construction; Lechner et al. 1987: pp. 5–6). *Fifthly*, it should be borne in mind that the stock of recyclable discarded material has constantly grown in many industrialised countries, raising the importance of secondary, recycled resources. *Sixthly* (and finally), it must also be mentioned that the collapse of the Eastern Bloc in the late 1980s prompted large reductions in the consumption of resources due to industrial closures, as well as rigorous cuts in the defence expenditures and the resulting reduced production of strategic raw materials (Messner, 1999: pp. 421–425).

This general stagnation trend in the usage of resources, which as of the late 1980s in particular also included copper, appears to indicate that careful, sustainable use of resources was brought about completely naturally by saturation effects in the world economy. However, the highlighted trends in the usage of resources do not indicate whether this effect will last or whether it will be accompanied by stagnating or even diminishing environmental impact. Answering these questions with respect to copper entails a more thorough analysis of the global copper industry and its economic and environmental development trends.

4.2 The structural transformation of the global copper industry and its environmental implications

4.2.1 The structural transformation of the global copper industry

The copper industry encompasses all the processes of mining, concentrating, recycling and processing copper into semi-finished products, and hence plays a major role in the entire copper life cycle. One important factor shaping the structure of the international copper industry was the geological distribution of copper deposits throughout the world. The average natural copper content of the earth's crust is about 0.006%.[8] Current opinion holds that copper is only worth mining at a concentration of at least 100 times this average, i.e., about 0.6%. Significant deposits of copper ore are located all along the west coast of the American continent, in the lake district of North America, in southern Africa, and in a few areas of Eastern Europe, South Asia and Oceania. This global copper distribution determined the development of the international copper industry, since the supply of the raw metal as an important (infrastructure) material was a major requirement for the industrial development of what are now the OECD member states. The USA and Canada have hardly ever had any problems with copper supplies thanks to their large deposits. The high investment necessary for mining led to the development of powerful, largely vertically integrated corporations in these countries, which in addition to mining and processing indigenous copper deposits also pursued various capital-intensive mining projects in South America, while domestic South American mining companies only tackled small projects (cf. Mezger 1980: pp. 21–26 and Seidman 1975: p. 4).

The industrialising countries *low* in raw materials in the OECD had to obtain their copper supplies either from their colonies or by means of international trade. For example, Great Britain and Belgium granted mining concessions in their African colonies, the countries now known as the Congo and Zambia, to US, South African and Belgian companies. Other industrialised countries which did not have colonies rich in copper deposits such as Japan and a number of countries in Western Europe purchased copper from various producers. In contrast to France and Italy, which mainly imported refined copper, Germany and Japan opted for a type of reverse integration for their copper-processing industries by building their own refining plants and importing copper concentrates (cf. Mezger 1975: pp. 62–67 and Seidman 1975: p. 4). In the socialist countries, copper was regarded as a strategic raw material, which was solely exchanged for predetermined purposes among the socialist countries. Thus it was that copper ore from Kazakhstan, Uzbekistan, Poland and China was not sold on the world market until the late 1980s.

Another important aspect which influenced the structure of global copper mining was the introduction of the capital-intensive open-pit mining of raw materials in the USA in 1905. Mass production in open-pit mines rapidly spread throughout the USA, and by 1910 60% of the world's copper output was produced by just a few corporations in the United States. Hence by the early 20th century the world copper market was largely dominated by a few US companies (Mikesell 1988: pp. 2–3 and Seidman 1975: pp. 8–11).

Owing to the international growth of mass production in mining, the USA's initially overwhelming dominance of the world copper market did not last very long. By 1960, 40% of the western world's copper output was extracted in open-pit mines, causing the USA's significance as a copper-mining country to decline after World War II. This development can be seen in figure 5-4, which shows the main copper-mining countries in 1955, 1975 and 1995, the mining countries being shown on the abscissa depending on their significance in global copper production in 1955. It can be seen that although in 1955 the USA remained the world's leading copper producer, its share of world output had dropped to around 30%. Other countries like Chile, Zambia, the USSR, Canada, the Congo, Japan, Mexico, Australia, South Africa and Peru all greatly increased their mining capacities, and by 1955 were jointly responsible for 60% of global copper production.[9] Nonetheless, this geographical diversification barely weakened the market power of the multinational corporations from the industrialised states, which were mainly behind the expansion of mining in developing countries, and following World War II seven multinational corporations – including four from the USA – controlled 70% of global copper production (cf. Seidman 1975: p. 10).

The economic boom in the post-war era had a major impact on global copper consumption, precipitating the doubling of world copper production between 1955 and 1975 to 8 million tonnes. This increase in global copper demand was chiefly met in this period by Chile, Zambia, the USSR, Canada and the Congo, all of whose mining capacities at least doubled, while Australia, South Africa, Peru and Yugoslavia bolstered their position in international copper mining by quadrupling their capacities. The copper boom in the post-war era also resulted in the emergence of copper-mining newcomers, with remarkable development mainly taking place in Asia (the Philippines, Iran, Indonesia and Papua New Guinea) and the socialist countries (China, Poland and Bulgaria), which jointly produced 30% of the world's copper output in 1975. In the USA, copper-mining capacities rose between 1955 and 1975 by just 41%, as the US corporations mainly concentrated on expanding mining operations in developing countries with highly concentrated copper deposits. As a result, the US share of world copper production fell to 17.5%.[10]

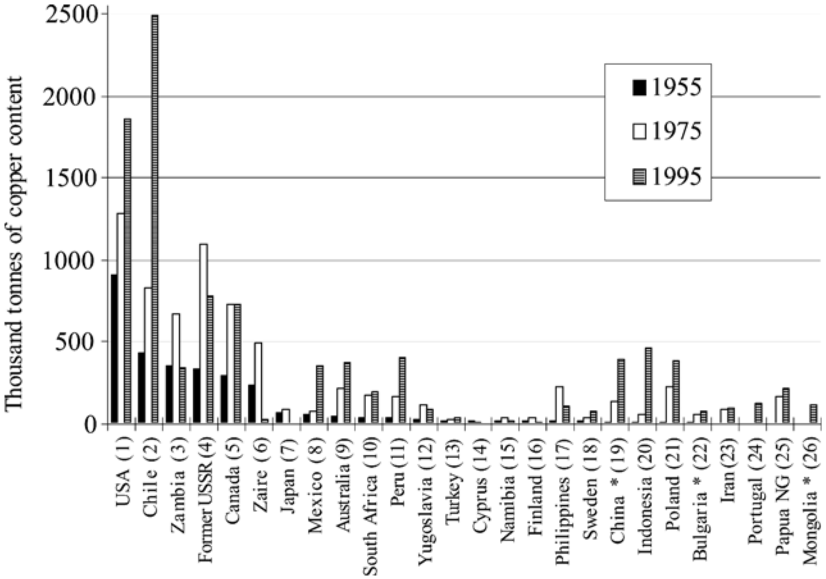

Figure 5-4. : Mining production of the main copper-mining countries in thousand tonnes of copper content (1955–95, * Estimated). Sources: Metallgesellschaft AG (Ed.) 1959: pp. 13–14; Metallgesellschaft AG (Ed.) 1984: pp. 29–30 and Metallgesellschaft AG/World Bureau of Metal Statistics (Eds.) 1996: pp. 25–26.

Moreover, considerable changes took place in 1975–1995 in the ownership structure of copper mining. Although the majority of new copper mines in developing countries were set up by multinational corporations from the industrialised nations, the influence of state organisations increased. This was partly due to the expansion of mining activities in the socialist countries, and partly a result of the nationalisation of mines in Chile, Peru, Zambia and the Congo originally established by multinational corporations (Mikesell 1988: p. 18 and Mezger 1980: pp. 145–160). This shifted the ownership structure in the global copper-mining industry, and by 1980, the 20 largest multinationals only controlled 31% of global copper-mining production, 27% was produced by state companies in Western developing countries, and 23% by state companies in socialist countries. Hence in the 1970s, global copper mining was largely under the control of state organisations

(Mikesell 1988: p. 13, own calculations using Metallgesellschaft AG (Ed.) 1984: pp. 29–30).

Stagnation in the consumption of copper and other raw materials began in the mid-1970s, with global production merely rising by some 40% in the 20 years until 1995. The main increases in this time occurred in Chile, where copper output tripled due to the development of highly concentrated deposits, making Chile the world leader in copper production since 1982.

The stagnation in copper consumption in the 1980s was mainly reflected in the production of the USA, Canada, the African countries and in the Soviet Union. During the crisis period of over-capacity in the early 1980s, US mine operators were forced to cut production costs – which were much higher than elsewhere in the world – by closing mines which were uneconomic and modernising others. Canadian copper mining, too, was affected by the crisis in the early 1980s and forced to reduce its output, and by 1995 production had merely re-attained the level of 1975 (Mikesell 1988: pp. 21–23). Significant drops in copper mining out also occurred in Zambia (owing to state mismanagement and the lack of new investment due to crushing debt) and the Congo (where copper mining had largely been paralysed by the early 1990s owing to hyperinflation and a military coup) (Messner 1996: pp. 416–422 and Körner 1993: pp. 514–522.). The decline of copper production in the states of the former Soviet Union reflected the economic decline following the collapse of the USSR in 1991, not to mention the fact that a considerable proportion of the mines there were unable to compete on the world market. This was in contrast to the situation in China and Poland, where the expanded copper mines mostly proved globally competitive (Göckmann 1992: pp. 731–733).

These developments from 1975 to 1995 affected the ownership structures in the global copper-mining industry. Although the position of the multinational corporations was weakened by the closure of mines in the industrialised countries, it was more than made up for by direct investments in promising projects in developing countries such as Peru, Indonesia and Chile (Mikesell 1988: pp. 21–25). Hence the economic importance of the world's 20 largest copper-mining companies remained stable, accounting for 32% of world copper output in 1991 compared to 31% in 1980. The same can be said of the economic influence of state companies in developing countries: the falling capacities in the African mining countries were largely compensated for by increases in South America, and so the share of world copper production accounted for by state copper companies (26%) was almost the same as in 1980. By contrast, state companies in the former socialist countries experienced losses and accounted for just 15% of copper production in 1991.[11] These data imply that the significance of small mining companies increased and thus the general market power within the global copper-mining industry decreased between 1955 and 1995, whereas the influence of private-sector organisations rose again after 1975.

The structural changes in the global copper industry were not limited to copper mining, but also encompassed copper refining and the manufacture of semi-finished products. Even in the 1970s, the majority of the main copper-rich countries (including the USA, USSR, Canada, China, Poland, Bulgaria, Yugoslavia, Australia, Mexico and Turkey) had an almost completely balanced, vertically integrated national copper industry, i.e. the copper ore mined domestically was mostly refined and processed in the same country. Only in a few developing countries such as Chile, Peru, South Africa, Zambia and Congo did mining and refining predominate in the absence of a domestic copper-processing industry (Messner 1999: pp. 480–482). In this respect, various changes had occurred by 1995. It can generally be stated that between 1970 and 1995 the developing countries considerably stepped up *all* processes of copper extraction and processing. Their share of copper mining on the world market rose in 1970–95 from 39% to 49%, with the proportion accounted for by the industrialised countries declining from 42% to 33%. This growth was largely taking place in the South American countries Chile, Peru and Mexico. As far as worldwide copper refining was concerned, the share of developing countries increased from 20% to 27%, with the industrialised countries' proportion dropping from 62% to 53%. This increase in the share of the world market can also be mainly attributed to the South American countries; the countries in Southeast Asia only experienced small increases, while the world market share of the African countries actually shrank. In terms of copper processing, the proportion of the developing countries within world production mushroomed from 4% in 1970 to 20% in 1995, largely as a result of the rapid development of the copper-processing industry in South-East Asia. Declining shares of the world market among the industrialised countries were especially experienced by Canada and the USA in all processes of the copper industry, while the UK's role in refining and processing also diminished.[12]

Concerning the trend towards the national vertical integration of the international copper industry, it can be stated that the degree of integration has dropped almost everywhere. With its own mining activities declining, the USA became a net importer of copper as its semi-finished copper product industry greatly expanded. By contrast, Canada and Australia increasingly turned to copper extraction rather than copper processing. And as far as the developing countries are concerned, between 1970 and 1995 their shares of the world market in copper refining *and* copper processing grew or at least stabilised (with the exception of Zambia and Congo). Nevertheless, the national proportion of domestic copper-mining output refined and/or processed domestically only rose in South Africa, Peru and the Philippines, whereas in the other countries mining capacities underwent disproportionately high expansion compared to copper processing. Similar tendencies of declining national forwards integration were also observed in Eastern Europe, which began specialising in the export of refined copper following the collapse of COMECON and their copper-processing industry. If we also take into account the fact that in addition to these developments some new and completely non-integrated copper countries became important in the world economy (such as Indonesia and Papua New Guinea), it can be concluded that the degree of overall national integration has in recent years significantly declined in the copper-rich countries. At the same time, this disintegration was offset by the expansion of refining and copper-processing capacities in industrialised and threshold countries low in copper (Japan, Germany, Taiwan, South Korea, France, Italy, the UK and Luxembourg), indicating a trend towards increased world economic specialisation in global copper extraction and processing (Messner 1999: pp. 480–486).

To sum up, it can be stated that over the past few decades the copper industry has undergone a far-reaching structural change. New locations for copper mining, refining and processing have become established; the influence of state companies greatly increased, only to somewhat decline again owing to mismanagement in a number of developing countries and the collapse of the Eastern Bloc; corporate market muscle has partly been reduced by the emergence of new players and fierce competition in periods of over-capacity. These developments did not only bring about economic effects in the global copper market, they also had implications for the environmental record of the global copper industry.

4.2.2 Environmental implications

The extraction of copper ore and the production of refined copper are highly environmentally intensive. As the average concentration of copper in ore is currently less than 1%, more than 100 tonnes of ore have to be extracted, ground, crushed, washed, treated with chemicals and finally disposed of as highly toxic liquid ore waste in tailing ponds in order to produce a tonne of refined copper. Should an accident occur at a tailing pond (such as a dike rupturing or seepage), causing waste to enter the water cycle, the results would be devastating for the drinking water reservoirs and ecosystems affected. Furthermore, the open-pit mining method usually used nowadays to extract metal ores with low concentrations involves drastic intervention in the natural landscape, with layers of soil and ore being gradually removed down to a depth of a few hundred metres in a series of terraces and the whole mine covering an area larger than 300 km^2 (Metallgesellschaft AG (Ed.) 1993: p. 18 and Onyekakeyah 1991: p. 126). In actual fact, the total size of the mine is certainly much larger, since land is required for operating and processing facilities, power stations, access roads, slag heaps, tailing ponds and mining settlements (BMZ 1994: pp. 20–21). Tapping a deposit of raw materials in an open-pit mine effectively means erasing a huge area of countryside and in countries like Brazil, Madagascar and Papua New Guinea, precious natural systems such as tropical rainforests are sometimes destroyed (cf. Moser/Moser 1994: p. 55, Goldau/Siepelmeyer 1991: pp. 71–74 and Siepelmeyer 1991a: p. 93). In addition to the destruction of the natural landscape, the region's water balance is significantly and irreversibly altered by mining activities and surface water, groundwater and the soil may all be severely harmed by the liberation of toxic substances. Another highly environmentally intensive process in copper production is smelting and refining to produce copper with up to 99.9% purity, a process which requires enormous quantities of energy and which may cause numerous harmful emissions. Processing copper ores, which frequently have high sulphur levels, can produce considerable amounts of SO_2, which, if freely emitted, may lead to the wide-scale contamination and acidification of ecosystems throughout the mine's entire surroundings. At the beginning of the 1990s, the total emissions from non-ferrous metal plants were some 6 million tonnes of SO_2 per year, making up about 8% of global SO_2 emissions. The non-ferrous metal plants – including copper operations – hence contribute considerably to the environmental problem of acid rain and acidification. Moreover, copper production consumes huge amounts of energy and releases large volumes of CO_2, making the copper industry one of the main factors responsible for the greenhouse effect. Even when copper ore extraction ceases in a mine, many environmental hazards persist and so recultivation is necessary. The tailing ponds and heaps and their heavy metals and acid chemical loads may pose a risk to the regional ecosystems and the water balance lasting for decades. If the mining region is not stabilised with vegetation and greenery is not planted, toxic dusts continue to be raised and bare soil is carried away by erosion. Following the closure of open-pit mines, what remains are almost impassable, often toxic, dead 'lunar landscapes', which especially in developing countries are often unsatisfactorily renaturalised and rehabilitated (if at all) (BMZ 1994: p. 21, Warhurst 1994: pp. 20–25, Siepelmeyer 1991b: pp. 102–103, Messner 1999: pp. 447–451 and Young 1993: pp. 23–30, 42).

This brief description of the high environmental impact of copper extraction and production is essential in order to understand the nature of the environmental effects that have accompanied the structural change of the copper industry within the world economy and which are dealt with below.

Stagnating demand in the Western industrialised countries during the oil crisis in 1975 and the subsequent over-capacity crisis in the copper industry looming throughout the world economy in the early 1980s marked a watershed. High investment in new copper mines and refining capacities by many mining companies in the 1970s in response to the oil crisis and the debate over dwindling resources (Club of Rome report, Meadows et al. 1972) proved excessive. As a result, utilisation of capacity in the Western copper industry was only 72% in 1983, compared to over 90% ten years previously (cf. Lechner et al. 1987: p. 94). The resulting supply surplus caused copper prices to drop and ushered in a period of sharp competition. Many mines, especially those with low ore concentrations, were closed down, technical and organisational rationalisation measures were introduced, mining was mainly restricted to highly concentrated deposits ("high grading"), and new mining projects were only begun if their production costs were low on an international scale. The over-capacity crisis was especially acute in industrialised countries, which had fewer high-grade copper deposits and where increasingly strict environmental legislation had been implemented since the 1970s, threatening the competitive position of various mining locations (cf. Messner 1999, pp. 437–446). It was not easy for the industry to adapt to these environmental laws. In particular the copper industry in the USA, which back in the 1970s was already at the upper end of the cost curve in international comparison[13], and which had been seriously damaged solely by the drop in demand in 1975, was seriously affected by the environmental regulations of the 1970s and 1980s. The requirements of US environmental standards and emission thresholds caused the successive shutdown of all the old smelting furnaces with high emissions, far more of which were still used at this time in the USA than in Japan or Western Europe (cf. Mikesell/Whitney 1988: pp. 139–140). As a consequence of these regulations – but also in view of their otherwise high production costs – many copper-processing capacities and uneconomic mines in the United States were shut down, significantly decreasing the US share of world copper production.

Nevertheless, those US mining companies which survived this crisis by using innovative measures and technologies to cut costs emerged from it newly fortified. It turned out that action to protect the environment could also be used to reduce costs. For example, the largest US copper producer, Phelps Dodge, which in 1984 had net unit costs exceeding the price of copper on the world market, managed to cut its unit costs by more than 30% by 1988. It did so by for instance treating previously dumped ore waste with additional acid in order to salvage the residual metal. This form of heap leaching reduced the level of environmentally harmful heavy metals in the waste ore and also produced additional refined metal at low cost (Abrahams 1988: pp. 1118–1119; and for the technology of heap leaching Messner 1999: pp. 502f.).

In other countries, too, innovative reactions to environmental legislation did not solely cause costs, but actually contributed to competitive improvements. This is highlighted by two examples from Norway and Canada. Since the environmental regulations in Norway called for 99% dust reduction at steelworks, the Elkem corporation developed its own filter systems. With 15,000 tonnes of dust being accrued every year, additional research was performed into the possibilities of reusing the filter dust. It turned out that the dust made a suitable cement additive which actually improved the cement's properties. Hence the introduction of this environmental regulation resulted in a new export item (Supplement to Mining Journal 1990: p. 23). Meanwhile, under their programme to combat acid rain, the Canadian environmental authorities demanded a 60% reduction in the SO_2 emitted by the processing plants run by the INCO corporation in Sudbury.[14] INCO responded with an investment programme to the tune of CAN$ 3 billion for research and modern technologies. In doing so, the corporation not only reached its emissions production target ahead of schedule, but also reduced its unit costs considerably (Warhurst 1994: p. 42 and Supplement to Mining Journal 1990: p. 2).

One important technological contribution to reducing energy consumption and air pollution in copper production, which in particular was accelerated by the stricter air pollution legislation implemented in the industrialised countries, was the spread of flash smelting, which replaced the previously used process known as bath smelting. In flash smelting, dried powdered copper concentrate is introduced into a shaft kiln, where during free fall it is oxidised and melts. The air in the kiln is enriched with oxygen, and so the concentrate particles are thoroughly mixed with the oxygen. This accelerates the oxidation processes and the chemical reaction energy is used more effectively. This in turn cuts energy consumption, reduces waste gases, and produces a higher concentration of pollutants per unit of the waste gas volume, which improves waste gas scrubbing (Langner 1993a). Even waste gas scrubbing has been improved in recent decades. Thanks to the complete encapsulation of the smelting furnace and the converter, nowadays all the waste gas can be sucked out of the processes and scrubbed, during which dust, arsenic, halogens and mercury are separated, and 97% of the SO_2 is turned into sulphuric acid. In view of the strict environmental conditions in some industrial countries, another treatment stage was developed which enables the conversion of 99% of the SO_2 into sulphuric acid. Although selling this sulphuric acid was initially profitable, the large-scale application of waste gas scrubbing flooded the market with sulphuric acid and caused its price to drop, with the result that in the end the manufacture of sulphuric acid no longer proved to be a permanently profitable sideline.

There have also been other important innovations in the area of copper recycling. The introduction of secondary copper-processing plants and optimised mechanical and non-mechanical separation techniques have enabled extensive material separation, allowing toxic waste to be properly separated from recyclables in an environmentally friendly manner. This enables the large-scale, environmentally friendly recycling of copper resources from cable, alloy and electronic scrap (Langner 1993b and Messner 1999: pp. 504–507).

These are just a few examples of the environmentally beneficial innovations which have been developed in the copper industry in industrialised countries chiefly as a reaction to environmental legislation and increasing competitive pressure (for more examples cf. Warhurst 1992: pp. 42–45 und Messner 1999: pp. 497–507). Generally speaking, the technological developments in the life-cycle stages of copper products in recent decades in industrialised countries have helped reduce the environmental impact of the copper industry. Frequently, new techniques and incremental improvements have reduced specific energy consumption and harmful emissions, especially in those stages responsible for the worst pollution. Sometimes energy consumption increased owing to the usage of new technologies, although this was often offset by reduced emissions. In the end, though, some technological developments also took place which worsened the copper industry's environmental impact, such as the spread of open-pit extraction. Nevertheless, all in all the development of new technologies in the copper life cycle has lessened environmental impact thanks to technological progress. The basic tenet holds for the extraction and processing of raw materials that reducing environmental impact is frequently compatible with a better competitive position. The reasons include the fact that economically efficient extraction and processing requires the efficient usage of energy and material in order to cut costs, and also that the aim is to maximise the ore's yield (including all by-products and related products) to achieve the maximum output per unit of ore. And these two forms of expression of economic efficiency simultaneously have the effect of reducing the environmental impact.

On the other hand, this trend towards reducing environmental impact is countered by the increasing role of state copper-mining companies in developing countries. The main reason for nationalising the multinationals in the 1970s was the fact that in the early years of independence many developing countries were apprehensive of multinational mining corporations, fearing the over-exploitation of colonial times. As many developing countries earned the majority of their hard currency and taxes from the mining sector, allowing multinational operations to remain independent appeared too risky and so they decided to manage domestic copper extraction and processing themselves. However, the mining of deposits of raw materials by state companies was often unsuccessful. A lack of management skills and technological know-how, appointing politicians to managerial positions, excessive taxation, ignorance of the basic business and management principles, high indebtedness and a lack of investment in expansion capacities and exploration are just some of the reasons why production in the hands of various state corporations was inefficient and ultimately deteriorated (Messner 1996: pp. 417–421; Mikesell 1988: pp. 97–99 and Fozzard 1990: p. 103). This mismanagement was reflected not only in the lack of economic viability of the state companies, but also in neglected equipment repairs and maintenance and a lack of investment in modernisation. Furthermore, ignorance of environmental management in developing countries with no environmental legislation led to enormous environmental damage caused by state copper companies. In addition to the lack of innovation in terms of environmental technology, the obsolete and polluting machinery – some of which dated back to the 1930s – was not properly operated, thereby exacerbating the severe pollution already caused. Moreover, many examples are known in which ecological disasters were deliberately brooked, especially in cases where thousands of tons of highly toxic ore waste were discharged daily into neighbouring rivers, such as in Peru or Papua New Guinea (Messner 1999: pp. 448–449), contaminating the water cycle and all the ecosystems dependent on it and even poisoning the drinking water for the local population.

The structural shift in the global copper industry towards state corporations ultimately also resulted in a widening technology gap with the Western industrialised nations – especially with respect to the degree of environmental pollution stemming from copper extraction. For example, the worldwide spread of economically and environmentally efficient flash smelting was impeded and in the early 1990s bath smelting was only employed for 38% of global copper production. To highlight the enormous difference in terms of environmental pollution, note that the bath smelting technique has an energy consumption of 37.1 gigajoules (GJ) per tonne of refined copper produced – about twice as much as that required for flash smelting. The energy difference between the two methods of about 18 GJ could be used to ship the amount of copper concentrate required (containing 30% copper) over a distance of 39,416 km by sea – about the length of the equator. If global copper production in 1991 had only used the flash smelting method, 186 petajoules of energy could have been saved (not to mention a vast amount of harmful emissions prevented), corresponding to the total commercial annual energy consumption of a developing country like Zimbabwe or Tunisia (203 petajoules each).[15] The rapid exploitation of the environmental relief potential stemming from the fast spread of environmental technologies in the copper industry was therefore blocked by the increasing importance of state corporations.

However, this is not to say that private-sector mining companies have always behaved in an exemplary manner regarding the transfer of environmental technologies to developing countries – especially whenever environmental legislation is weak or the existing laws are not satisfactorily enforced, as is frequently the case in the developing world.[16] The environmental behaviour of foreign corporations is frequently a question of company philosophy. There exist dynamic companies, which are geared towards strict internal environmental standards or react innovatively to the environmental regulations in developing countries. For example, the US corporation Exxon introduced heap leaching in response to the strict wastewater regulations in Chile, whereas the Canadian company ALCAN developed a method for the usage of ore waste as tiles for equipment buildings in response to imminent environmental regulations in Jamaica and public protest in Canada. Yet innovation has not been restricted to corporations from industrialised countries; domestic mining companies have also reacted creatively to environmental regulations in the developing world. One particularly successful example is the company REFIMET in Chile, which extracted arsenic from copper concentrates and hence, turned a harmful emission into a profitable by-product (Warhurst 1992: pp. 42–45).

However, not all companies react innovatively to environmental regulations; defensive behaviour is sometimes also encountered. For instance, protracted negotiations have been conducted by some firms in order to delay the implementation of environmental regulations and to moderate the conditions imposed. Occasionally, companies prefer to pay fines for non-compliance, as this is often cheaper than the required environmental investments (Warhurst 1994: p. 49 and Auty/Warhurst 1993: p. 25).

To sum up, it can be stated that the structural change in the global copper industry in recent decades has doubtlessly altered the environmental impact of copper production. At this point we will not go into the combined effect of the reduced environmental impact in industrialised countries and the generally greater environmental impact in developing countries. From the angle of sustainability, the greatest challenge in coming years will be to organise copper mining (which for simple geological reasons will increasingly shift to developing countries) applying existing technologies and environmental management skills, so that the level of viability and environmental sustainability achieved by industrialised countries can also be attained in the developing countries. Furthermore, it is essential that developing countries with rich deposits of raw materials diversify their national economies and hence, reduce their dependence on their dwindling copper stocks as a source of taxes, hard currency and income.[17]

5. SUBSTITUTION OF COPPER: POSSIBILITIES AND LIMITATIONS

If a non-renewable resource is to be used sustainably, it is essential that ways be found of replacing it by other, renewable or at least less scarce materials in order to safeguard the resource's functions for society in the long term.

According to neo-classical resource economics, the diminishing supply of a resource is not a serious problem for society as long as there are enough substitute resources. As a resource becomes increasingly scarce, its price rises and market players make increasing use of substitute resources. The price mechanism hence ensures a smooth process of substitution (Dasgupta/ Heal 1979: chapter six).

The school of evolutionary economic theory is somewhat less optimistic. It holds the view that the substitution of materials is all part of the technical progress of the final product and that substituting a proven material is never easy. Instead, replacing one material by another affects the quality of the end product and sometimes technical modifications are necessary. Moreover, replacing a material which is running out may devalue existing expertise and production capital and entails the expensive, time-consuming development of new knowledge and capital for the usage of new materials. These and other factors, which can impede the substitution process, may lead to a path dependency in the usage of resources. This in turn can in extreme cases seriously delay the substitution of a dwindling resource despite its spiralling price. In this view, the price mechanism is a necessary but not in itself sufficient process for rapid substitution. Instead the players carrying out substitution must take into account the path dependencies and try to deal with these obstacles to substitution (Messner 2002, Messner 1999: pp. 363–381, Tilton 1983: pp. 1–11).

A phase of increasing copper substitution began after World War II. At that time copper was valued in many high-quality areas of application and appeared to be irreplaceable. Consequently, copper producers hardly had to concern themselves with marketing. This situation changed in 1946–65 when demand sometimes outstripped supply and the copper price, which was subject to extreme fluctuation, increasing by a factor of nearly six, whereas prices for other materials developed moderately by comparison, despite growing demand in the post-war boom (Brown/Butler 1968: pp. 164 and Prain 1975: pp. 153, 163). The price increase of copper paved the way for competition in various applications among materials, which mainly raged in the 1950s: new steel alloys appeared as copper substitutes, especially for structural applications and when the first plastics were developed they competed with copper in the construction sector, chiefly in the area of water and gas pipes. Yet the most serious competition for copper came from aluminium, buoyed by aggressive marketing on the part of the still young aluminium industry.[18] Aluminium has characteristics in the areas of electrical and thermal conductivity that are almost as good as those of copper; moreover its low density gives aluminium a weight advantage compared to the same volume of copper. Given the plentiful aluminium deposits, the comparatively high concentration of the metal in bauxite (over 20%),[19] continuously rising aluminium production and stable, low prices, the proven material copper was threatened by a destructive substitution competition in its main field of usage.

The scale of the ‘threat’ to copper from aluminium is illustrated in figure 5-5, which shows the development of the relative price ratio between copper and aluminium with the same electrical conductivity. Whereas copper and aluminium had almost the same prices in 1946 with respect to electrical applications, by 1966 aluminium was five times cheaper. This advantage diminished as of 1975 (partly as a result of the price increase for oil) and in 1986/87 a relative price low was reached, when aluminium was only 1½ times less expensive than copper. In the 1990s copper again became 3–4 times more expensive than aluminium. Throughout the whole period, aluminium was thus cheaper than copper and therefore a significant substitution process can be expected for the period concerned.

Figure 5-6 indicates the pattern of material substitution in the area of electrical applications. The figure shows the weight-related usage ratio of copper to aluminium in the production of conductors in Germany and Japan in 1946–96. It can be seen that the development of the usage ratio in both these copper-processing countries was similar, especially after 1965. The usage ratio of the two competing conducting materials dropped significantly after 1949 in favour of aluminium, reaching a low in the late 1970s with values of 5–7. For Germany this means – taking into account the fact that a material based on aluminium with the same conductivity only weighs 48.5% of the copper required – that by 1978 aluminium had achieved a market share of 23.2% within German conductor production, compared to 27% in Japan by 1980. This development trend highlights that between 1949 and 1980 copper was replaced for various electrical applications by aluminium.

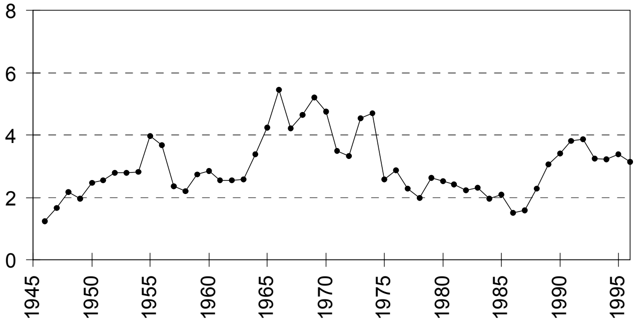

Figure 5-5. Development of the nominal price ratio between copper and aluminium with equal electrical conductivity (1946–96). *Data sources:* Metallgesellschaft AG/World Bureau of Metal Statistics (Eds.) 1994: p. 460 and p. 469; Metallgesellschaft AG/World Bureau of Metal Statistics (Ed.) 1997: p. 460 and p. 469, and own calculations.

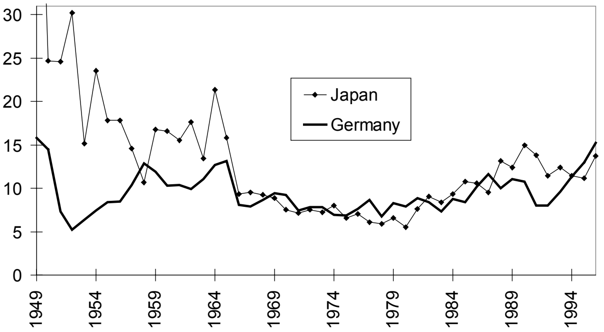

Figure 5-6. Weight-related usage ratio of copper to aluminium in conductor production in Germany and Japan (1949–96). *Data taken from:* Metallgesellschaft (Ed.) 1958: pp. 47, 71, 117, 145; Metallgesellschaft (Ed.) 1967: pp. 53, 85, 143, 175; Metallgesellschaft (Ed.) 1977: pp. 65, 115, 185, 225; Metallgesellschaft (Ed.) 1984: pp. 73, 133, 219, 264; Metallgesellschaft AG/World Bureau of Metal Statistics (Ed.) 1994: pp. 72, 157, 261, 325 und Metallgesellschaft AG/World Bureau of Metal Statistics (Ed.) 1997: pp. 72, 157, 261, 325.

However, in the early 1980s the substitution trend underwent a reversal, so that in 1996 usage ratios of copper to aluminium exceeding 10:1 were encountered again in German and Japanese conductor production. This means that the market share of aluminium has declined in Germany and Japan since 1980, despite a price ratio of copper to aluminium of 3:1 in 1995.

These data trends on the usage ratio of copper and aluminium in conductor production and the development of the relative price appear at first sight to deviate from the axioms of resource economics. Until 1965 the situation still appears as expected, with the relative usage of copper declining as it became more expensive.

Afterwards, however, the link between the price of copper and its usage becomes less clear. Between 1965 and 1985 the price of copper dropped, whereas at the same time its relative usage in conductor production continued to decline. After 1985 the copper price rose again – and was accompanied by a relative increase in copper usage! Given this, it is hardly surprising that a simple regression analysis of the link between the relative price and usage ratio of copper and aluminium for 1946–96 fails to indicate any statistical link (Messner 1999). Instead the data rather indicates that after 1965 a positive relationship existed between the relative price and the usage ratio.

However, these data can be better explained using the evolutionary economic theories of material substitution, which attributes great importance to the *time* of the substitution process. In a comprehensive distributed-lag regression analysis in which the relationship between the relative price and the usage ratio of copper to aluminium is studied with time lags up to 25 years, statistical links between the relative copper use and the relative copper price of previous years and even decades were revealed for Germany, Japan and the US (cf. Messner 2002). These findings can also be confirmed in Figs. 1-5 and 1-6. The rise in the copper price in the 1950s corresponds with declining copper usage in the 1960s, the price stagnation in 1957–63 is accompanied by the stagnation of the usage ratio as of the late 1960s, and the relative drop in the price of copper after 1974 makes the greater usage of copper between 1985 and 1995 seem plausible. These findings show that copper price and usage are closely interrelated via a time lag. Based on the data and the findings, the prediction could be ventured that given the higher relative prices in the 1990s the relative usage of copper in the first decade of the 21st century will again decline.

Despite the discovery of this link, the question still remains as to why copper only surrendered relatively little of its market share on the conductor market to aluminium as global stocks dwindled despite being much more expensive. To answer this question, we need to study the product branches concerned.[20] This reveals for example that large volumes of aluminium cables with the same conductivity as copper cables are disadvantageous for certain applications. The electronics industry, for instance, is subject to a constant miniaturisation drive and so using aluminium to replace copper (despite the latter's rising price) is not an option; aluminium would necessitate larger products and the low financial savings would be out of proportion to the additional expenditure required to adapt the products accordingly. Moreover, using aluminium cables for domestic installations also proved to be beset by problems. As aluminium cables eventually stretch or even break under high pressure and sometimes snap in plug sockets, initial trials involving the use of aluminium cables in domestic applications in the USA and Eastern Europe resulted in an upsurge in cable-related fires. Consequently, indoor aluminium cables were banned in many countries. These examples show that despite its good properties, the quality shortcomings of aluminium still prevented it from penetrating a number of markets.

Successful substitution processes took place almost exclusively in product branches where the greater volume of aluminium was not an obstacle and where at the same time the light metal's low density was an advantage. For example, aluminium quickly dominated the market for high-voltage overhead cables since the larger cable volume in the air was not an issue; moreover the lower weight of aluminium cables meant that less of the expensive pylons could be used. Aluminium has also been increasingly used for low- and medium-voltage cables in recent years. Substitution was initially delayed by the high price of the insulating material required, for thicker aluminium cables need more insulation. Thus it was that substitution in this field only began following the introduction of new, cheaper insulating materials. Yet here, too, diverse technical modifications were required in order to reach the same quality as copper products – for instance improving connection techniques for aluminium cables.

To sum up, it must be stated that in many areas of electricity transmission there is still a lack of technically and qualitatively comparable substitutes. The study of substitution processes in Messner (1999, 2002) indicated that not only high price differences (market-pull factors) are essential for the successful substitution of a dwindling material, but also that time-consuming R&D (science-push factors) are necessary in order to overcome the initial quality shortcomings and to carry out the modifications to the products and production stemming from the usage of potential substitute materials.

Sustainable resource usage entails not only replacing the diminishing resources but also that the environmental impact resulting from substitution does not exceed that of the traditional material. In the case of copper-aluminium substitution, Messner (1999, pp. 536–548) showed with the help of a life cycle assessment drawn up for power cables that owing to the substitution process, lower interventions in the water balance, lower dust emissions and a much lower amount of ore waste can be expected. At the same time, however, it must be stated that the increased usage of aluminium is combined with greater energy consumption and higher CO_2 and SO_2 emissions. Hence aluminium does not seem to provide overall environmental relief when used to replace copper – a trade-off remains. Then again, as aluminium production is a relatively young technical process compared to copper production and harbours much potential in terms of environmental progress, it could be argued that the substitution process of copper by aluminium will in the long term be compatible with the principles of sustainability, assuming environmental progress continues to be made in the aluminium industry.

6. OUTLOOK

Some aspects of copper production have in recent years improved with respect to sustainability aims. In addition to being a material which can be very well recycled, good progress has been made in the production processes over the past few decades thanks to the development of environmental technology improvements.

This is not to say that the overall aim of sustainability has been achieved in the copper industry. Below, the three main shortcomings of the global copper industry, which need to be eliminated if the copper industry is to be made genuinely sustainable, are outlined.

1. Given the shift of copper mining to developing countries, it is now more urgent than ever that the advanced environmental technologies in mining and copper processing be transferred to the developing world. In addition to the state regulatory authorities in the countries concerned, in particular the multinational

corporations are obliged to deploy their best technologies and management practices not only in response to the pressure of environmental regulations but also under the conditions of developing countries. Initial steps have already been taken in this direction. At an international conference in Berlin in 1992, various mining corporations, development aid organisations and government representatives from mining countries drafted a document entitled "Environmental mining guidelines", which could provide a basis for voluntary self-imposed obligations.[21] It is now up to these organisations to translate the ideas specified therein into practice.

2. If sustainability is to be achieved in developing countries, it is essential that economic and state dependence on mining be reduced. In several instances, state-run mining companies in developing countries have been misused in the face of huge debts or dwindling state income as a way of earning cash quickly without observing viability concerns or ecological standards (Messner 1996). In addition to placing copper mining under competent management, the main objective is to ensure that the dependence of the entire economy on the mining sector in countries rich in raw materials is reduced by means of economic diversification. Only this way it will be possible to prevent the economic disaster that threatens once the main (copper) sources of income of the countries concerned have been exhausted.
3. As far as safeguarding applications involving the dwindling, non-renewable resource copper are concerned, it is essential that substitution processes be quickly accompanied by research and development – not only to preserve the availability of important products and services, but also to ensure substitution can take place without increasing the impact on the environment. In this respect, research activities must in particular be stepped up in the field of renewable resources in order to gradually reduce dependence on shrinking copper deposits.

All this goes without saying that copper today and in future needs to be used sparingly and that high recycling rates are to be realised – if the copper industry and society's copper use is to be called sustainable.

NOTES

[1] Own calculations using Metallgesellschaft AG/World Bureau of Metal Statistics (Eds.) 1996: pp. 30–31.

[2] These rules for a sustainable copper industry are based on the general management rules for a sustainable industry involving non-renewable resources pursuant to Messner 1999: pp. 398–403. Cf. also the Enquete Commission: Schutz des Menschen und der Umwelt 1993: pp. 25–26 and *Rat von Sachverständigen für Umweltfragen* 1994: pp. 47, 84.

[3] For a discussion of sustainability and copper-exporting countries cf. Messner 1996.

[4] The material usage of fossil resources is not yet very highly developed. In the case of oil, only 8% of global oil consumption is employed for petrochemical usage (mainly plastics production). Cf. Mineralölwirtschaftsverband e.V. (ed.) 1996: p. 29. The discrepancy between material and energy usage is shown in Fig. 1-2 using the different scales of the production of oil and plastics.

[5] It should be pointed out that comparing masses of wood with other resources is problematic, since it is usually measured in cubic metres. In view of the high proportion of wood used to produce energy, the volumes of wood have been converted for Fig. 1-2 in terms of their energy content into tons of oil equivalents. In energy terms, 2.1 billion cubic metres of wood correspond to 520 million tonnes of oil. Cf. Alexandratos (ed.) 1995: pp. 215–220.

[6] For a detailed analysis of the stagnation in the global usage of resources cf. Messner 1999: pp. 413–433 and Messner 2001.

[7] In 1960–73 the average GNP growth rate was 5.2% (5% in OECD countries, 6.7% in developing countries). In 1973–79 the rates were about 2% lower and by 1987 average world growth had dropped to 2.7%. Cf. Warhurst 1994: p. 40.

[8] These average concentrations make copper the 23rd most frequent element in the Earth's crust. Cf. Deutsches Kupferinstitut 1987: p. 2.

[9] Own calculations using Metallgesellschaft (Ed.) 1959: pp. 13–14.

[10] Cf. Mikesell 1988: p. 21-22 and own calculations using Metallgesellschaft (Ed.) 1984: pp. 29–30 and Metallgesellschaft (Ed.) 1959: pp. 13–14.

[11] The data on the shares of global copper-mining output of various groups of owners in 1991 are based on own calculations using the international copper mine directory reprinted in: Metallgesellschaft AG (Ed.) 1993: pp. 120–133.

[12] All details are based on own calculations using data quoted in Metallgesellschaft AG (Ed.) 1975: pp. 26–33 and Metallgesellschaft AG/World Bureau of Metal Statistics (Eds.) 1996: pp. 25–31.

[13] For instance, the net costs of copper production in the US were more than twice as high as the net costs in Mexico or Papua New Guinea in 1975. Cf. Mikesell 1988: p. 69 (table 4.4).

[14] The INCO corporation was one of the largest air polluters in North America. Significant damage to vegetation is visible in an area of 104 km², while acid rain has wiped out whole shoals of fish in lakes 63 km away; cf. Warhurst 1992: p. 42 and Warhurst 1994: p. 26.

[15] For a detailed analysis of the potential environmental relief caused by the faster spread of flash smelting cf. Messner 1999: pp. 508–517.

[16] For a survey of environmental legislation governing mining in industrialised and developing countries cf. Messner 1999: pp. 437–453.

[17] For a formulation of a sustainable raw materials policy cf. Messner 1999: pp. 453–471.

[18] Cf. Prain 1975: pp. 153–160. In a study on copper substitution written in the 1970s, it was calculated that aluminium accounted for 54% of the material substitution of copper, other substitute materials being plastics (8%), steel (5%) and non-ferrous metals (18%). The outstanding share is accounted for by material-saving product design. Cf. ibid.: pp. 155–156.

[19] Cf. Warhurst 1994: p. 20 and Moser/Moser 1994: p. 16. Aluminium is the third most common element in the Earth's crust after oxygen and silicon. Cf. Speidel 1992: pp. 18–19.

[20] For a full discussion of copper/aluminium substitution processes for selected product branches, cf. Messner 1999, pp. 532–536.

[21] These guidelines were, however, not so much intended as a self-imposed obligation but rather as 'green guidelines' for the mining industry in developing countries. The minimum standards listed include "Introduction of environmental management", "Environmental training for personnel", "Involvement of the local population", "Selection of the best technologies with the lowest environmental impact", etc. Regarding this context and concerning the contents of these mining guidelines, see: Wälde 1992: pp. 4–8.

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Chapter 6

AN APPLICATION OF EXERGY ACCOUNTING TO FIVE BASIC METAL INDUSTRIES

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1. INTRODUCTION: THE EXERGY CONCEPT

The idea of available energy dates back to the last century, when it was first understood by the French engineer Sadi Carnot for the specialized case of heat engines. In the next decades the concept of "available work" was further developed theoretically, especially by Herman Helmholtz and J. Willard Gibbs. It has been applied to many kinds of processes, for different purposes, under several different names-availability, available work, essergy, physical information – but only recently has a standard definition been formulated and the name *exergy* definitely adopted (Rant 1956; Gyftopoulos *et al.* 1974; Wall 1977; Szargut *et al.* 1988). However, for the purposes of this study, it is sufficient to present only the essential features of the theory. An adequate definition of exergy is the following: "Exergy is the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes, involving interaction only with the above-mentioned components of nature" (Szargut *et al.* 1988). In short, exergy is an extensive non-conservative variable, which synthesizes in a concise and useful expression both the first and second law of thermodynamics. It is definable and computable (in principle) for any substance, or system, with respect to the real environment in which the system is located and/or operates. In principle, four different types of exergy B can be identified. These are denoted, respectively, as kinetic, potential, physical and chemical exergy, viz.

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A. von Gleich et al.(eds.), Sustainable Metals Management, 141-194.

$$B = B_k + B_p + B_{ph} + B_{ch}$$

Kinetic and potential exergy have the same meaning as the corresponding energy terms. Kinetic exergy is relevant for analyzing a flywheel or turbine. Potential exergy is relevant for electrical or hydraulic systems. However, these two terms can safely be disregarded for the purposes of analyzing most common industrial processes. Physical exergy is “the work obtainable by taking a substance through reversible physical processes from its initial state (temperature T, pressure p) to the state determined by the temperature T_o and the pressure p_o of the environment” (Szargut *et al.* 1988). Physical exergy assumes an important role for the purposes of optimization of thermal and mechanical processes, including heat engines and power plants. But it is of secondary — in fact negligible — importance when attention is focused on very large-scale systems, such as chemical and metallurgical processes at the industry level. In this case, chemical exergy plays a major role for the purposes of resource accounting and environmental analyses. Chemical exergy is “the work that can be obtained by a substance having the parameters To and po to a state of thermodynamic equilibrium with the datum level components of the environment” (Szargut et al.1988). It has two components: a component associated with chemical reactions occurring in isolation and a component associated with the diffusion of reaction products into the surroundings. All the foregoing definitions stress the importance of defining a reference state, or system, when calculating both physical and chemical exergy. As a matter of fact, the exergy function is a measure of the difference between two states, namely the state of the “target” system and that of its surroundings — or, more precisely, the ultimate state of the combined system + surroundings, after they have reached mutual equilibrium. This, in reality, is never the case since the actual environment is not in equilibrium. In short, exergy cannot be calculated without defining appropriate parameters for the environment where the target system operates, in terms of temperature, pressure and chemical composition. The importance of defining the parameters for the common environment emerges clearly when we consider the analytical expressions for exergy. They also show that exergy is a measure of the thermodynamic “distance” of the target system from equilibrium. Another way of saying this is that exergy is a measure of the “distinguishability” of the target system from its environment. These statements follow from the fact that exergy vanishes when the target system under consideration has the same thermodynamic state as the environment. In general, for a closed system with temperature T, pressure p, entropy S, and volume V, exergy can be written as:

$$B = S(T - T_0) - V(p - p_0) + \sum_i N_i(\mu_i - \mu_{i0)}$$

where N_i is the number of moles of the i^{th} component and μ_i is its chemical potential. The subscript “0” refers to the final state of equilibrium of the system plus the environment, combined together. The exergy of a flow crossing the system boundaries of an open system can be written as the sum of three terms:

$$B = (H - H_0) - T(S - S_0) - \sum_i \mu_i (N_i - N_{i0})$$

where the letter H stands for enthalpy and N_{i0} is the number of moles of the i^{th} component in the reference state. The summation term of these expressions takes account of the contribution due to the chemical transformation of the system. In both of these expressions it is straightforward to recognize how the choice of the reference state affects the value of the function B. For the purpose of calculating physical exergy, this choice does not represent a major problem, as it is relatively easy to define an appropriate level for pressure and temperature of the environment, namely ambient atmospheric temperature and pressure. This is not the case for calculation of chemical exergy. The latter step requires knowledge of the detailed average chemical composition of the reaction products and the environmental sink with which the system interacts. In this context, considerable efforts have been undertaken by a number of authors. One possible approach would be to assume, as the reference level, the average chemical composition of the Earth's crust after reaching a hypothetical (calculated) equilibrium with the atmosphere and oceans (Ahrendts 1980). However, the results vary dramatically according to the depth of the crustal layer that is assumed to be equilibrated. A more practical generic solution has been proposed by Szargut et al. (1988). This approach recognizes that the three main sinks — atmosphere, oceans and crust — are not in equilibrium with each other, but assumes that the reaction products in any given case must go to one of the three, depending on whether they are volatile (to air), soluble in water (to oceans) or neither (to Earth's crust). They calculate standard chemical exergy for a number of chemical compounds and pure elements. The latter procedure has been adopted and extended in several later works (Ayres et al. 1995; Ayres and Martinàs 1995; Ayres and Ayres 1996; Ayres 1998; Ayres and Ayres 1998) and its results have been also used in the present study. Nevertheless, the current methodology is not ideal, inasmuch as the three `sinks' are really in a dynamic interaction with each other.

2. EXERGY AS A TOOL FOR RESOURCE AND WASTE ACCOUNTING.

The intensive use of natural resources for anthropogenic activities is progressively depleting the reservoirs accumulated over the millennia. At the same time the large quantities of waste materials and effluents released to the atmosphere, the oceans, or to the land surface are altering the delicately balanced natural cycles that make the life possible on Earth. Therefore, minimization of resource use, as well as reduction of dangerous emissions associated with industrial processes, constitute the primary objective of policies to be pursued for sustainable development. For this purpose it is of great importance to develop a general measure capable of accounting both for materials use and waste residuals. We suggest that exergy is the most suitable indicator for both resource accounting and waste accounting. Nonetheless, up to now it has not been adopted for this role. For historical reasons, resources have been always divided into two categories, namely fuels (measured in energy units) and mineral, agricultural or forest resources (measured in a variety of mass units). This distinction leads to some incongruities and much confusion, as the choice of a different "currency" for each flux does not enable analysts to evaluate and compare all inputs and outputs on a common basis. In particular, non-fuel flows — such as minerals — are often neglected. The use of exergy as a general environmental indicator for resource accounting would improve the situation in two important ways. First, an exergy balance automatically combines both mass and energy flows, thus providing a concise representation of the process. This makes processes easier to characterize. Second, the use of exergy enables the analyst to take into account automatically both the first law (energy conservation) and the second (entropy) law of thermodynamics. In addition, by virtue of reflecting second law constraints, exergy analysis — rather than energy analysis — is a suitable tool to identify areas of potential technological improvements. In fact, irreversibilities and process inefficiencies cause exergy losses (i.e., the difference between exergy of inputs and outputs of the process), which reflect increasing entropy. Any exergy loss shows that the system under consideration could be further improved — at least in principle — in order to increase its thermodynamic efficiency and to reduce the use of natural resources. More important, however, comparing the relative magnitude of such losses both within a complex process and between alternative processes, is a useful guide to identifying the most promising technology choices and targets for R&D. A third advantage for exergy accounting, in contrast to conventional approaches, is that it opens the possibility of comparative evaluation of different kinds of materials, not only in mass terms but also in terms of available energy "saved" in the sense of not being required for separation and purification from the average composition of the environment. This is essentially equivalent to the "energy content" of an ore or mineral. (Here we use the term energy in the familiar but inexact sense of normal language, rather than the language of specialists. In fact, it is exergy we are talking about). As already remarked, metal ores, minerals and even agricultural products, as well as chemical compounds, are all precious resources for which heat of combustion (which is the usual measure of energy) is zero or irrelevant. These substances can easily be measured and compared in terms of exergy. Finally, chemical exergy "content" can be used as a tool for a first-order evaluation of the environmental impact associated with the waste effluents of any industrial process. In fact, exergy is not only a natural measure of the resource inputs, it is also a measure of the material outputs. Indeed, as emphasized in a previous work by one of the authors, the exergy content (or "potential entropy") of a waste residual can be considered as its potential for doing harm to the environment by driving uncontrolled reactions (Ayres and Martinàs 1995; Ayres et al. 1998). Admittedly, this is a very crude approximation, since the environment is a very complex system and the exergies of effluents are only some of the many parameters that affect a reaction. The use of chemical exergy as a tool for evaluating the potential harm of wastes could lead to over-simplification if directly applied to emissions. As a matter of fact, the chemical exergy content of any substance cannot be directly related to its toxicity to humans or other organisms. On the other hand, it represents a measure of how far the substance is from equilibrium with the common state of the environment. In this sense, a high exergy content is a simple indication that the substance under consideration is likely to drive further chemical reactions when it is discharged to the atmosphere, watercourses, or deposited in landfills. Or, under a different perspective, it suggests that the materials discharged could be further processed to extract potentially useful work. Ores, fuels, intermediate materials and even finished “pure” metals are, in fact, mixtures. In order to construct balances, either of mass or exergy, it is necessary to assume the average chemical composition of each mixture. For a given mine, metals processing plant or petroleum refinery, relatively precise data might be available; for anything larger, enormous simplifying assumptions must be made. We have done so for the materials involved in this analysis, using data available from authoritative sources. Nevertheless we think that the results can be taken as representative of the US as a whole in 1993. Yet it must be constantly kept in mind that the presentation is exemplary only.

3. THE US METALLURGICAL INDUSTRIES: 1993

We have conceptually divided the processes of mining, concentration (or winning), reduction or smelting and refining as shown schematically in figure 6-1. There are four stages of separation or recombination. The first two, being physical in nature, are assigned to the mining sector (Standard Industrial Category or SIC 11) or the quarrying sector (SIC 14). The last two stages, being chemical in nature, are assigned to the primary metals sector (SIC 33). At each separation stage, wastes are left behind and a purified product is sent along to the next stage. In principle, the wastes can be determined by subtracting useful outputs from inputs at each stage, bearing in mind that inputs may include water and oxygen from the air.

Unfortunately, from the analytic point of view, published data is rarely available in appropriate forms. There are significant imports and exports of concentrates and crude metals (and even some crude ores) but trade data is often given in terms of metal content, rather than gross weight. Domestic data is also incomplete, due to the large number of data withheld for proprietary reasons. Thus, in a number of cases, we have been forced to work back from smelting or concentration process data to estimate the input quantities of concentrates. Inputs to the U.S. primary metals sector consist of concentrates (produced in the mining sector, or imported), fuels, fluxes, and processing chemicals. Major purchased material inputs, other than concentrates, are mostly fluxes. These are mineral substances that make molten metals and slag flow more easily. The most important fluxes are limestone (calcium carbonate) and dolomite (magnesium carbonate), with fluorspar (calcium fluoride) being another. Manganese ore is also added to blast furnace feeds for metallurgical reasons that we need not consider in detail. For 1993 in the US we estimate approximately 91.6 MMT (million metric tons) of limestone, dolomite, fluorspar and silica were used, mostly in blast furnaces. Figure 6-2 presents a simplified outline of the major materials flows within the US steel industry in 1993. Throughout this paper the designation “MMT” is used for “million metric tons”.

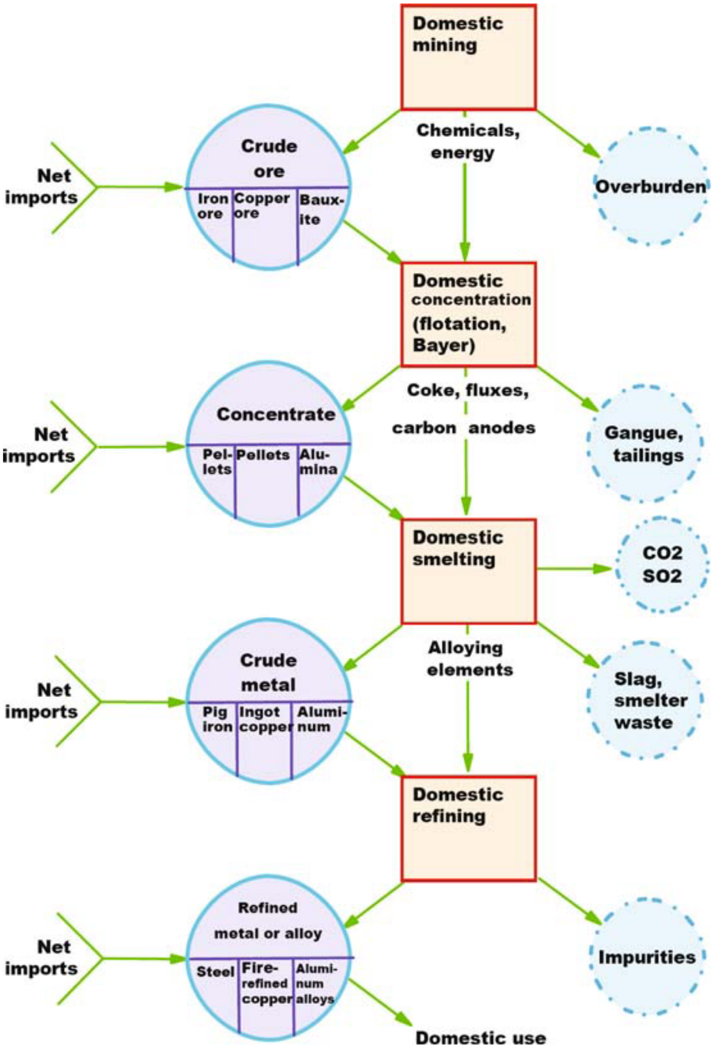
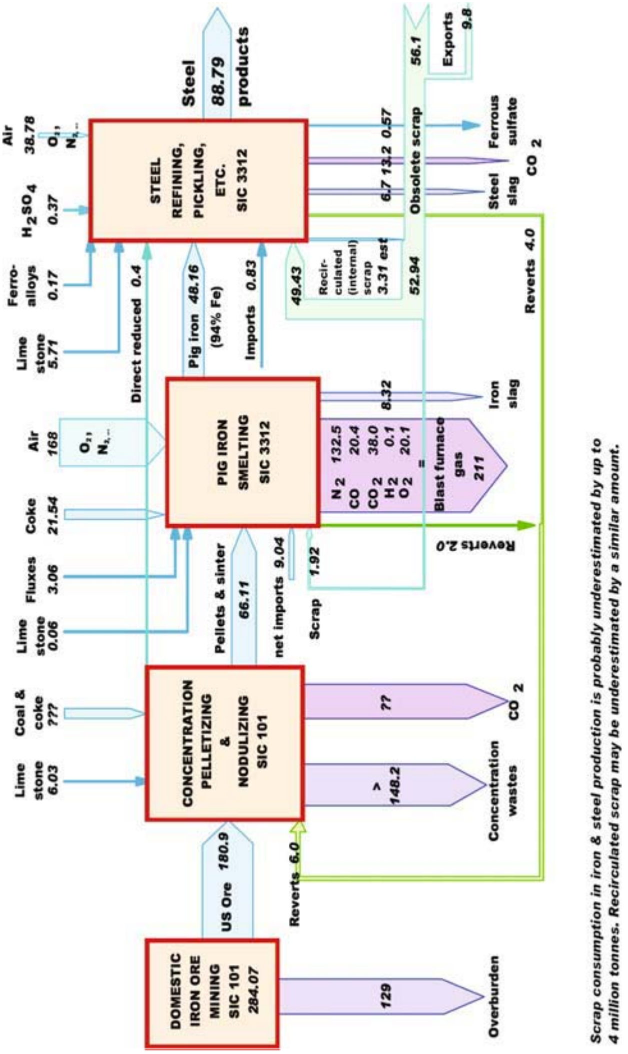


Figure 6-1. Metals processing relationship.

3.1 Iron and Steel

By far the major product, in tonnage terms, is crude (or pig) iron[1]. US blast furnace output of pig iron in 1993 was 48.155 MMT (USBuMines annual, “Iron and Steel”, table 6-1).



Scrap consumption in iron & steel production is probably underestimated by up to 4 million tonnes. Recirculated scrap may be underestimated by a similar amount.

Figure 6-2. Iron and steel materials flows; USA 1993, MMT.

Pig iron has an iron content of 94% and a carbon content of 4.5%. It is almost entirely used for carbon steel production, mostly (>90%) via the basic oxygen process. (Electric minimills use scrap metal, almost exclusively and are therefore not considered here). Blast furnace feed consumed in 1993 was 77.068 MMT (USBuMines annual , "Iron and Steel", table 6-2), of which 60.730 MMT was pellets (produced at mines, or imported) and 12.451 MMT was sinter produced at integrated steel mills. Domestic pelletizing and sinter operations provided 66.11

MMT of feed to domestic blast furnaces, and consumed about 6 MMT of upstream "reverts" (dust, mill scale). The other blast furnace feed was 1.924 MMT of scrap. The US consumed 14.097 MMT of imported ores and agglomerates, mostly pellets. in 1993 (USBuMines annual , "Iron Ore", table 6-14) and exported 5.061 MMT (ibid table 6-12). Blast furnace inputs (mainly pellets) averaged about 63% iron, 5% silica, 2% moisture and 0.35% other minerals (phosphorus, manganese, alumina). The iron content of the feed was 47.3 MMT; roughly 30% (22.5 MMT) was oxygen combined with the iron. Flux materials must also be counted. The most important is limestone. It appears from data published by the U.S. Bureau of Mines (USBuMines annual , p. 548) that in the steel industry the limestone (flux) was mostly calcined on site (to drive off carbon dioxide) and consumed as "slaked lime", or calcium oxide (6.3 MMT). Other specific mineral inputs to SIC 33 reported by the Bureau of Mines include salt (0.33 MMT), manganese ore (0.123 MMT) and fluorspar (0.137 MMT). Slag consists of the silica and other non-ferrous minerals in the sinter and pellets, plus the fluxes. Total iron blast furnace slag production in the US in 1993 was 12.3 MMT, or 0.255 tonnes (tonnes) of slag per tonne of pig iron. (About 20% of this mass originates as mineral ash from the coking coal). Some of the flows are imputed from others. In the blast furnace, the oxygen in the iron-bearing concentrates reacts with carbon monoxide from partial combustion of the coke. The carbon monoxide is actually the reducing agent within the blast furnace. In 1993 just 21.537 MMT of coke were consumed (plus other fuels for heat) to produce pig iron. The coke includes 2.8 MMT of ash from the original coal (28 MMT, @ 10% ash), so its carbon content was about 18.7 MMT. Most of this combines with the oxygen in the feed, but pig iron also contains 4.5% C, so 2.16 MMT of the carbon from the coke remains in the metal. Thus 18.70 – 2.16 = 16.54 MMT (or 88%) of the carbon from the coke combines with oxygen to produce a mixture of carbon monoxide (CO) and carbon dioxide (CO2). The gaseous product that emerges from the blast furnace (`blast furnace gas') is mostly nitrogen but it contains excess CO, hence energy (exergy) content. It can be utilized as low quality fuel within the integrated steel mill or in an electric power plant. Coke ovens and steel rolling mills are significant sources of hazardous wastes, even though the coke oven gas is efficiently captured for use as fuel. About 44 kMT of ammonium sulfate (N-content) was produced as a by-product of US coking operations in 1993. This material is used as fertilizer. Coke is cooled by rapid quenching with water and some tars, cyanides and other contaminants are unavoidably produced. Unfortunately, materials balances alone cannot be used to estimate the quantities of these hazardous wastes. Also, in the rolling process, steel is cleaned by an acid bath ("pickling"), resulting in a flow of dilute wastewater containing ferrous sulfate or ferrous chloride (depending on the acid used). The excess acid is usually neutralized by the addition of lime. In 1993 about 0.37 MMT of 100% sulfuric acid (0.074 MMT S content) were used for this purpose, producing 0.57 MMT of ferrous sulfate. Ferrous sulfate can, in principle, be recovered for sale. However, dehydration is costly, the market price is low and the market is insufficient to absorb the quantity potentially available, whence most of it is simply discarded as (waterborne) waste. Considering the iron/steel process as a whole, all of the carbon (from coke) is eventually oxidized to CO_2 except for a very small amount left in the raw steel. Carbon is added back to the finished steel in carefully controlled amounts as `spiegeleisen' (ferromanganese) and other ferroalloys. In 1993, the US steel industry accounted for 32.5 MMT of CO_2, from coke, which is included in the grand total from fossil fuel combustion, discussed later. In addition, some other hydrocarbon fuels were used, mainly for preheating the blast air and heating the steel ingots prior to rolling). A simplified schematic of the steel process chain for the production of 1 tonne of steel is shown in figure 6-3. We use this simplified version for purposes of the exergy analysis hereafter.

3.2 Aluminum

Light metals, mainly aluminum, phosphorus and magnesium, are reduced electrolytically. Only aluminum is discussed in this paper. The oxygen in the purified alumina (from the Bayer process) reacts with a carbon anode, made from petroleum coke. The reaction emits 0.065 tonnes of CO_2 per tonne of primary aluminum produced. In addition, primary aluminum plants emitted about 0.02 tonnes of fluorine, per tonne of aluminum, partly as HF and partly as fluoride particulates. This is due to the breakdown of cryolite (an aluminum-sodium fluoride electrolyte used in the process, in which the alumina is dissolved) at the anode. Total airborne emissions from primary aluminum production in the U.S. (3.944 MMT) were, therefore, 2.564 MMT of CO_2, 0.08 MMT of fluorides and about 0.17 MMT of other particulates (Al_2O_3). Fluoride emissions, in terms of contained fluorine, can be estimated quite precisely from cryolite and aluminum fluoride consumption. Inputs per tonne of aluminum are shown in figure 6-4.

3.3 Other Non-ferrous Metals

In the case of other non-ferrous metals from sulfide ores (copper, lead, zinc, nickel, molybdenum, etc.), the smelting process is preceded by, but integrated with, a roasting process whereby the sulfur is oxidized to sulfur dioxide, SO_2. Roughly 1 tonne of sulfur is associated with each tonne of copper smelted, 0.43 tonnes of sulfur per tonne of zinc, and 0.15 tonnes of sulfur per tonne of lead. An increasing fraction of this sulfur (currently close to 95%) is captured. Most of it is converted into sulfuric acid. In 1988, 1.125 MMT of by-product sulphuric acid (S- content) was produced at U.S. non-ferrous metal refineries. In terms of sulfuric acid (100% H2SO4), the quantity produced in 1988 was 3.54 MMT. By 1993 the byproduct acid recovery was significantly higher, viz. 3.04 MMT from copper smelters, 1.15 MMT from lead smelters and 1.82 MMT from zinc smelting, for a total of 6.01 MMT. Over half was used within each metal-processing industry, for leaching purposes, leaving 2.78 MMT for sale to other sectors. Leaching, the first step in the so-called SX-EW process, now accounts for a significant proportion (over 30%) of copper concentrates produced in the U.S. and the fraction is increasing, both in the US and abroad. Leached copper sulfate is subsequently concentrated by precipitation or solvent extraction and then smelted or converted without an intermediate flotation stage. The combined process is called the solvent extraction-electro-winning (SX-EW) process.

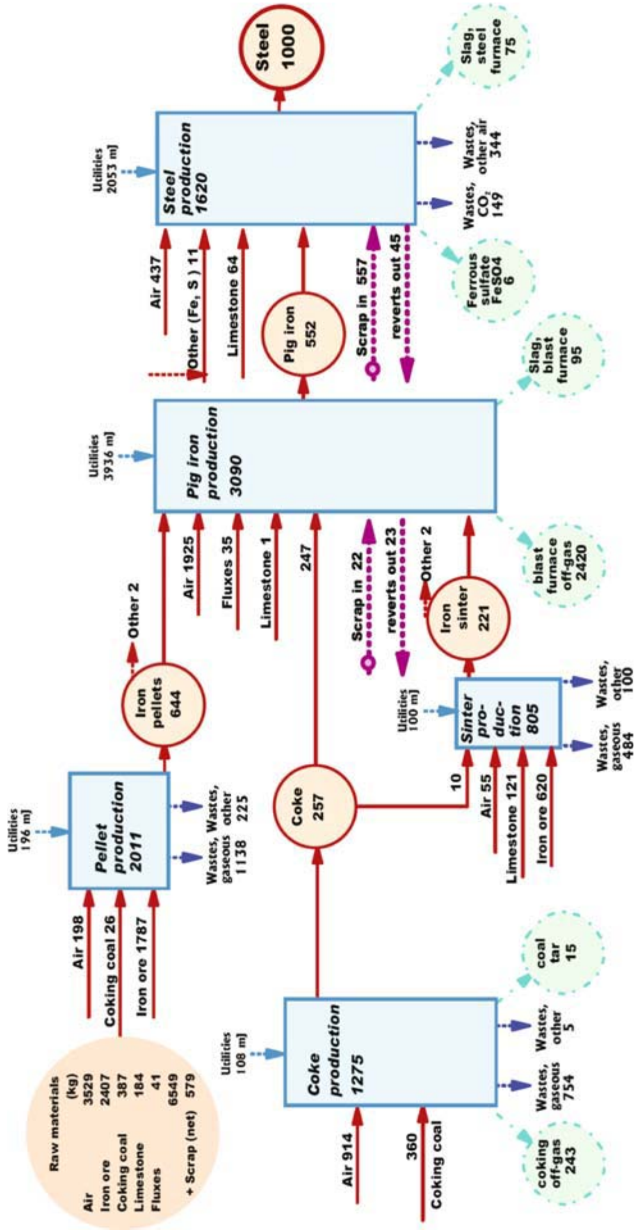


Figure 6-3. Mass flows (kg) in the production of 1 MT steel (simplified processes, typical material mixes).

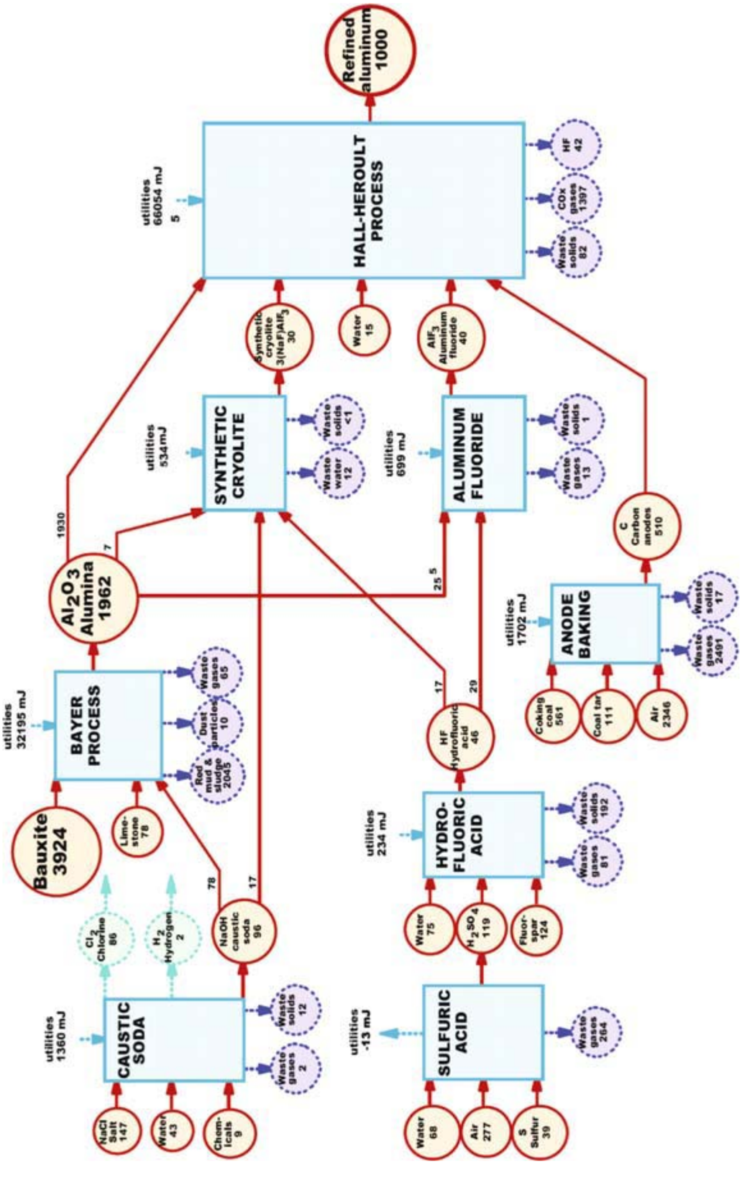


Figure 6-4. Mass flows (kg) in the production of 1 MT aluminum (simplified processes, typical material mixes).

In the smelting step, typical sulfide concentrates fed to the roaster/smelter consist of Cu (20%-35%), S (25%-35%), iron (25%-35%) and other elements (10%–20%). In addition, about 2.1 tonnes of limestone and silica flux are added to the furnace per tonne of refined copper (Gaines 1980). Slag production amounts to roughly 3 tonnes per tonne of primary refined copper. US primary copper production in 1993 was 1.79 MMT, generating about 5.4 MMT of slag. In the case of lead, the corresponding numbers for the concentrate appear to be (about) 75% Pb, 15% S, and 10% other. About 3 tonnes of flux materials are added for sintering and another 92 kg of flux materials are added to the blast furnace. Slag output is 15.8 metric tonnes/metric tonne for lead. In the case of zinc, a typical concentrate would be about 48% Zn (40%–64%), and 26% S, with other minerals accounting for the rest. Little or no flux is needed. Slag from smelting amounts to roughly 1 tonne per tonne of refined slab zinc. US 1993 primary zinc production was 0.24 MMT; lead 0.335. This implies total US 1993 slag output of 0.07 MMT for zinc smelting and 0.13 MMT for lead smelting. Total 1993 unrecovered US slag production for the three main NF metals was therefore roughly 1.3 MMT in toto, as compared to 1 MMT in 1988. Carbon monoxide and carbon dioxide emissions for the zinc and lead sectors as a whole are not known exactly, but they are quite small in comparison with other sources. The waste numbers for other metals are comparatively insignificant, on a national basis. Simplified schematic mass flows for the production of 1 tonne of copper, lead and zinc are shown in figures 6-5, 6-6 and 6-7 respectively.

4. EXERGY ANALYSIS OF THE METALLURGICAL INDUSTRIES

A number of efforts have been undertaken to apply exergy analysis to metal production processes, e.g., (Gyftopoulos *et al.* 1974; Hall *et al.* 1975; Morris *et al.* 1983; Wall 1986; Szargut *et al.* 1988). These studies presented exergy accounts for individual process stages, in order to identify major losses and evaluate the potential for further technical improvements in the metallurgical processes. On the other hand, the results obtained for different stages of the overall process are not typically combined to give an overall representation of the metallurgical industries from an exergy perspective. Without such an approach it is not possible to evaluate the environmental burden associated with the use of metals from “cradle to grave”as required by a life cycle (LCA) approach. As a matter of fact, such a common framework enables the analyst to evaluate the exergy flows, not only for each step in the chain, but for the whole chain of production. In the present work, exergy analysis has been applied to the overall production processes of steel, aluminum, copper, lead and zinc “from ore to ingot” but not all the way to disposal or recycling of final metal products. Therefore, the same system boundaries have been chosen for all of the five metal industries. All data were first normalized to 1 tonne of primary product, as was shown in figures 6-3 to 6-7. At a later stage we have calculated the associated exergy flows for each metal. It is worth stressing that the flow charts have to be regarded as schematics corresponding to realistic combinations of process steps and roughly consistent with averages of the major industry flows over a reasonably long period. Moreover, as the selected metal industries use different technologies, the figures are industry-level composites that do not fully reflect the complexity of the processes to which they refer. Each processing stage has been considered as a single unit-box, linked to the other sequences by means of material or energy flows. Many recycling streams are not shown explicitly. Each stream entering or leaving the box (system boundary) represents a net value. Many different sources of data have been utilized and compared, in order to build an overall flow diagram. The next five sections deal with individual metals in greater detail.

5. THE STEEL INDUSTRY

5.1 Process Description

Many different processes are used in the steel industry, depending on availability of feedstocks (scrap and ores), the availability of different fossil fuels — especially good quality coking coal – and on the mechanical and chemical properties needed for the final products. The integrated iron and steel sector consists mainly in two parallel but linked chains, the ore-to basic oxygen furnace (BOF) chain (with some scrap reprocessing) plus the secondary (scrap) steel reprocessing chain via electric arc furnaces (EAFs). The main integrated steel chain – from ore to ingot – involves five major steps, namely: ore mining, pelletizing or sintering, pig iron production, and, finally, conversion of pig iron to steel. Two additional processes have been included in our model to take into account coking and lime production (calcination of limestone). The simplified mass flow diagram of the whole industry was presented already in figure 6-2, while mass flows per tonne of product were shown in figure 6-3. The associated exergy flows are shown in figure 6-8. Brief process descriptions follow:

5.2 Iron Ore Mining and Beneficiation

Iron is mostly found in nature in the form of oxides (hematite: Fe_2O_3, magnetite Fe_3O_4). The iron content of the material mined may vary appreciably. A large part of the iron ore produced in the U.S. consists of taconite, a low grade ore with a 25% average iron content. Overall, roughly 3 tonnes of crude iron ore is extracted to produce 1 tonne of primary steel in the US, while 1.65 tonnes are used per tonne of integrated steel, allowing for scrap recycling. The steel produced in EAFs use only scrap as feedstock. Of the material moved at the mine, around 450 kg per tonne of steel is discarded as overburden and left at the mine site. The remaining material from the mine is crushed, ground and concentrated. This process, known as beneficiation, is needed to separate the iron rich material from the useless gangue. It is usually accomplished by means of magnetic separation and flotation. The wet residues from beneficiation are usually disposed of in ponds.

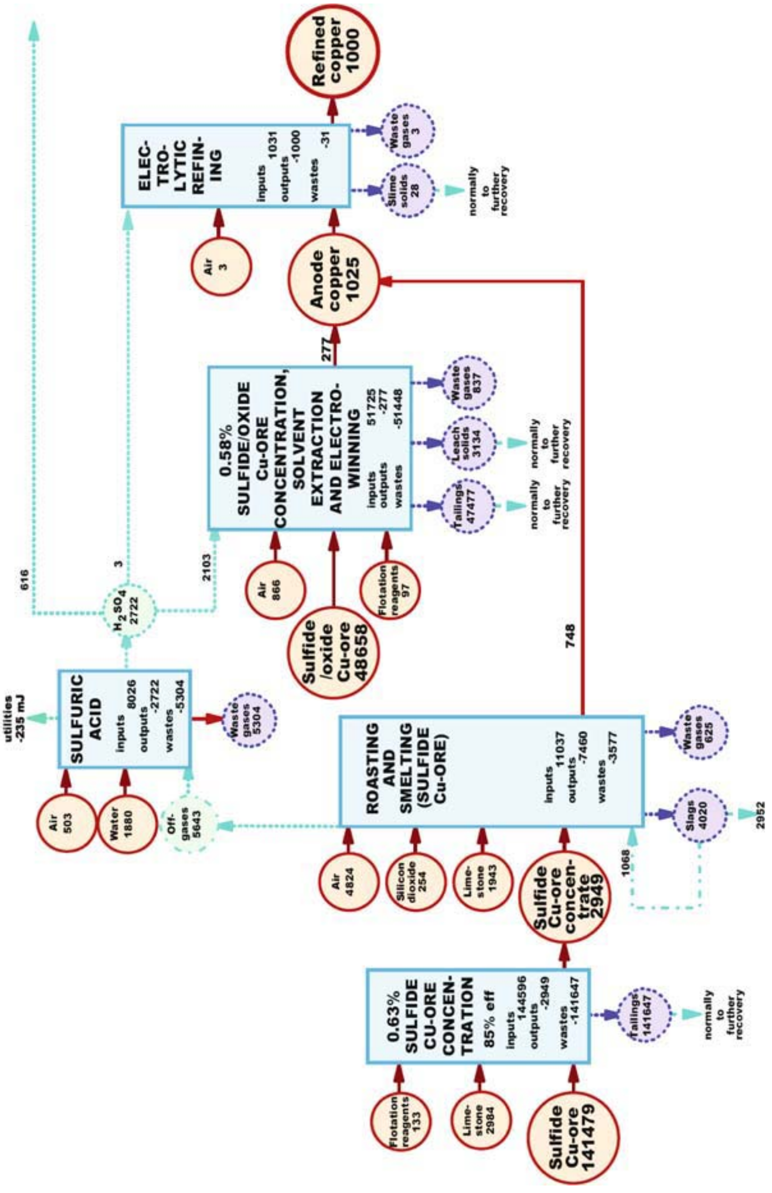


Figure 6-5. Mass flows (kg) in the production of 1 MT copper (simplified processes, typical material mixes).

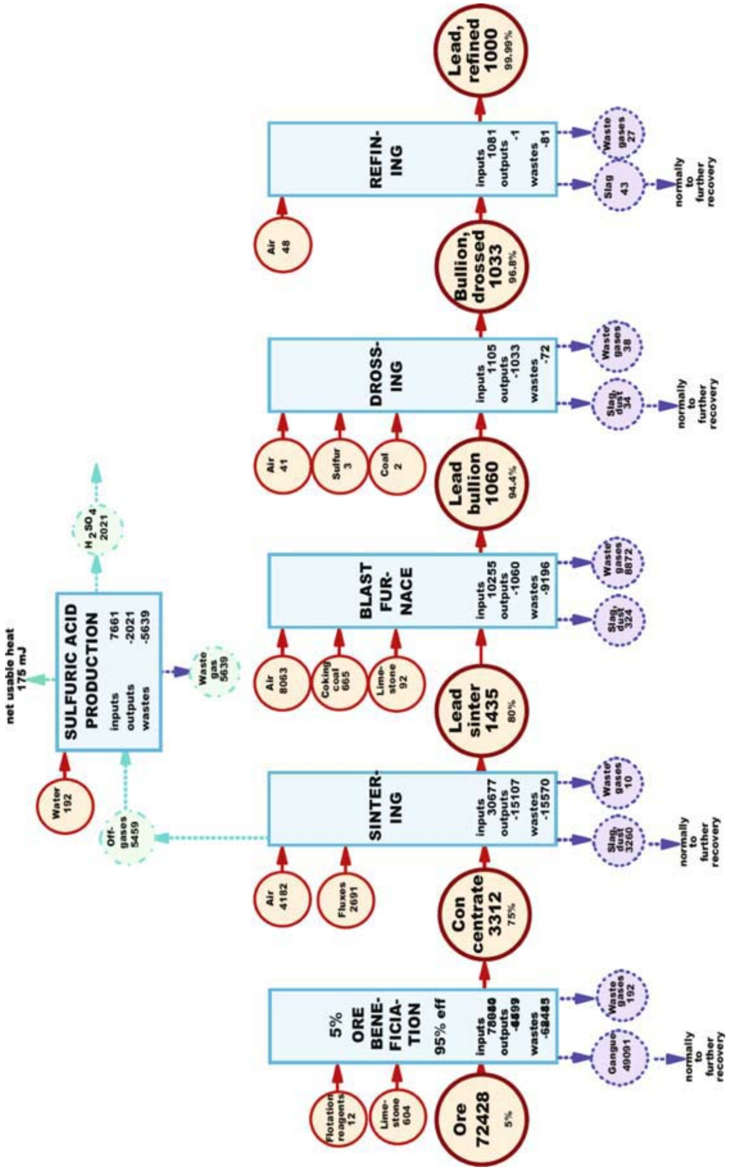


Figure 6-6. Mass flows (kg) in the production of 1 MT lead (simplified processes, typical material mixes).

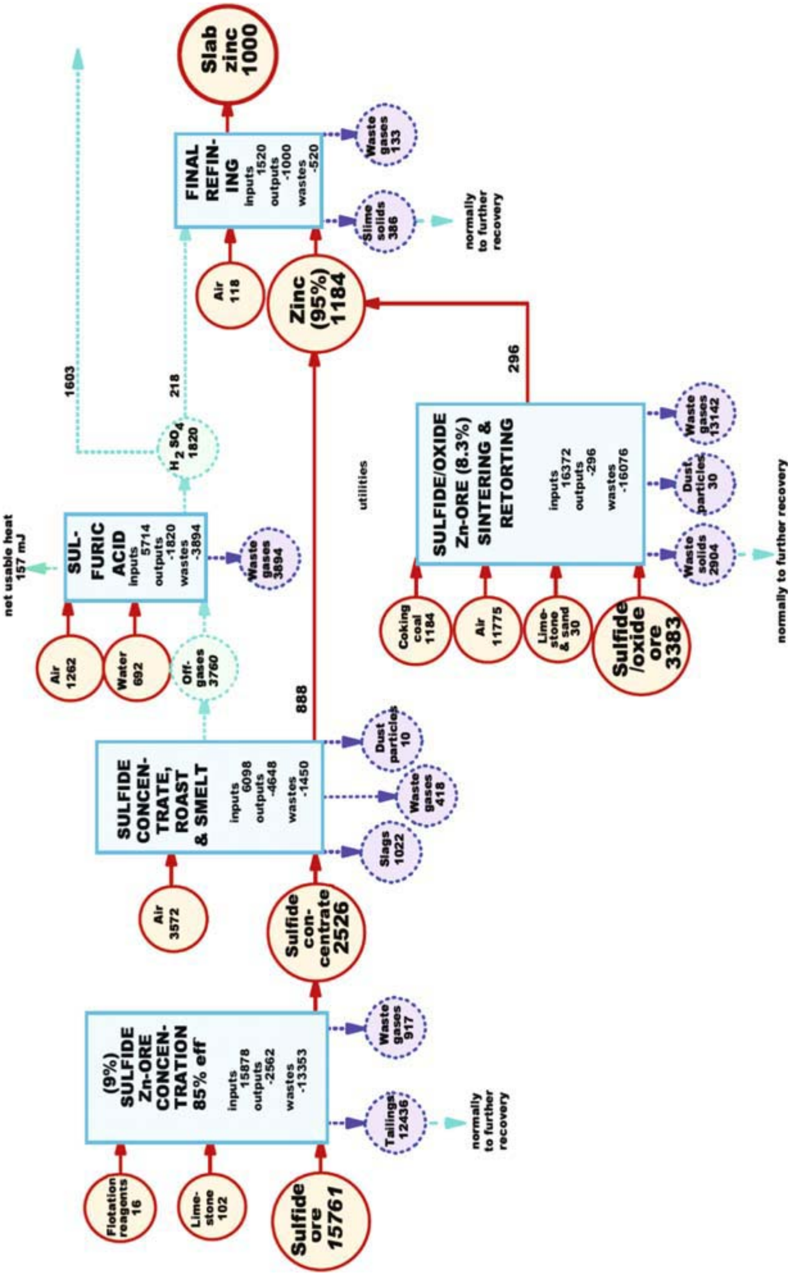


Figure 6-7. Mass flows (kg) in the production of 1 MT zinc (simplified processes, typical material mixes).

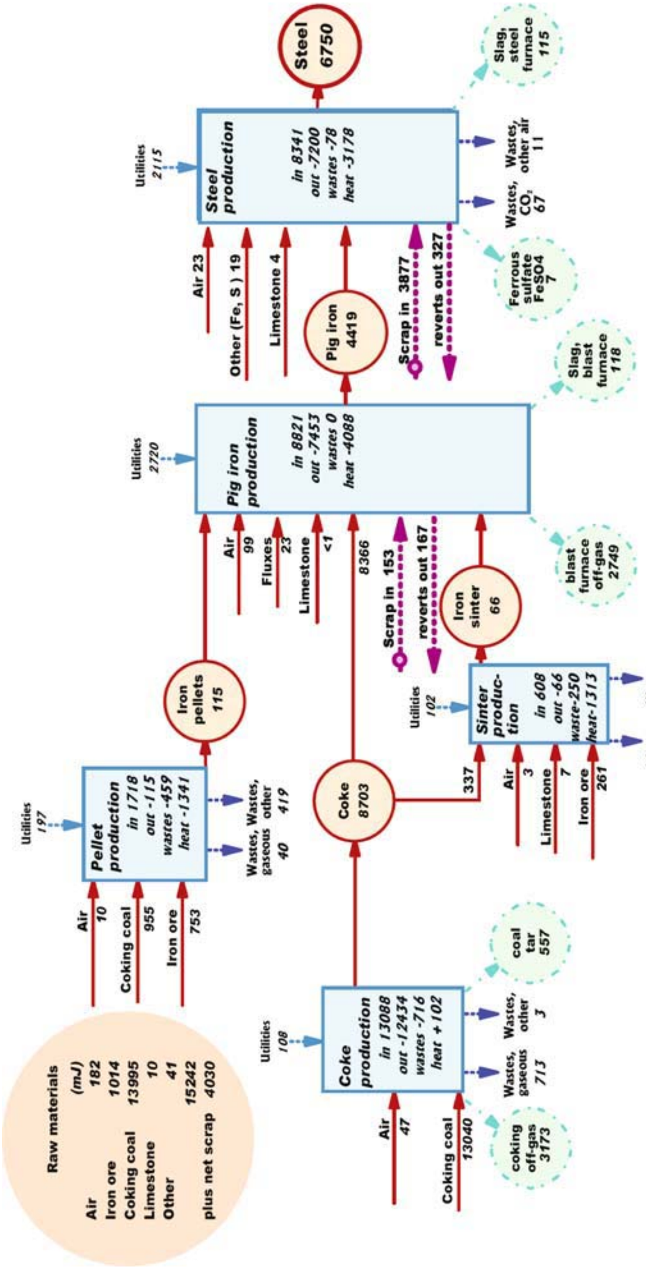


Figure 6-8. Exergy flows (MJ) in the production of 1 MT steel.

The concentrates resulting from this process are conveyed either to the pelletizing process (881 kg), the sintering machine (170 kg), or directly used in the blast furnace (598 kg). In calculating the exergy flows, the contribution of overburden has been neglected, as no accurate data were available on its composition. However the relative error is probably negligible.

5.3 Pelletizing and Sintering

Pelletizing and sintering are agglomeration processes used to meet the specific characteristic required for blast furnace feed, especially in terms of particle size and hardness. In the pelletization process iron ore concentrate is mixed with a binder (usually bentonite) then hardened in a furnace. Sintering is also a form of internal recycling: it is used to agglomerate fine dust particles which are too small to pelletize or be directly charged in the blast furnace. Iron pellets and sinter constitute the major constituents of the blast furnace charge (684 and 140 kg per tonne of steel, respectively).

5.4 Blast Furnace

The blast furnace is a large cylindrical tower lined with refractory bricks (made from chromite). It can be considered as the real “core” of steelmaking. The furnace is charged with a batch of iron ore (sinter and pellets) coke and limestone. Approximately 243 kg of coke and 143 kg of limestone are required for the production of 1 tonne of steel in our model process chain. During the reduction process the hot coke gases remove oxygen from iron oxides in the top part of the furnace, while in the high-temperature bottom part of the furnace the molten iron, mixed with a compound of iron and carbon is collected together with a slag. The latter contains silicon oxide and lime, together with small amounts of magnesium oxide and plays an important role in controlling the sulphur content of the liquid metal — called “pig iron”. Pig iron and slag are periodically removed from the furnace. By-product off-gases (called blast furnace gas), consisting mainly of carbon monoxide and nitrogen, are usually recovered and used as low heating value fuel for preheating the blast furnace feeds, or for other purposes. Finally, approximately 358 kg of CO_2 per tonne of steel are discharged into the atmosphere at this stage of the process.

5.5 BOF Steel Production

The hot liquid pig iron (94% iron, 5.5% C) is converted to steel in the basic oxygen furnace (BOF), while a small (but growing) fraction is cast directly, without being further processed. The furnace is charged with molten pig iron (905 kg/ton of BOF steel or 478 kg/ton of “average” steel) and steel scraps (302 or 159 kg/ton respectively). Oxygen is blown through the molten metal (hence the furnace name) to oxidize carbon and silicon impurities. Oxygen requirements amount to 100 kg per tonne of BOF steel, eliminating contamination by atmospheric nitrogen[2]. Lime and fluorspar are also typically added to form a fluid slag with the impurities. The slag floats on the liquid steel and is easily removed. The oxidation process is exothermic and no external heat is needed. The liquid steel is then cast into ingots or conveyed to a continuous casting machine. The amount of CO_2 generated by the BOF is about 150 kg per tonne of steel. This value has been estimated assuming that all the carbon contained in the pig iron is removed and converted eventually into carbon dioxide. When calculating the exergy content of finished steel – very nearly the exergy equivalent of the heat that would be recovered by burning it in air – no differences have been considered among the different types of steel. Our composite model considers an average of several processes (543 kg/ton pig iron, 560 kg/ton scrap iron). As a matter of fact, despite the great importance that carbon and other alloying elements, such as manganese, represent for determining the mechanical properties of finished steel, small variations of their content from one steel alloy to another cannot strongly affect the overall exergy content of the metal. (The case of stainless steel is slightly more complex because of the comparatively large chromium content but we do not consider it in this paper.)

5.6 Lime and Coke Production

Extraction and processing of limestone and coal are not actually part of the primary production process of steel. However, coke produced today is almost exclusively produced by steel companies and used in steelmaking: for each tonne of steel, 243 kg of coke is consumed by the blast furnace and 6 kg of coke breeze (dust) are consumed by the sintering machine. The steel industry also consumes a significant quantity of limestone per tonne of steel: 21 kg is consumed by the sinter process, 154 kg is consumed by the blast furnace and 370 kg is calcined to produce lime, used in the BOF. Hence the related emissions should reasonably be attributed to the final steel product. For a more detailed discussion of the allocation problem see Tellus (1992).

Mass and Exergy Flows

The main mass and exergy flows entering or leaving the iron/steel system boundary are summarized in figure 6-9.

The exergy analysis shows that the low-exergy content iron ore is progressively upgraded in exergy terms during the process. At the same time, of course, a large amount of exergy — mainly provided by coal — is lost as low grade heat or in process wastes and emissions. The largest loss occurs in the reduction stage, which involves combustion. About 15000 MJ of exergy per tonne of steel are consumed in the steelmaking process. Most of this (13000 MJ) is discharged to the environment as low grade heat. Emissions of carbon dioxide have been also included. However, in spite of their relative importance in terms of mass, they account for a small exergy content. The emissions into water are considerably smaller, but cannot be completely neglected: the main contribution is due to ammonia (7.9 MJ), phenol (about 5 MJ), and the heavy hydrocarbons contained in the lubricants used in the plant (about 2 MJ). It is worth stressing that because of the extreme complexity of the steel industry, a number of different possibilities can be used to represent the waste streams that are ejected to the environment. We have decided to take account of such contributions by calculating the exergy content of the airborne emissions contained in the gas flows. One weakness of this approach is that the internal recovery of coke oven and blast furnace off- gas cannot be correctly represented when analyzing the whole industry at a national level, because of the lack of consistent national data.

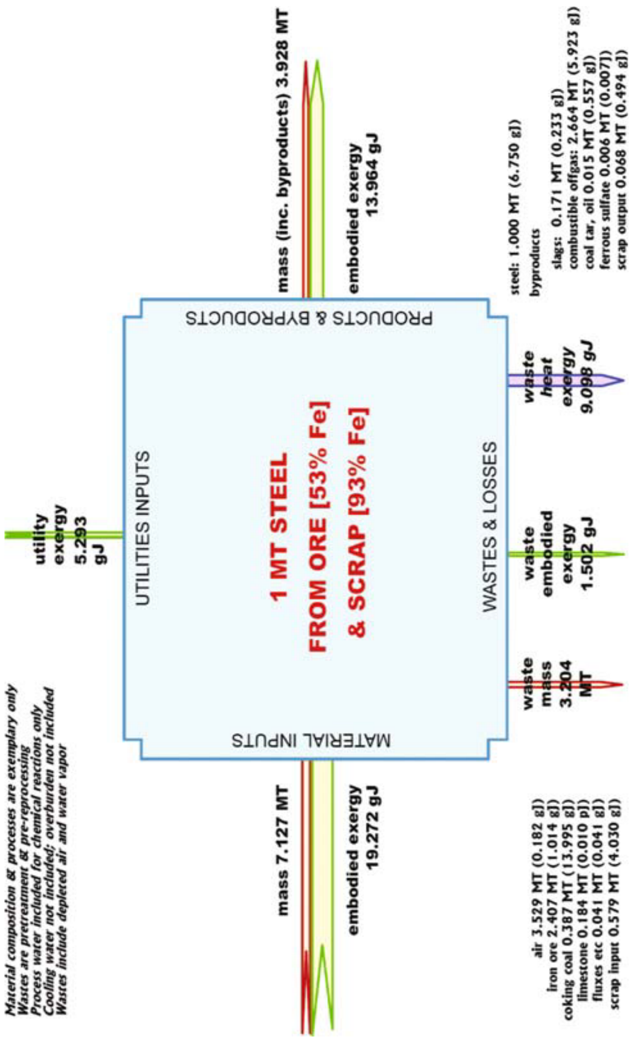


Figure 6-9. Steel unit mass and exergy flows.

6. THE ALUMINUM INDUSTRY

In the case of aluminum, we made use of an analysis carried out by the Tellus Institute (Tellus 1992) and revised by TME (TME 1995). This has been used as a supplementary reference for the material balance. This study presented a detailed list of air and water emissions but was incomplete in terms of mass balance. Therefore, data have been integrated with other sources(Altenpohl 1982; Ayres and Ayres 1996, chapter 2) or mass balance calculations in order to achieve a satisfactory degree of accuracy for exergy flows related to materials and wastes of the process.

6.1 Process Description

Aluminum never occurs in nature in metallic form as it is highly reactive and tends to combine with oxygen or other elements. Its only important mineral source, at present, is bauxite, which contains 40% to 60% aluminum oxide (Al_2O_3). The production process of aluminium involves three major processes, namely (1) bauxite mining, (2) alumina production by the Bayer process and (3) electrolytic smelting by the Hall-Heroult process. Material inputs and outputs for the process were adapted from (TME 1995) and from (Tellus 1992). The simplified mass flow diagram of the whole industry was presented in figure 6-4. The associated exergy flows are shown in figure 6-10. Brief process descriptions follow:

6.2 Bauxite Mining

Bauxite is a mixture of aluminum oxide (Al_2O_3), other oxides, such as Fe_2O_3, SiO_2, TiO_2 and water. It is mostly mined by the open pit method; the largest deposits are usually located in tropical regions. After mining, the bauxite ore is crushed, washed and screened to separate clay and useless impurities, it is then dried in a rotary kiln and conveyed to mills to be processed. Average composition — adapted from (Hall *et al.* 1975) — indicates a high content of aluminium oxide, both mono-hydrate and tri-hydrate. The exergy content of the material handled has been made equal to the exergy content of the bauxite ore, as the contribution of the overburden is certainly negligible.

6.3 Alumina Production (Bayer Process)

In the standard Bayer process the hydrate aluminum oxide is transformed into dehydrated alumina (Al_2O_3). Major inputs of the process are bauxite ore (3924 kg/ton of aluminum), caustic soda (96 kg/ton of aluminum) and limestone (78 kg/ton of aluminum). Raw materials are mixed together then conveyed to the digester, where hot steam is added to the mixture. Due to the high pressure and heat of the solution, the available alumina dissolves in the caustic soda forming sodium aluminate ($NaAlO_2$). The purified solution of sodium aluminate, called `green liquor', is further processed to remove suspended solids and other insoluble impurities and, finally, to produce aluminum trihydrate by means of precipitation.

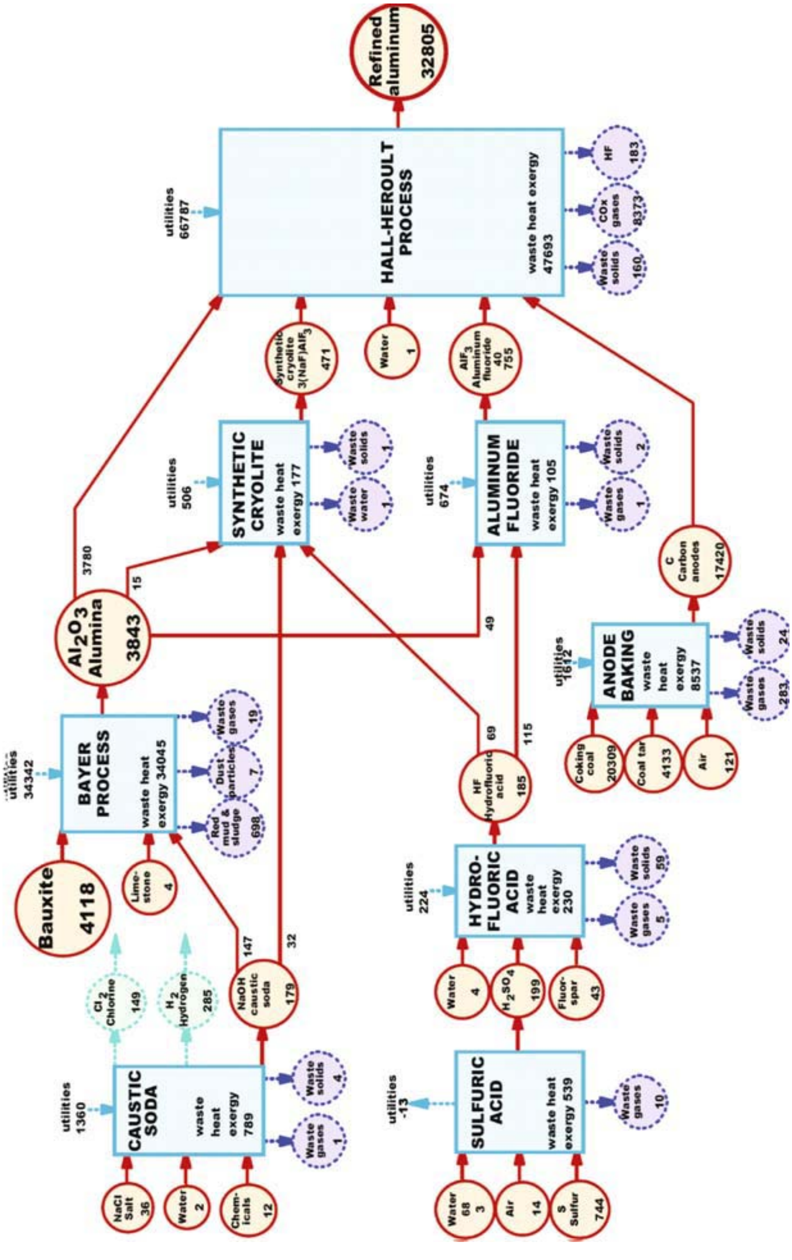


Figure 6-10. Exergy flows (MJ) in the production of 1 MT aluminum.

The latter is next filtered, washed and calcined to drive off water and produce alumina. The pure alumina is then conveyed to the aluminum production plant, while the remaining liquor solution is processed to recover caustic soda. The residual of this process, called `red mud', is a batch of insoluble metal oxides – mostly iron – which are generally disposed of in ponds. Approximately 2.05 tonnes of red mud are produced for each tonne of pure aluminum.

6.4 Aluminum Smelting (Hall-Heroult Process)

Metallic aluminum is produced by electrolytic reduction of alumina in the so-called Hall-Heroult process. The reduction plant consists in a series of electrolytic cells made of steel. Each cell is equipped with a consumable carbon cathode and anode made of petroleum coke and pitch. Purified alumina from the Bayer process (approximately 1.96 tonnes per tonne of aluminum) is dissolved in a molten bath constituted of cryolite (Na_3AlF_6), fluorspar (CaF_2) and aluminum fluoride (AlF_3). This bath serves as an electrolyte. When a low-voltage direct current passes through the bath, alumina is reduced to pure metallic aluminum and oxygen. The oxygen combines with carbon from the anode forming CO_2 and CO, and a small amount of fluorine-carbon compounds. Aluminum is then removed from the bottom of the cell and transferred to the casting house. The specific emissions of carbon dioxide have been estimated (Ayres and Ayres 1996 , chapter 3).

6.5 Mass and Exergy Flows

The main mass and exergy flows entering or leaving the aluminum system boundary are summarized in figure 6-11. Among the five metals considered, aluminum is responsible for the largest unembodied exergy losses per unit output. This is mainly due to the large amount of electricity needed in the final step of refining as well as to the considerable quantity of fuel oil used in the Bayer process. The high exergy content of the energetic inputs is not totally transferred to the final product, but instead almost entirely destroyed. When focusing attention on wastes and emissions, it can be seen that major emissions are discharged into air: carbon monoxide accounts for the largest exergy content, but also the contribution of carbon dioxide and sulfur dioxide seems to be relevant (364 and 295 MJ/ton of aluminum, respectively). On the other hand, emissions into water are of minor importance, amounting to less than 20 MJ/ton of aluminum.

7. THE COPPER INDUSTRY

7.1 Process Description

Several processes have been implemented in the last decades for intermediate steps in copper production both to improve process efficiency and to reduce its environmental impact. However, the major use of this metal, for wire used in electrical equipment, requires a high level of purity that can be achieved only by means of a final electrolytic refining.

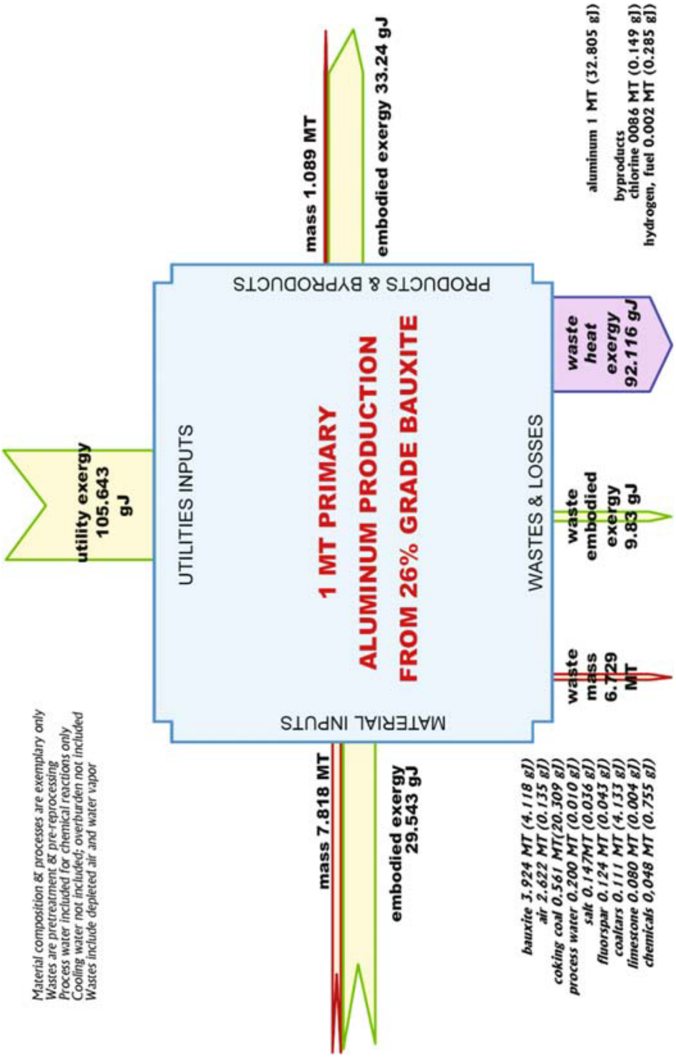


Figure 6-11. Primary aluminum unit mass and exergy flows.

Thus, a standard process for the production of primary copper involves five major stages, namely: ore mining, beneficiation (by flotation or leaching), desulfurization, smelting and converting, followed by electrolytic refining. The simplified mass flow diagram of the whole industry was presented in figure 6-5, derived from processes described in (Gaines 1980; PEDCoCu 1980; USBuMines 1991). See also (Ayres and Ayres 1998).

7.2 Ore Mining

Recoverable copper deposits are nowadays mostly sulfide minerals, such as chalcopyrite ($CuFeS_2$), chalcocite (Cu_2S), bornite (Cu_5FeS_4) and enargite (Cu_3AsS_4). By far the most important deposits are of the porphyry copper type, in which the dominant mineral is chalcopyrite. Arsenic is associated with some US porphyry copper deposits. Another type of porphyry deposit is the copper-molybdenum type, in which the mineral molybdenite (MoS_2) is interspersed with chalcopyrite. Most mines are of the open pit type. So called oxide ores are weathered products of sulfides, notably malachite ($CuCO_3 .Cu(OH)_2$), azurite ($2CuCO_3 .Cu (OH)_2$), cuprite (Cu_2O) and chrysacolla ($CuSiO_3 .2H_2O$). Globally about 90% of copper mined comes from sulfide ores and 10% from oxide ores.

7.3 Beneficiation

The specific processes appropriate for beneficiation of copper ores are dependent on the combination of minerals in the ores. Individual mining companies have developed a variety of proprietary processes to recover various by-products or co-products. In general, the average copper content of US ores is now around 0.6%, so that large amounts of inert material must be processed to obtain a small amount of copper. (Almost 200 tonnes of material are mined, on average, to produce 1 tonne of refined metal). The main technique for concentration of sulfide ores is froth flotation. Flotation agents are fatty acid soaps, pine oil frothers, cresylic acid, alkyl or alkyl aryl xanthates, dithiophosphates, dithiocarbamates, thiols, sulfates, sulfonates, or amines. Lime is used to adjust pH and as a pyrite depressant. Copper concentrates from sulfide ores in the US range from 20 to 35 percent Cu, 30-38 per cent S, 20-30 percent Fe, plus 0.2-4 percent Zn, 0-4 percent As, 0-0.67 percent Pb, and 0.13 percent Ag, plus 31.5 gm Au per tonne of copper and variable traces of other metals such as selenium. Oxide ores (and low grade sulfide ores) can best be concentrated by hydrometallurgical techniques, notably heap or vat leaching followed by precipitation or solvent extraction. In all leaching processes crushed ores are flooded by sulfuric acid, which converts most of the copper to copper sulfate. Sulfide ores of very low grades (less than 0.4 percent Cu) can also be treated by heap leaching. The sulfuric acid oxidizes the copper minerals. It also reacts with iron pyrites in the waste, creating additional sulfuric acid and ferric sulfate, which dissolves copper minerals. Once the process starts it continues naturally if water and air are circulated through the heap. Soluble copper is then recovered from drainage tunnels and ponds. Recovery of 70–80 percent is possible in ideal conditions.

7.4 Precipitation and Solvent Extraction

Solutions of copper sulfate from vat or heap leaching are too dilute for electrowinning (EW). The next step is concentration, either by precipitation (cementation) or solvent extraction (SX). Cementation is a process in which soluble copper sulfate reacts with iron – usually scrap – yielding soluble iron compounds (ferrous or ferric sulfate) and precipitating the copper. The `cemented' precipitate – typically 70 percent Cu, with iron and other impurities – is later fed to a smelter, along with other feeds. The spent liquor is recycled back to the heap or vat. Recovery by cementation is around 95 percent. Solvent extraction (SX) is a method to produce a relatively pure solution of copper sulfate suitable for electrolysis (electro-winning.). Kerosine, with a 12 percent mixture of a proprietary organic solvent, is used in an agitated vessel. The solvent combines with the copper, forming a complex. When agitation is stopped, the copper-containing organic complex forms a separate dense layer from which the water can be drained off. Sulfuric acid then breaks down the complex and regenerates the solvent for further use. The sulfuric acid, together with dissolved copper sulfate, is then recycled through the electrowinning (EW) cells. Recovery is about 95 percent. The combined SX-EW process can be continuous and is suitable for large-scale operations.

7.5 Roasting and Smelting

Roasting is a process to convert copper and iron sulfide concentrates (25–35 percent Cu) to oxides, thereby removing most of the sulfur as sulfur dioxide. Two main types of furnace have been used, viz. multiple hearths and fluidized bed roasters. The sulfur dioxide, if sufficiently concentrated, is subsequently converted to sulfuric acid (H_2SO_4) in a contact acid plant. The next stage (often combined with roasting) is smelting. There are four major types of copper smelter, namely reverberatory furnaces, electric furnaces, flash smelters and Noranda smelters. There are two types of flash smelters, Outokumpu and INCO. The choice among them depends on the specific characteristics of the concentrate feed. However, the first two types are inherently batch-type and consequently less efficient than the latter two types, flash smelters and Noranda smelters, both of which are suitable for continuous operation. The Noranda design comes closest to one-step operation, combining the functions of roaster, smelter and partial converter, yielding a low sulphur matte. It is also the most efficient design in terms of energy conservation. However it has other drawbacks. The Outokumpu flash furnace is the most prevalent among newer or upgraded facilities. The primary output in all cases is a copper-iron matte, with silica and other inert minerals consigned to slag. The slag is typically recycled through the smelter to increase the recovery rate.

7.6 Converting

Molten copper-iron matte from the smelting furnace, together with copper scrap, is converted by blowing air through it, to oxidize any remaining sulfur. (This step is analogous to the old Bessemer process in steel making). A flux is added that combines with the iron yielding slag and relatively pure `blister copper' (98% percent Cu). There are two types of converter, namely Pierce-Smith (the most common) and Hoboken[3]. They differ primarily in the method of capturing sulfur dioxide off-gases. In principle the Hoboken design is preferable, because it achieves better sulfur dioxide recovery but the design was still semi-experimental in the late 1970s.

7.7 Electrowinning(EW)

As noted above, pure copper sulfate dissolved in sulfuric acid is generated by the vat leaching process and the solvent extraction (SX) process. This material is suitable for feeding directly to electrolytic cells. The combination, which now accounts for over 30 percent of US production is known as the SX-EW process. It differs from electrolytic refining (below) in that the anodes are inert. Copper is deposited on the cathode, liberating oxygen and regenerating the sulfate ion as sulfuric acid. Purity can be as high as 99.9 percent, comparable to the best electrolytic copper. Oxygen (from the cells) can be utilized in the Noranda smelter, for example. However, the fact that the EW cells decompose water is a disadvantage, in terms of energy consumption.

7.8 Fire Refining and Electrolytic Refining

Blister copper (about 98% Cu) is not pure enough for electrical applications and needs to be further treated. Fire refining is an old technique, similar to the Bessemer converter, in which air is blown through the melt and flux is added to eliminate the last impurities. Excess oxygen was originally removed by `poling' with logs, which decomposed into carbonaceous products that quickly oxidized. Nowadays natural gas, hydrogen or ammonia are used for this purpose. The product is mostly cast into anodes (>99 percent Cu) and sent on to an electrolytic refinery; however, given a high enough quality blister (e.g., from a Noranda smelter), fire refined copper can be used for alloys and special castings. The electrolytic refining process uses fire refined anodes from the fire refinery, or recycled anodes from the electrolytic refinery itself, copper sheets as cathodes and sulfuric acid as an electrolyte. Impurities collect as a `slime' at the bottom of the cell. This slime, or anode mud contains many of the precious and other by-product metals and is recycled for additional processing. At the end of the process pure copper is collected on cathodes, together with small amounts of precious metals deposited as anode mud, which can be easily recovered.

7.9 Mass and Exergy Flows

The exergy flows for copper are summarized in figure 6-12, while the combined mass and exergy flows for the industry are summarized in figure 6-13. The copper industry shares one of the features of the aluminum industry, being very exergy-intensive. Efficient use of the exergy embodied in sulfur is one of the keys to increasing efficiency.

8. THE LEAD INDUSTRY

8.1 Process Description

The process for the production of primary lead consists in five basic stages, namely: ore mining and beneficiation, sintering (desulfurization), smelting, drossing, and final refining and casting. Each subsidiary process can be split again into several different operations. A general mass flow diagram for lead production was shown in figure 6-6. Quantitative data were obtained from several sources (Thomas 1977; PEDCoPb 1980; Morris *et al.* 1983; Szargut 1988; USBuMines 1991) and integrated with gross mass balance estimates.

8.2 Ore Mining and Beneficiation

Lead is found in nature almost exclusively as galena (PbS), which is its primary sulfide. Oxidized ores can also occur, such as anglesite ($PbSO_4$) and Cerussite ($PbCO_3$), which are the weathered products of Galena. Lead ore often contains iron, copper and zinc sulfides or sulfates, as well as a small percentage of precious metals (especially silver), which can be recovered during the lead smelting. The average lead content of the material currently mined in the US is approximately 6%, albeit somewhat higher for Mississippi Valley ores and lower for the partially oxidized ores mined in the west (USBuMines 1991). Antimony and bismuth, as well as copper, zinc, silver and gold are by-products of lead mining. Lead ore is crushed, ground, and then concentrated by froth flotation. The process is similar to that for copper. In the mechanical process used for Missouri (galena) ores, separation is achieved thanks to the difference in specific gravity of the lead ore and the gangue particles. After concentration, the lead content of Mississippi Valley ores is increased to around 72–75% by weight. Western ores are concentrated by the chemical froth flotation process, achieving 45–60% lead content.

8.3 Sintering

Sintering consists in roasting the concentrate to drive off the sulfur. Metal sulfides are transformed to oxides, suitable for carbothermic reduction in the blast furnace. The sinter machine is charged with ore concentrate, limestone and silica. Where lower grade concentrates are used, up to 45% of the produced sinter is recovered and recycled. The reaction is exothermic. About 85% of the sulfur is removed from the concentrate during sintering as sulfur dioxide. The latter is normally sent to a sulfuric acid plant. The sinter composition is effectively the same as the concentrate, except that lead sulfides have been replaced by oxides.

8.4 Smelting

There are two main cases. Lead concentrates low in zinc are smelted in a blast furnace. In the blast furnace lead oxides are carbothermically reduced to lead bullion. The process is very similar to iron smelting. The insoluble light metal. oxides (silica, alumina, lime) form a slag which floats over the liquid metal so that it can be easily removed. Slag is cooled and crushed, then partially recycled to the sinter machine. The remaining part is discharged. Approximately 2900 kg of slag leaves the blast furnace for each tonne of lead and about 50% of it is recycled internally. Other output streams are dust and off-gases. Despite of their heat content, the latter are not usually re-used in the process. Concentrates high in zinc content are normally sent to a so-called `imperial smelter', which removes the zinc in vapor form for subsequent condensation (retorting). The rest of the reduction process is the same as above.

8.5 Drossing and Final Refining

Lead bullion from the blast furnace or imperial smelter needs to be further refined to remove residual sulfur and other metallic impurities for industrial applications. Smelted lead bullion passes through a multi-step process, whereby metal impurities are removed in the form of slag. A matte rich in copper, a silver-gold alloy (known as doré metal) and small quantities of antimony, bismuth and zinc oxide are also by-products of lead refining. Approximately 30 kg of copper matte are recovered per tonne of lead in the US. No quantitative data were available to evaluate the amounts of other by-products produced.

8.6 Mass and Exergy Flows

The main exergy flows are shown in figure 6-14. Combined mass and exergy flows entering or leaving the system boundary are summarized in figure 6-15. On the one hand, exergy losses are considerably smaller than in the case of aluminum, mainly because the refining processes are not electrolytic. Also a considerable amount of exergy is embodied in a byproduct (sulfuric acid)

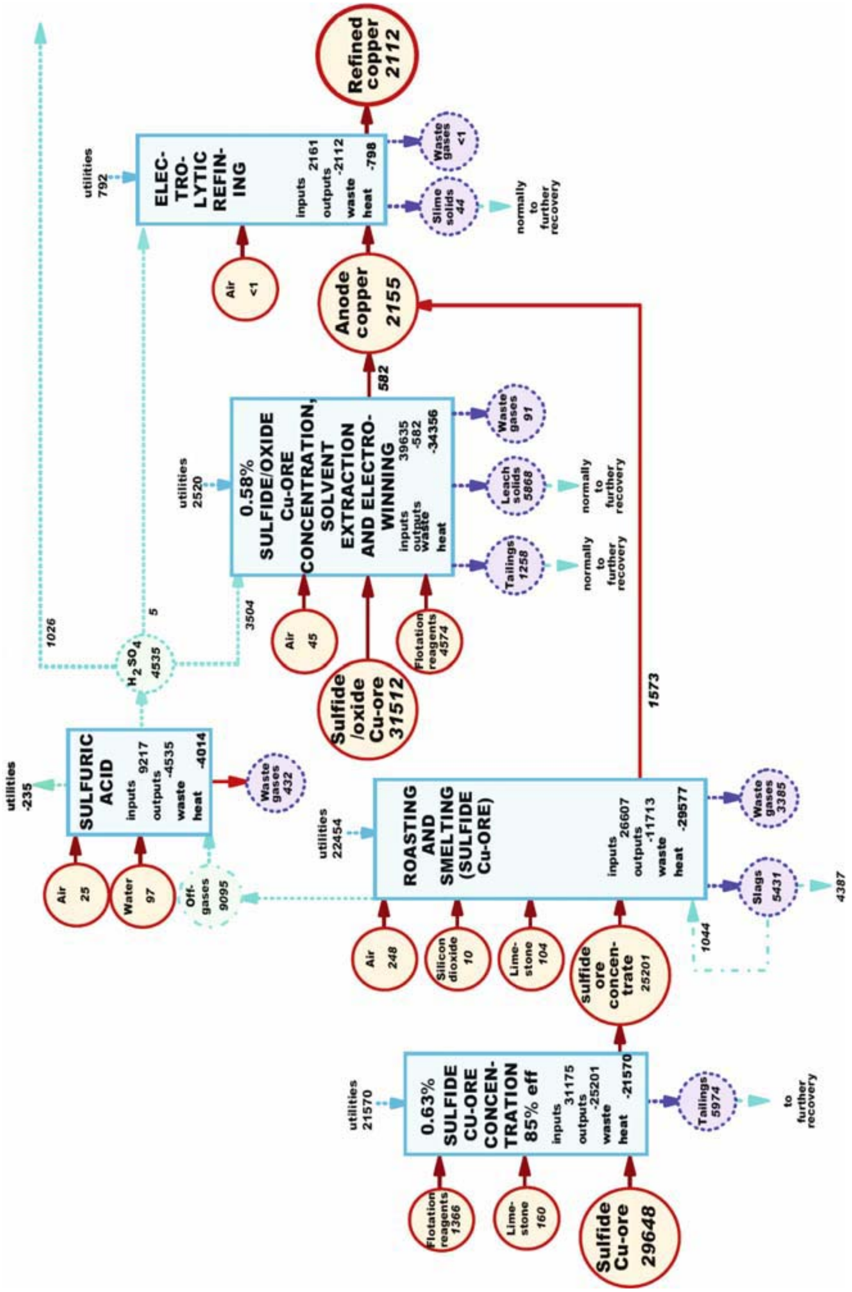


Figure 6-12. Exergy flows (MJ) in the production of 1 MT copper.

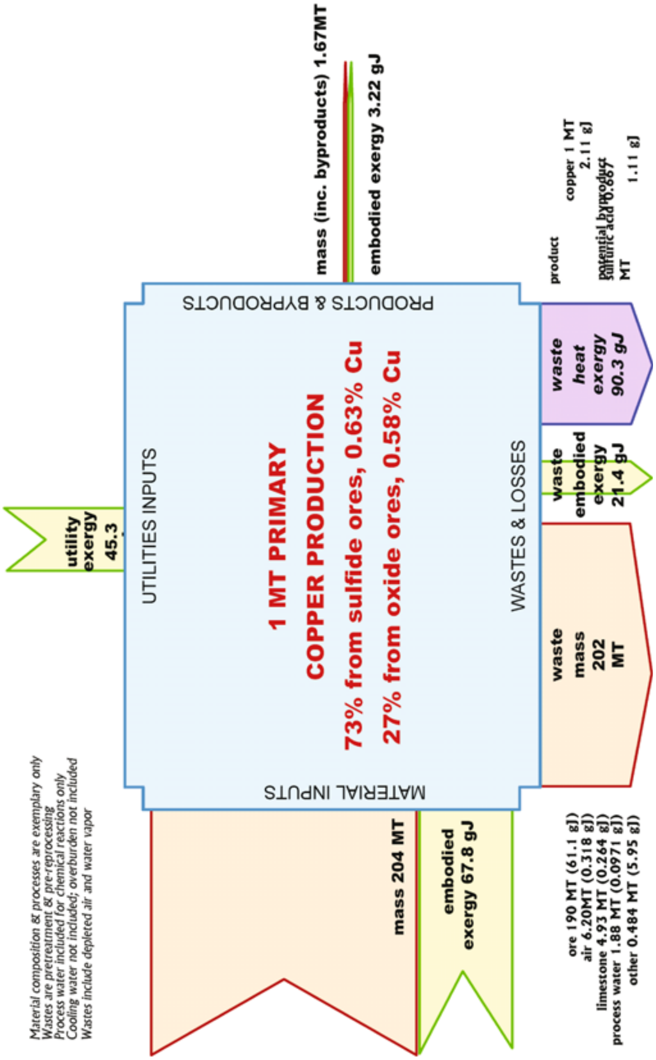


Figure 6-13. Primary copper mass and exergy flows.

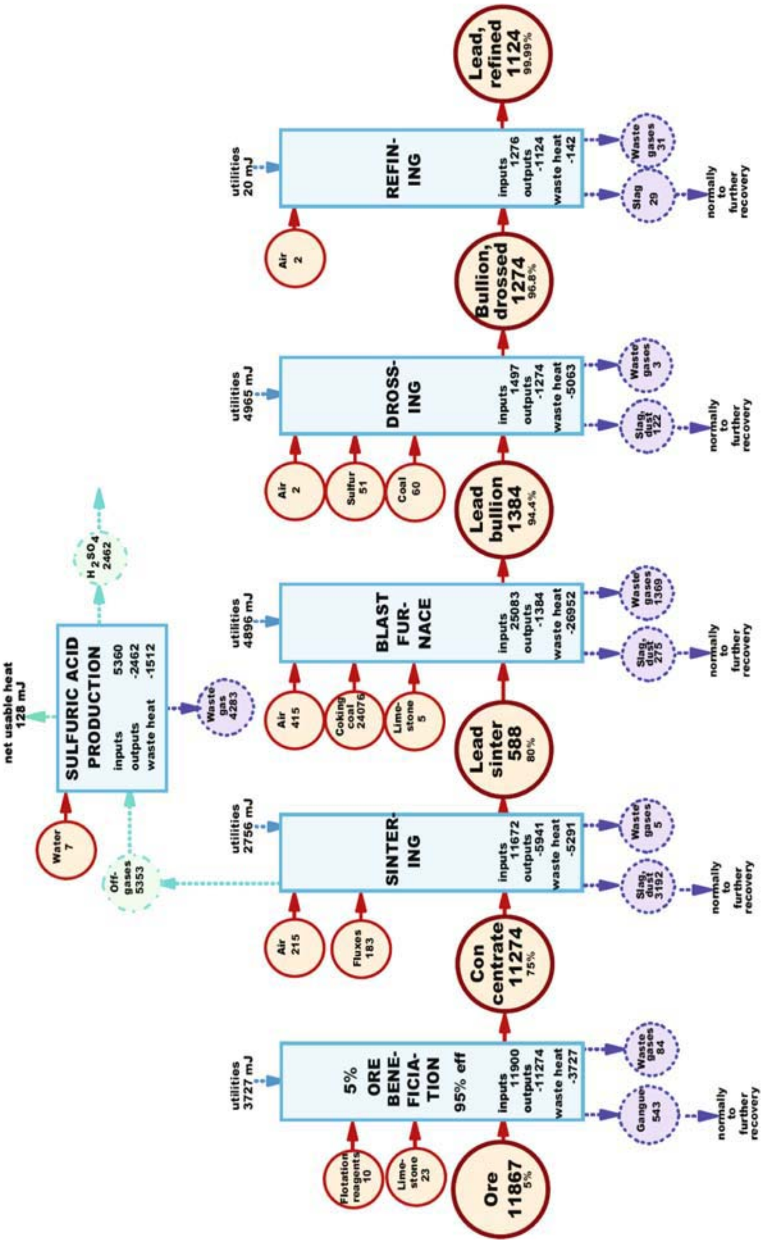


Figure 6-14. Exergy flows (MJ) in the production of 1 MT lead.

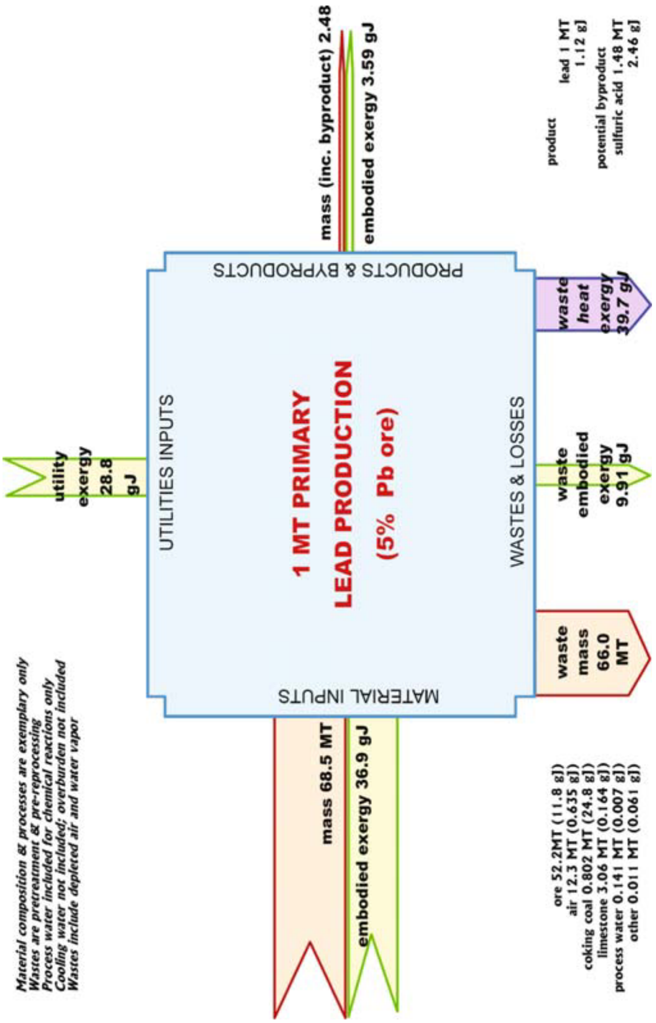


Figure 6-15. Primary lead unit mass and exergy flows.

9. THE ZINC INDUSTRY

9.1 Process Description

The overall process for the production of primary zinc metal (slab zinc) is very similar to that for lead. It also consists in five basic stages, namely: ore mining, beneficiation, sintering, smelting and final refining. However, zinc ores are more variable than lead ores and treatment is more complex. A general mass flow diagram for zinc production was shown previously (figure 6-7). Quantitative data were obtained from several sources (PEDCoZn 1980; Szargut et al. 1988) (USBuMines 1991) and integrated with the help of mass balance estimates.

9.2 Ore Mining and Beneficiation

The most common zinc mineral is the simple sulfide, sphalerite (ZnS) and the zinc-iron sulfide (Zn, Fe)S known as marmatite, but zinc is also extracted commercially from a number of other minerals, including oxides (e.g., zincite, franklinite), carbonates (smithsonite, hydrozincite), sulfates (goslarite), and silicates (willemite, hemimorphite). Some zinc sulfide ores are associated with iron pyrites, copper minerals (chalcopyrite) and lead minerals (galena). Zinc ores mined contain 3 to 11 percent zinc. Cadmium (as cadmium sulfide, or greenockite) is the second most abundant impurity of zinc, after iron, having an average abundance of 1 part per thousand of zinc and a maximum abundance of 1-2 percent of zinc. Zinc oxide ores are mostly not mined for their zinc content but are by-products of mines for other metals and are typically sent to ferroalloy (e.g., spiegeleisen) operations. Zinc sulfide ores are beneficiated by froth flotation. Concentrates range from 52–60 percent zinc, 30–33 percent sulfur and 4–11 percent iron.

9.3 Roasting, Sintering and/or Leaching

Zinc concentrates are roasted, with sodium or zinc chloride, to drive off the sulfur (as sulfur dioxide, sent to a contact sulfuric acid plant) and convert the zinc to zinc oxide for subsequent reduction. The product of roasting is known as calcine, with a typical residual sulfur content of 2 percent. The calcine is then either sintered (with sand and coke) or leached by sulfuric acid.

9.4 Retorting

Sintered calcine is reduced by reaction of the zinc oxides with carbon monoxide from coke in a vertical retort, which is similar in function to a blast furnace. However, the zinc metal is removed as vapor and condensed to molten metal, which is subsequently cast into slabs. Impurities are separated at the retort for by-product recovery.

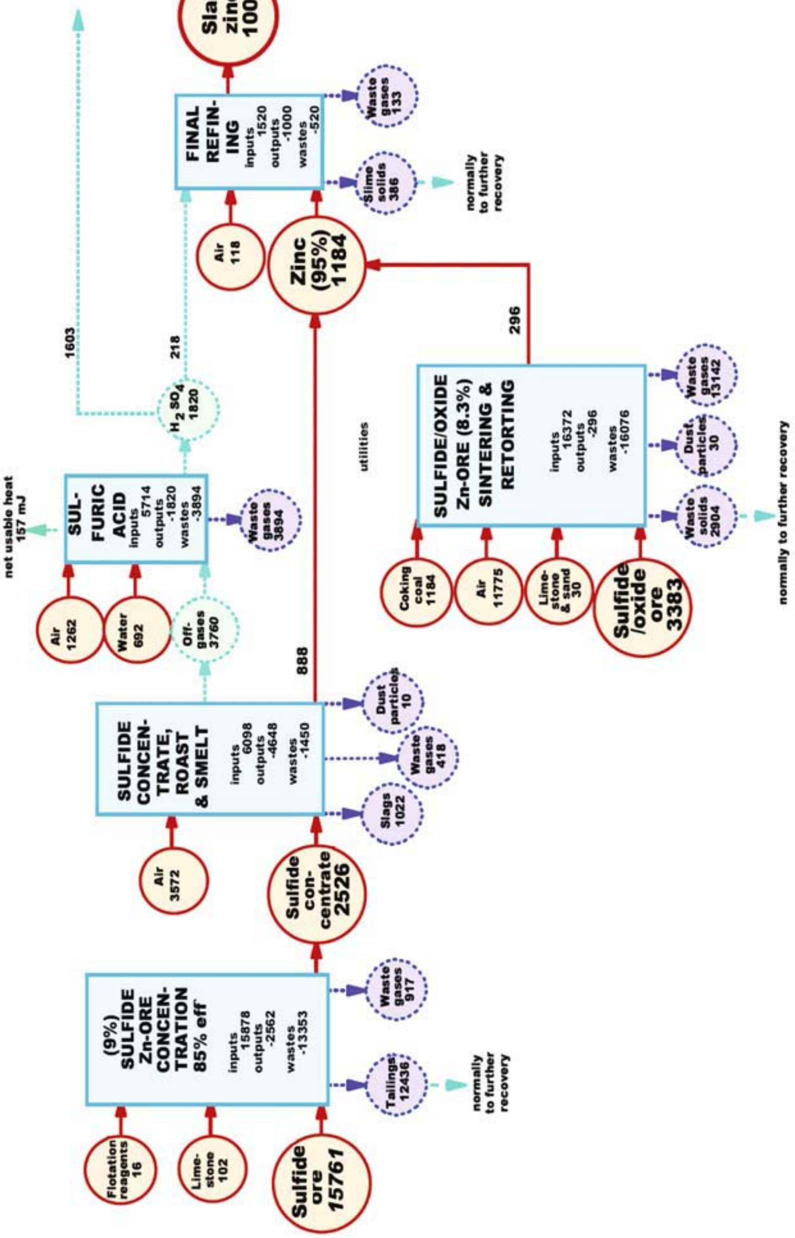


Figure 6-16. Exergy flows (MJ) in the production of 1 MT zinc.

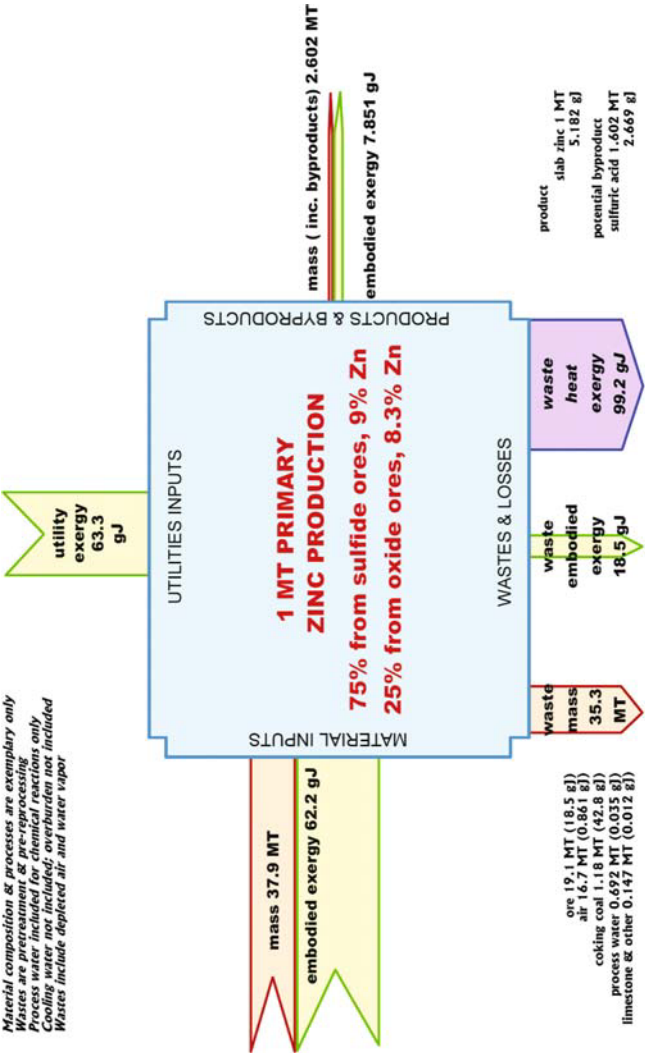


Figure 6-17. Overall unit zinc mass and exergy flows.

9.5 Leaching and Electrolysis

Some of the calcine is treated by leaching (with sulfuric acid) and the zinc is recovered by electrolysis as cathode zinc. Flue dusts from roasting and sintering operations, along with leach residues are leached again for cadmium recovery and purification.

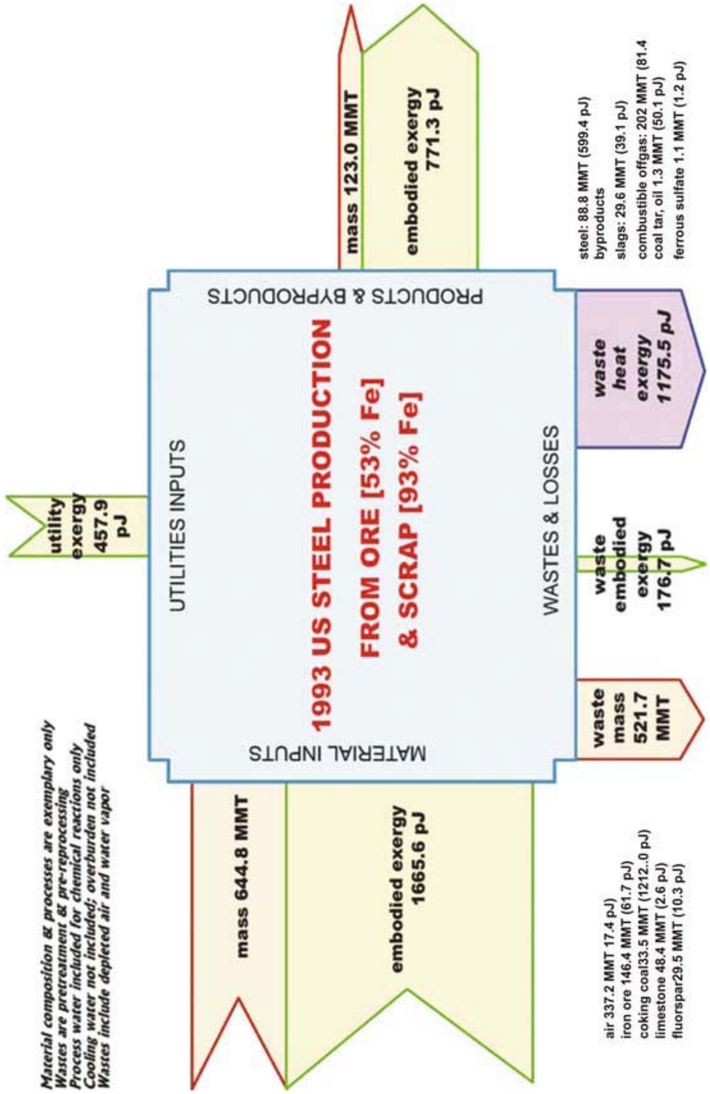
9.6 Mass and Exergy Flows

The pattern for zinc is comparable but slightly different from that of lead. Waste heat exergy losses are slightly higher. Material wastes are somewhat less. Zinc itself is considerably more exergetic than lead (5 GJ/MT as compared to 1 GJ/MT) and there is 50% more sulfuric acid by-product per unit mass of metal. The associated exergy flows are shown in figure 6-16. Combined mass and exergy flows are shown in figure 6-17.

10. CONCLUSIONS

The analysis clearly demonstrates how exergy analysis can be used for resource and waste accounting purposes. It enables one to compare the systems under consideration on a common basis, both to identify major loss streams that may correspond to inefficiencies and to provide a first evaluation of their environmental burden. Figures 6-18 to 6-22 present such an evaluation for 1993 in the United States for all five metals, arrived at by applying 1993 US production data multiples to the unit mass/exergy process-product values shown in the diagrams.

The data clearly indicate that the aluminum industry is characterized by a very large exergy consumption, mainly because of the energy-intensive electrolysis used for reduction. Exergy losses in all the non-ferrous metals industries, per tonne, are about five times the losses of the steel industry. In fact, about 100 GJ of exergy are required for the production of 1 tonne of refined primary aluminum, while only 5 GJ are needed by the steel industry to produce the same quantity of metal. Aluminum competes in certain applications only because it is lighter than steel and non-corroding. Among the lessons that can be drawn we include the need for greater recycling and the need for further technical improvements in the production process currently in use. The cases of copper and lead (and zinc) represent an intermediate situation between steel and aluminum. The former industries show the lowest exergy efficiency among the analyzed processes, but the absolute exergy consumption are relatively smaller than those of the aluminum sector (less than 40 GJ per tonne of metal in both cases). On the emissions side, even though accurate data about the whole spectrum of pollutants were not available for these industries, one can state that sulfur dioxide emitted in the smelting process is more likely to be the largest emission to air. For both copper and lead production, the exergy content of this substance has been accounted for under the item “wastes and useless by-products”. In the case of lead production it was possible to estimate the overall flow of the blast furnace off gas. However, instead of considering the disaggregated contribution of each component of the gas as an air emission, we have preferred to include the overall exergy content of the stream under the item “wastes”. This choice was due to the fact that it was not clear whether the off-gas was directly discharged to the atmosphere or further processed in any emission control system.



Material composition & processes are exemplary only
Wastes are pretreatment & pre-reprocessing
Process water included for chemical reactions only
Cooling water not included; overburden not included
Wastes include depleted air and water vapor

Figure 6-18. 1993 US steel mass and exergy flows.

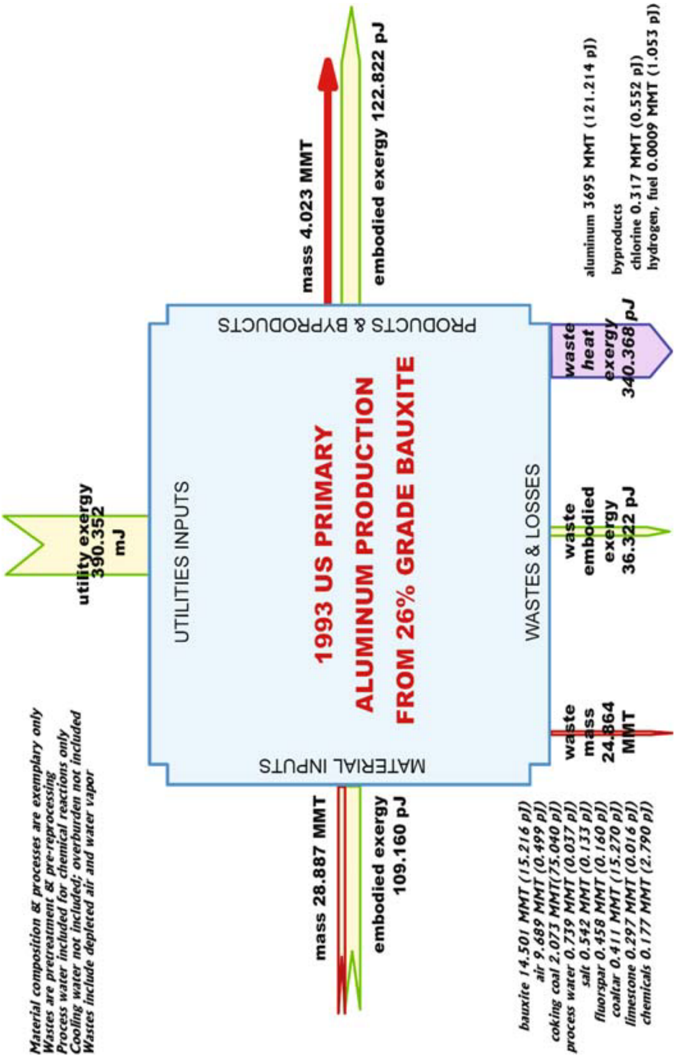


Figure 6-19. 1993 US aluminum mass and exergy flows.

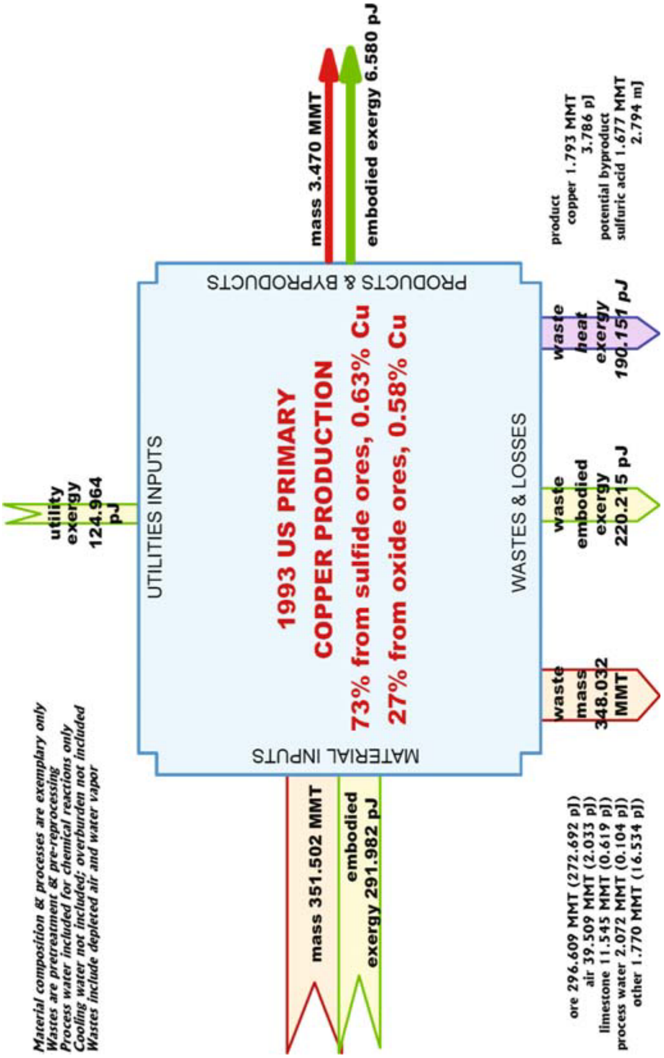


Figure 6-20. 1993 US copper mass and exergy flows.

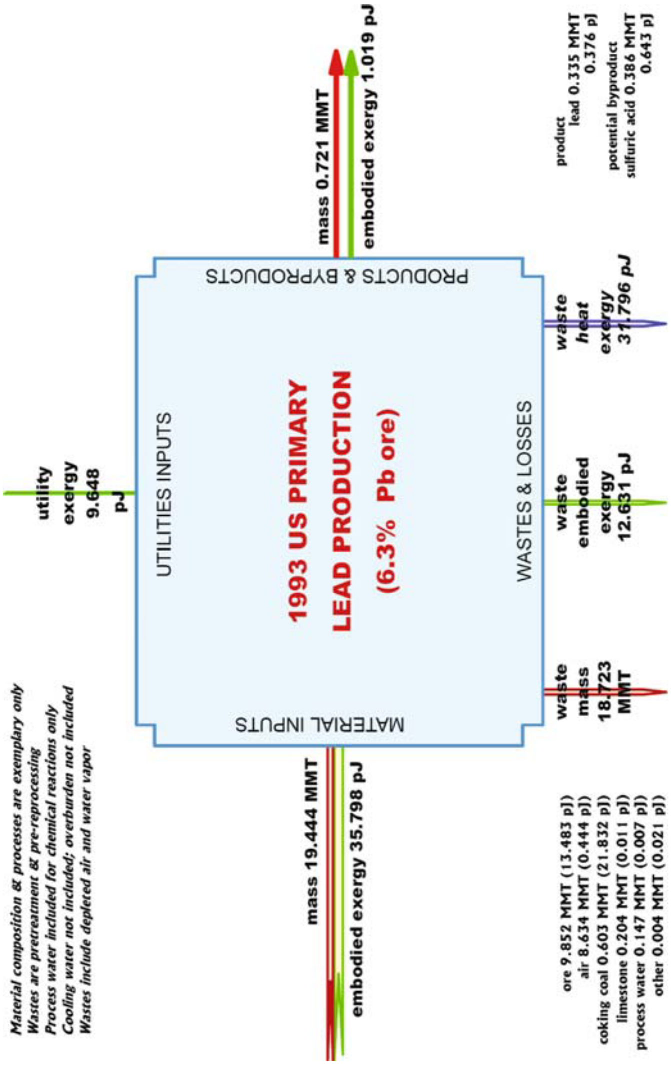


Figure 6-21. 1993 US lead mass and exergy flows.

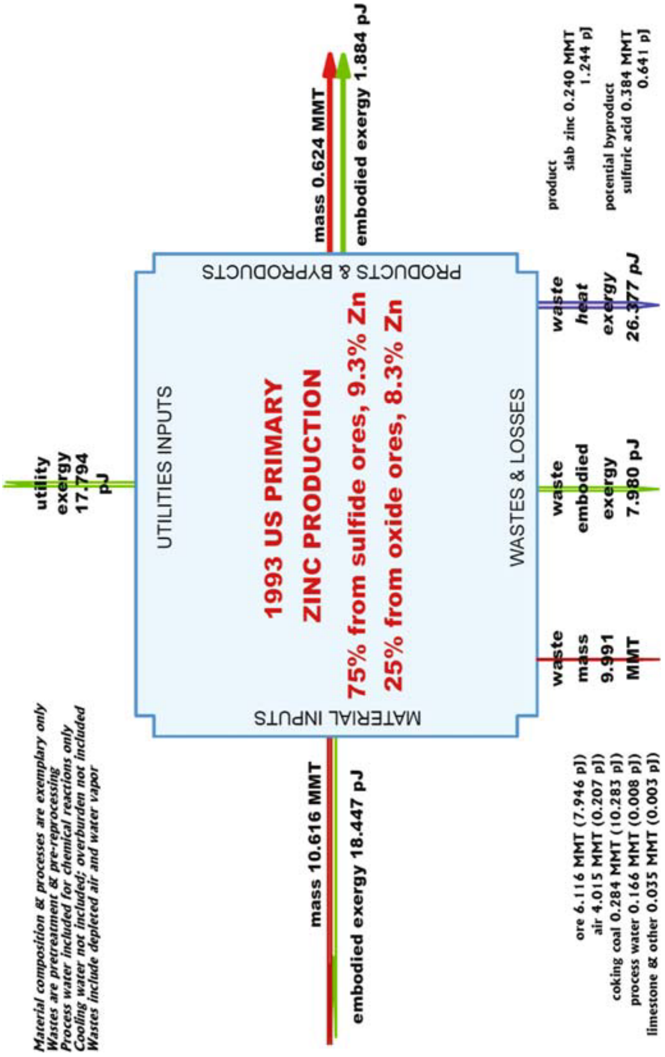


Figure 6-22. 1993 US zinc mass and exergy flows.

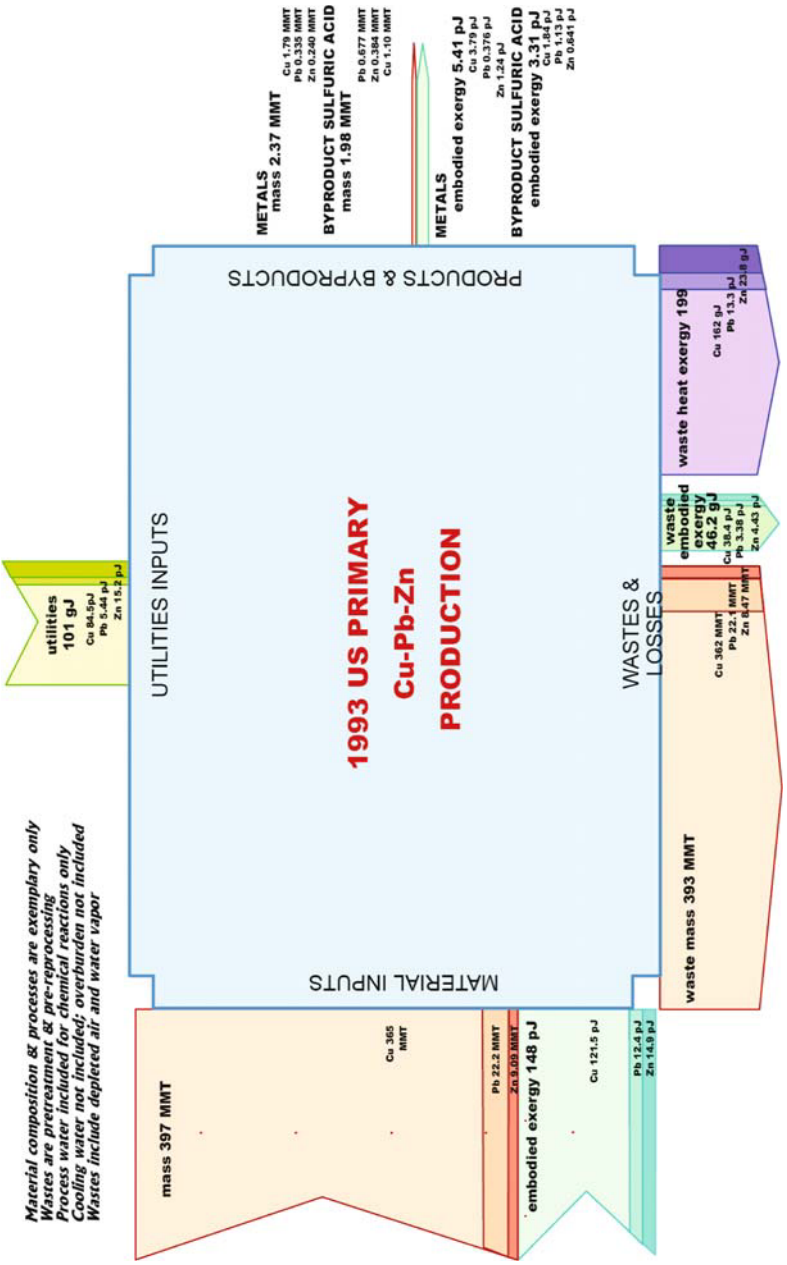


Figure 6-23. Copper, lead & zinc mass and exergy flows for the USA 1993.

APPENDIX: METHODOLOGY FOR EXERGY CALCULATIONS

In the following analysis only chemical exergy of the substances has been taken into account, for reasons explained earlier. For purposes of resource/waste accounting at the industry level, the inherent error of this approximation is negligible. When attention is focused on the overall processes, most of the materials involved in the production enter or leave the system boundaries at normal pressure and temperature so that thermal exergy can be neglected and total exergy content of the main streams can be equated to the chemical exergy content. On the other hand, it has to be stressed that the overall results cannot be used as second-law efficiency indicators at the plant level. For pure chemical substances (i.e., substances composed of a simple constituent) tabulated values for standard chemical exergy have been directly used. For complex substances (i.e., those substances or materials formed by several different pure compounds) chemical exergy can be computed by means of a simple formula (Szargut et al. 1988)

$$B_{ch} = \sum_i t_i z_i$$

where:

B_{ch} standard chemical exergy of the complex substance (kJ/kg)

t_i Szargut coefficient for the i^{th} pure substance (kJ/kg)

z_i mass fraction of the i^{th} pure substance in the complex substance

Szargut coefficients are usually coincident with the standard chemical exergy of the pure substances, except when the latter have particular chemical bonds in the complex substance under consideration. When Szargut coefficients were not available, standard chemical exergies have been directly utilized instead. Only for melted pig iron and steel Szargut suggests the use of a slightly different expression, viz.

$$B_{ch} = B_{Fe} + \sum_i t_i z_i$$

where B_{Fe} = standard chemical exergy of iron (kJ/kg) and the other expressions are as above.

As already remarked by Wall (1986) in the case of mixtures, the above is a crude approximation, inasmuch as the entropy of a mixture is not the sum of the entropy of its constituents but depends on a number of other factors, which are difficult to evaluate. However, although the relative error can be significant (> 10%) it will usually be smaller and for the purposes of this paper it will be ignored. Chemical exergies of the major inputs and outputs as well as by-products and wastes for the processes under consideration have been computed using the above formulae.

Particular care has been taken to calculate the chemical composition of the substances entering and leaving the system boundaries. Where not available in literature, the composition has been estimated by the authors. Unfortunately, values of chemical exergy are found in published sources only for a limited numbers of pure substances. However, when not available, the chemical exergy content of any pure substance can be computed by means of an approximate formula, viz.

$$B_{ch} = \Delta G_{F_0} + \sum_i N_i b_i$$

where

ΔG_{F_0}	standard Gibbs free energy of formation of the compound
b_i	chemical exergy of the -ith pure element of the compound
N_i	molar fraction of the -ith pure element of the compound

The Gibbs free energy of formation is available in standard reference sources for a large number of chemicals, so that the previous expression can be easily applied to calculate exergy once the chemical composition of the substance is known. A list of the mixtures as assumed in the selected processes, giving their composition and chemical exergy content calculated using the methodologies above, is presented in table 6-2- 6-7 at the end of this Appendix. It must again be emphasized that in the case of mixtures, compositions are only typical and in no sense should be taken as precise. The exergy values of pure compounds can be found in Szargut (1988, Appendix Tables I & II, pp. 297-309). In the case of fuels and electricity, a different procedure has been adopted. Data for both of them are usually given in energy units (GJ). In the case of fuels — namely coal, fuel oil and natural gas — the exergy content has been estimated by multiplying the net heating value by an appropriate coefficient. This coefficient can be used to estimate the chemical exergy content of any fuel from its heating value or enthalpy (Szargut et al. 1988). It is a function of the ratio C/H and C/O of the substance and it is usually higher than 1, because it takes into account the imputed contribution of diffusion. A short list of fuels with their net heating value and chemical exergy content is presented in table 6-1.

Table 6-1. Chemical exergy content of some fuels

Fuel	**Exergy coefficient**	**Net heat value(kJ/kg)**	**Chemical exergy(kJ/kg)**
Coal	1.088	21680	23587.84
Coke	1.06	28300	29998
Fuel oil	1.073	39500	42383.5
Natural gas	1.04	44000	45760
Diesel fuel	1.07	39500	42265

For convenience, the exergy coefficient of electricity has been assumed to be equal to 1.00, so that 1 kJ of electrical energy corresponds to an exergy flow of 1 kJ. This assumption could lead to some incongruences, as electricity, which is “pure” exergy and is certainly the most useful form of energy, has a quality factor smaller than some of the fuels that are used for its production. For this reason, it might seem more appropriate to account for electricity in terms of the chemical exergy content of the fuels used for its production, thus taking also into account the efficiency of the conversion process. Moreover this procedure would enable us to evaluate all the energy inputs in terms of primary resources. The contribution of some input fuel streams has been disaggregated where part of it is used as a reducing agent (e.g., coke in the blast furnace or carbon anodes in the Hall-Heroult process) and part of it is simply a source of process heat. In the flow diagrams and in the tables, values are expressed in mass units for raw materials and in energy units for fuels. In the exergy balance they are both accounted for in terms of exergy units (MJ) but their contribution was still considered separately.

Table 6-2. Typical mixtures assumed for copper, lead and zinc flow analysis (part 1 of 3_left side)

DESCRIPTION	EXERGY (kJ/g)/mw	Al 27.0	Ag 107.9	As 74.9	Ba 137.3	Ca 40.1	Cd 112.4	Cl 35.5	Cu 63.5	F 9.0	Fe 55.8	K 9.1	Mg 24.3	Mn 54.9	Na 23.0
Coal ash	28.6839	11.6%		tr		2.7%			tr		12.2%	1.3%	0.6%	tr	0.5%
Coal tar	37.1331	tr		tr		tr			tr		tr	tr	tr	tr	tr
Coal (HVc)	33.7210	1.1%		tr		0.2%			tr		1.1%	0.1%	tr	tr	tr
Coke	33.8921	tr		tr		tr			tr		tr	tr	tr	tr	tr
Coking coal (MV)	36.2008	0.3%		tr		tr			tr		0.4%	tr	tr	tr	tr
Fluorspar	0.3481	0.5%				45.0%				39.4%	0.7%			0.8%	
Limestone	0.0536	0.2%				38.1%					0.2%		0.3%	0.2%	
Offgas, coking	38.7107														
Waste gases, coking	0.1313														
Alumina, produced	1.9583	52.4%							tr		0.2%		tr	tr	
Aluminum, refined	32.8048	99.3%							tr		0.3%		tr	tr	
Bauxite	1.0493	26.3%							0.1%		12.9%		tr	0.1%	
Waste gases, Bayer	0.2324														
Waste gases, H2SO4 from S	0.0377														
Waste solids, Bayer	0.6594	0.4%				3.1%			0.4%		52.7%		0.4%	0.4%	4.7%
Cu sulfide ore smelting dusts	1.8222		0.1%	0.1%		41.1%	tr		0.5%		29.2%		0.4%	0.2%	
Cu, anode	2.1029		tr	0.1%					99.5%						
Cu, cathode	2.1117		tr	tr					100.0%						
Cu, concentrate	8.5463	1.6%	0.1%	0.1%		1.0%	tr		25.8%		29.9%		0.5%	tr	
Cu, oxide ore	0.6476	7.9%	tr	tr		5.3%	0.4%	0.5%	0.6%		4.1%		2.2%	tr	
Cu, sulfide ore	0.2096	8.0%	tr	0.4%		5.3%	1.0%		0.6%		1.5%		2.2%	tr	
Flotation reagents CuS concentrate	10.2977							12.4%							28.0%
Leachate-water, Cu oxide ore	1.8723	1.2%	tr	tr		0.8%	tr	7.8%	tr		0.6%		0.3%	tr	
Natural antlerite	0.2921								56.7%						
Natural azurite	0.2222								56.0%						
Natural chrysacolla	0.0565								26.6%						
Natural malachite	0.2059								58.3%						
Offgas, Cu smelting	1.6116														

Table 6-3. Typical mixtures assumed for copper, lead and zinc flow analysis (part 1 of 3_right-hand side)

Ni 58.7	P 1.0	Pb 207.2	S 2.1	Sb 121.8	Si 28.1	Sn 118.7	Ti 47.9	V 0.9	Zn 65.4	C 2.0	H .0	N 4.0	O 6.0	EXERGY (kJ/g)/mw	DESCRIPTION
tr	0.1%	tr	1.0%		21.3%		0.5%	tr	tr	48.0%				28.6839	Coal ash
tr	tr	tr	0.6%		tr		tr	tr	tr	89.7%	5.4%	1.4%	2.8%	37.1331	Coal tar
tr	tr	tr	2.6%		1.9%		tr	tr	tr	77.6%	4.8%	1.5%	8.9%	33.7210	Coal (HVc)
tr	tr	tr	tr		tr		tr	tr	tr	97.0%	0.6%	0.4%	1.8%	33.8921	Coke
tr	tr	tr	0.6%		0.6%		tr	tr	tr	87.8%	4.9%	1.6%	3.6%	36.2008	Coking coal (MV)
			1.0%		2.2%					1.0%	0.2%		9.1%	0.3481	Fluorspar
	tr		tr		0.8%					11.4%	0.2%		48.5%	0.0536	Limestone
			tr							41.9%	22.9%	18.0%	17.2%	38.7107	Offgas, coking
			tr							9.5%	tr	77.7%	12.7%	0.1313	Waste gases, coking
					tr		0.1%	tr	tr		tr		47.2%	1.9583	Alumina, produced
					0.2%		0.2%	tr	tr				tr	32.8048	Aluminum, refined
					0.4%		1.4%	tr	0.1%		3.1%		55.4%	1.0493	Bauxite
			tr							13.8%			86.1%	0.2324	Waste gases, Bayer
			tr							tr	1.9%	83.0%	15.0%	0.0377	Waste gases, H2SO4 from S
	tr				1.4%		5.7%	0.3%	0.5%		tr		29.8%	0.6594	Waste solids, Bayer
0.1%	tr	0.3%		tr		tr			2.0%				25.9%	1.8222	Cu sulfide ore smelting dusts
0.1%		0.1%	tr	tr									tr	2.1029	Cu, anode
tr		tr	tr	tr									tr	2.1117	Cu, cathode
0.1%		0.2%	30.9%	tr	2.9%	tr			1.5%				5.5%	8.5463	Cu, concentrate
tr		1.1%	0.3%	0.4%	29.3%	0.4%			0.7%	tr	tr		46.5%	0.6476	Cu, oxide ore
tr		tr	1.4%	1.3%	30.3%	1.0%			0.5%				46.0%	0.2096	Cu, sulfide ore
			8.7%							17.5%	3.6%	4.9%	25.0%	10.2977	Flotation reagents-Cu S concentrate
tr		0.2%	21.7%	tr	4.5%	tr			0.1%	1.7%	2.3%		58.3%	1.8723	Leachate (ex water), Cu oxide ore
			6.7%								1.4%		35.2%	0.2921	Natural antlerite
										6.5%	0.7%		36.8%	0.2222	Natural azurite
					15.6%						3.7%		54.1%	0.0565	Natural chrysocolla
										4.9%	1.0%		35.8%	0.2059	Natural malachite
			15.8%							0.1%	tr	67.4%	16.7%	1.6116	Offgas, Cu smelting

Table 6-4. Typical mixtures assumed for copper, lead and zinc flow analysis (part 2 of 3_left-hand side)

DESCRIPTION	EXERGY (kJ/g)/mw	Al 27.0	Ag 107.9	As 74.9	Ba 137.3	Ca 40.1	Cd 112.4	Cl 35.5	Cu 63.5	F 9.0	Fe 55.8	K 9.1	Mg 24.3	Mn 54.9	Na 23.0
Slag, Cu CuS concentrate	0.9774	4.2%		tr		3.2%	tr		0.5%		31.1%		1.2%	tr	
Slime, Cu, refining (solids)	1.5488		1.8%	3.7%					70.7%						
Solid tailings, Cu oxide ore	0.0265	8.1%	tr	tr		5.4%	0.4%		tr		4.1%		2.3%	tr	
Solid tailings, Cu sulfide ore	0.0422	8.0%	tr	0.4%		6.1%	1.0%	tr	tr		0.9%		2.2%	tr	tr
Waste gases, Cu oxide ore	0.1092														
Waste gases, H2SO4 from Cu	0.0814														
Iron ore	0.4215	3.7%				1.4%					52.8%		1.8%	1.2%	
Iron pellets	0.1791	0.6%				0.5%					65.4%		0.9%	tr	
Iron sinter	0.2960	1.2%				0.9%					64.0%		0.2%	0.5%	
Iron, pig	8.0092										93.8%			1.5%	
Iron/Steel, scrap with tin	6.9636										98.1%			0.4%	
Offgas, iron blast furnace	4.3474														
Slag, iron blast furnace	1.2388	4.4%				29.8%					12.3%		4.1%		
Slag, steel refining	1.5291	1.2%				11.1%					22.6%		1.2%	19.4%	
Solid waste, iron blast furnace	0.7614	4.6%		tr		0.1%			tr		52.1%	tr	1.5%	0.1%	tr
Solid waste, iron pelletizing	1.1002	14.8%		tr		4.6%			tr		9.0%	tr	4.9%	4.9%	tr
Solid waste, iron sintering	1.4211	11.5%		tr		22.5%			tr			tr	7.3%	3.4%	tr
Solid waste, steel refining	0.9082	0.2%				55.4%				26.0%	3.1%			tr	
Steel	6.7501										99.9%			tr	
Waste gases, iron blast furnace	0.1911														
Waste gases, iron pelletizing	0.1767														
Waste gases, iron sintering	0.2088														
Waste gases, steel refining	0.1880														
Lead bullion	1.3056		0.1%	1.0%					2.0%		0.7%				
Lead concentrate	3.4041		1.4%	tr		0.7%			0.6%		2.1%		0.5%		
Lead gangue	0.0111	tr	tr	tr	tr	0.4%	tr		tr		tr		tr	tr	tr
Lead ore	0.2275	tr	tr	tr	tr	0.1%	tr		tr		0.1%		tr	tr	

Table 6-5. Typical mixtures assumed for copper, lead and zinc flow analysis (part 2 of 3_right-hand side)

Ni 58.7	P 1.0	Pb 207.2	S 2.1	Sb 121.8	Si 28.1	Sn 118.7	Ti 47.9	V 0.9	Zn 65.4	C 2.0	H .0	N 4.0	O 6.0	EXERGY (kJ/g)/mw	DESCRIPTION
tr		tr	1.5%	tr	18.7%				0.8%				38.6%	0.9774	Slag, Cu CuS concentrate
3.8%		3.6%	3.7%	1.8%									10.9%	1.5488	Slime, Cu, refining (solid portion)
tr		1.2%	0.4%	0.4%	29.7%	0.4%			0.7%				46.9%	0.0265	Solid tailings, Cu oxide ore
tr	tr	tr	0.8%	1.3%	30.3%	1.0%			0.4%	0.3%	tr	tr	46.9%	0.0422	Solid tailings, Cu sulfide ore
										5.0%	tr	81.6%	13.4%	0.1092	Waste gases, Cu oxide ore
			tr							0.1%	tr	99.6%	0.2%	0.0814	Waste gases, H2SO4 from Cu
	0.4%		0.2%		4.7%								33.8%	0.4215	Iron ore
	tr		tr		1.5%								31.0%	0.1791	Iron pellets
	0.1%		tr		2.1%								30.9%	0.2960	Iron sinter
	0.3%		tr		0.1%					4.3%				8.0092	Iron, pig
	0.1%		tr		tr	0.2%				1.1%			tr	6.9636	Iron/Steel, scrap with tin
										17.8%	0.2%	58.7%	23.2%	4.3474	Offgas, iron blast furnace
			0.5%		4.9%								43.8%	1.2388	Slag, iron blast furnace
	1.2%		0.9%		10.4%								32.1%	1.5291	Slag, steel refining
tr	0.4%	tr			7.5%		tr	tr	tr				33.6%	0.7614	Solid waste, iron blast furnace
tr	1.9%	tr	tr		15.8%		tr	tr	tr				43.9%	1.1002	Solid waste, iron pelletizing
tr	1.4%	tr	tr		12.7%		tr	tr	tr				41.3%	1.4211	Solid waste, iron sintering
	0.3%		0.5%		0.3%								14.1%	0.9082	Solid waste, steel refining
	tr		tr							tr			tr	6.7501	Steel
										27.6%	0.2%	35.3%	36.8%	0.1911	Waste gases, iron blast furnace
			0.8%							10.3%	0.6%	69.5%	18.8%	0.1767	Waste gases, iron pelletizing
			0.9%							23.4%	0.2%	43.0%	32.5%	0.2088	Waste gases, iron sintering
										30.4%	0.4%	26.9%	42.2%	0.1880	Waste gases, steel refining
tr		94.4%	0.2%	1.5%		tr			tr				tr	1.3056	Lead bullion
0.1%		74.8%	15.1%		1.3%				0.1%				3.3%	3.4041	Lead concentrate
tr	tr	0.3%	tr	tr	46.2%	tr			tr			tr	52.9%	0.0111	Lead gangue
tr	tr	5.0%	1.1%	tr	43.6%	tr			tr				49.9%	0.2275	Lead ore

Table 6-6. Typical mixtures assumed for copper, lead and zinc flow analysis (part 3 of 3 left-hand side)

DESCRIPTION	EXERGY (kJ/g)/mw	Al 27.0	Ag 107.9	As 74.9	Ba 137.3	Ca 40.1	Cd 112.4	Cl 35.5	Cu 63.5	F 9.0	Fe 55.8	K 9.1	Mg 24.3	Mn 54.9	Na 23.0
Lead sinter	0.4097		1.4%	1.0%		0.7%			1.5%		2.5%		0.4%		
Lead, drossed	1.2332		0.1%	0.8%		tr			tr		0.7%				
Lead, refined	1.1238		tr	tr		tr			tr		tr				
Offgas, lead sintering	0.9807														
Slag, lead blast furnace	0.8512	0.7%	5.8%	1.2%		14.0%					9.7%	tr	1.9%	tr	tr
Slag, lead drossing	3.5823	tr	0.1%	6.9%					62.3%		0.8%	tr	tr	tr	tr
Solid waste, lead refining	0.6832		3.1%	19.2%		tr			tr		16.7%				
Solid waste, lead sintering	0.9791	0.1%	0.8%	tr		30.0%					1.2%		0.5%	0.1%	
Waste gases, lead blast furnace	0.1543														
Waste gases, lead concentrating	0.1033														
Waste gases, lead drossing	0.0913														
Waste gases, lead refining	0.0320														
Waste gases, H2SO4 from Pb	1.0390														
Offgas, zinc roasting, purifying	1.5912														
Sludge, zinc, final refining (solid)	0.7287	tr	0.3%	0.4%		tr	3.7%		0.8%		1.5%		tr	tr	
Solid waste, zinc leaching	0.7843	0.3%	0.1%	1.3%		4.3%	3.1%		2.9%		40.4%	tr	tr	tr	tr
Solid waste, zinc s ore roast/pur	0.3872	tr	0.2%	1.6%		7.1%	0.1%		6.6%		23.3%		tr	tr	
Waste gases, zinc leaching	3.4399														
Waste gases, zinc refining	0.0374														
Waste gases, ZnS ore concentrate	0.0850														
Zinc, leachate	3.2107	tr	0.1%	0.7%		3.0%	tr		3.0%		7.9%		tr	tr	
Zinc, oxide ore (8.3%)	0.8096	tr	tr	tr	tr	0.1%	0.1%		0.2%		1.3%		tr	tr	
Zinc, prerefined	4.9846	tr	0.1%	0.1%		tr	1.3%		0.3%		0.5%		tr	tr	
Zinc, s ore tailings	0.0008	tr	tr	tr	tr	0.2%	tr		tr		1.1%		tr	tr	tr
Zinc, slab	5.1822			tr		tr	tr		tr		tr				
Zinc, sulfide concentrate	6.1896	tr	tr	0.7%		2.9%	0.5%		2.8%		9.7%		tr	tr	
Zinc, sulfide ore (9.0%)	0.9968	tr	tr	0.2%	tr	0.4%	0.1%		0.4%		2.4%		tr	tr	

Table 6-7. Typical mixtures assumed for copper, lead and zinc flow analysis (part 3 of 3_right-hand side)

Ni 58.7	P 1.0	Pb 207.2	S 2.1	Sb 121.8	Si 28.1	Sn 118.7	Ti 47.9	V 0.9	Zn 65.4	C 2.0	H .0	N 4.0	O 6.0	EXERGY (kJ/g)/mw	DESCRIPTION
0.1%		79.8%	1.1%	1.5%		tr			0.1%				9.9%	0.4097	Lead sinter
tr		96.8%		1.5%		tr			tr	tr			tr	1.2332	Lead, drossed
		100.0%		tr					tr	tr			tr	1.1238	Lead, refined
			8.9%							5.3%	0.3%	60.4%	25.2%	0.9807	Offgas, lead sintering
0.4%	tr	45.2%		1.7%	1.5%	tr	tr	tr	0.5%				17.2%	0.8512	Slag, lead blast furnace
tr	tr		15.8%	1.7%	0.1%	tr	tr	tr	tr				12.2%	3.5823	Slag, lead drossing
tr		tr		36.0%		tr			tr				24.8%	0.6832	Solid waste, lead refining
tr	tr	40.8%			2.0%				tr				24.3%	0.9791	Solid waste, lead sintering
			0.2%							6.7%	0.4%	71.8%	21.0%	0.1543	Waste gases, lead blast furnace
										3.6%	9.7%		86.7%	0.1033	Waste gases, lead concentrating
										3.7%	0.2%	84.4%	11.7%	0.0913	Waste gases, lead drossing
										tr	tr	100.0%	tr	0.0320	Waste gases, lead refining
			tr							7.0%		80.0%	13.0%	1.0390	Waste gases, H2SO4 from Pb
			15.9%							tr	tr	67.4%	16.7%	1.5912	Offgas, zinc roasting, purifying
		5.2%	18.9%	tr					33.1%				35.9%	0.7287	Sludge, zinc, final refining (solid)
tr	tr	7.9%	6.7%	0.7%			tr	tr		tr		tr	32.1%	0.7843	Solid waste, zinc leaching
	tr	0.6%		1.2%					35.0%				24.3%	0.3872	Solid waste, zinc s ore roast/pur
			15.3%							3.1%	0.7%	65.6%	15.3%	3.4399	Waste gases, zinc leaching
										tr	3.4%	69.8%	26.8%	0.0374	Waste gases, zinc refining
										3.1%	9.4%		87.4%	0.0850	Waste gases, ZnS ore concentrate
	tr	0.3%	0.2%	0.5%	4.4%				55.5%	1.0%	tr		23.3%	3.2107	Zinc, leachate
	tr	6.2%	3.3%	tr	34.0%				8.3%	0.2%	0.5%		45.4%	0.8096	Zinc, oxide ore (8.3%)
		1.8%	0.2%	tr					95.2%	tr			0.6%	4.9846	Zinc, prerefined
	tr	7.7%	2.0%	tr	41.5%				1.7%	tr		tr	45.5%	0.0008	Zinc, s ore tailings
		tr		tr					99.9%	tr			tr	5.1822	Zinc, slab
	tr	0.8%	26.4%	0.5%					47.7%				7.8%	6.1896	Zinc, sulfide concentrate
	tr	6.2%	5.8%	0.1%	32.7%				9.0%	0.1%	0.5%		41.9%	0.9968	Zinc, sulfide ore (9.0%)

NOTES

[1] This material is usually called “pig” iron for historical reasons. It was formerly solidified in ingots called “pigs”. Nowadays most crude iron moves on to the steel furnace as a liquid, to conserve energy.

[2] The BOF is very similar in concept to the old Bessemer process, except for the fact that the Bessemer process oxidized the excess carbon by blowing air through the molten pig iron. This procedure took place very rapidly and was difficult to control. If not done exactly right, the Bessemer process left trace quantities of nitrogen in solution in the steel, which made it brittle.

[3] Named after a town in Belgium where Union Minière, the inventor of the furnace design, maintains its largest facility

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Chapter 7

ENTROPY AS A MEASURE FOR RESOURCE CONSUMPTION – APPLICATION TO PRIMARY AND SECONDARY COPPER PRODUCTION

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1. INTRODUCTION

A great step towards the practical application of the concept of sustainable development was made by the formulation of four basic rules for the management of substances (Daly & Cobb, 1989) based on the recommendations of the *United Nations Conference on Environment and Development* in Rio de Janeiro in 1992 (UNCED, 1993). These rules were supplemented with a fifth rule by the *Enquete Commission of the German Bundestag on 'Protection of Humanity and the Environment'* in 1994 (Enquete-Kommission, 1994). The five rules specify how the use of natural resources and the input of substances to the environment should be managed in order to preserve the functionality of nature as a supplier of resources and an absorber of residuals from economic activities. However, these rules need to be further specified to derive operational guidelines for the decision-makers on the global, regional and local level. Tools have to be developed that aid in the assessment of the progress towards sustainability on these levels. Introducing the concept of sustainable development thus opens a wide range of questions addressed to all members of humanity as to how it can be put into practice. Some of these questions must be answered by natural scientists, since they require quantitative answers which have to be derived from measurements performed on the metabolism of the technosphere[1]. One of the research fields especially apt for the physical sciences is the measurement of the quantities mentioned in the five rules of sustainable development: depletion and renewal rates of resources, consumption (or use) of resources, inputs of substances to the environment, time scales of interventions in the environment, and time scales of reactions of the environment. In a PhD thesis at the University of Hamburg (Gößling, 2001), the aspect of resource use was investigated aiming at the development of an adequate measure. Based on

A. von Gleich et al.(eds.), Sustainable Metals Management, 195-235.

the notion that 'using' a resource is equivalent to transforming it, entropy production was introduced as a measure for resource use.

In recent years, several attempts have been made to quantify resource use, or find an approximation at least. Each of the measures so far proposed singles out one physical property of the materials and energy flows that make up the metabolism of the technosphere and use it as an indicator for, or as an approximation to, the overall resource use. Three of these measures have been compared to entropy production (Gößling, 2001).

The *MIPS (Material Intensity per Service Unit)* concept (Schmidt-Bleek, 1993) measures the mass of the flows of matter being moved during the production of an economic good or service (*Ecological Rucksack*). This approach does not, however, consider the actual *use* of the material flows, since it does not quantify their transformation. It rather measures the *throughput* of resources through the respective production system. Therefore, it cannot serve as a valid measure for resource use.

The *Cumulative Energy Demand (CED)* (Klüppel et al., 1997) is defined as the cumulative sum of all energetic inputs (flows of matter that have a non-zero heat of combustion) to the production system of a good or service. As with the MIPS approach, it also fails to consider the transformation of material flows and can therefore not be considered a valid measure for resource use either. It merely measures the throughput of energetic resources through the production system.

The *Exergy Analysis* (Rant, 1956, Szargut et al., 1988, Kotas, 1984, Ayres et al., 1996) measures the loss of available work due to the transformation of matter and energy and therefore quantifies the actual use of these flows. This loss is very closely linked to entropy production, the measure for resource use adopted here and reflects the fact that exergy analysis is based on the second law of thermodynamics. However, the definition of exergy is based on the postulation of a *reference environment* that approximately describes the equilibrium state of the natural environment. This definition is not only based on the questionable assumption of an environment in equilibrium, but also introduces an unnecessary complication to the quantification of resource use. The interesting quantity, lost exergy, can more easily be determined by computing the associated entropy production, thereby sidestepping the mentioned difficulties, see chapter 3.3.

From the first and second law of thermodynamics we know that energy is never destroyed or created, but merely transformed. From special relativity we know that matter is a form of energy. In physical or chemical processes, the state of the energy or matter is changed, not the quantity[2]. A valid physical measure for the extent of this transformation process is the produced entropy, which makes it a well defined candidate for the sought measure for resource use. The rate of resource use is then equally well defined by the entropy production rate. Thus, entropy production can serve as a measure for the human population's resource use.

The entropy produced inside the technosphere has to be exported to the environment in order to avoid deterioration. The environment also produces entropy, which also has to be exported to maintain its thermodynamic stability. On the other hand, the entropy export ability of the planet is mainly determined by the temperature of the upper atmosphere. Energy conservation dictates that this temperature is more or less fixed[3], setting a natural limit for Earth's entropy export. Knowing the actual entropy production of the human population would allow one to quantify its role in the dissipative system Earth and eventually give rise to establishing real 'limits to growth'.

The entropy production of a system is found by balancing the entropy of incoming and outgoing flows of matter and energy and by determining the internal entropy accumulation. This is referred to as the *entropy balance*. In many cases the internal accumulation is negligible. The results can be further analysed to find the main causes of entropy production and thus locate the stages with the largest irreversibilities. This step is referred to as *entropy analysis*.

When analysing the entropy balance of a process one can distinguish between three sources of entropy production, namely:

- Heat transfer across temperature gradients (convection, conduction and radiation)
- Mixing of substances (diffusion and dissipation)
- Chemical and physical transformation of materials (phase transitions, chemical reactions, etc.)

In most industrial processes the main source of entropy production is the transformation of chemical (or electrical) energy into thermal energy, e.g., by burning fuel. This is of course no surprise, since energy is one of the main production factors in almost any industry. In standard energy analysis, however, there is no reference to the 'quality' of the energy, i.e., what part of it can be utilised and how much is simply wasted inside the process boundaries. However, the main advantage of the entropy analysis approach to measuring resource use is that it takes into account *how* the energy was transformed and how much of it was wasted[4].

The validity of the hypothesis that entropy production measures the use of resources was shown by theoretically examining the meaning of entropy production (and export) for complex dissipative structures and by finding basic examples that show the connection between entropy production and resource use (Gößling, 2001). Additionally, a framework for the general application of the method of entropy analysis was developed by describing arbitrary processes in terms of their material and energy flows and deriving the formulae determining the associated entropy production.

The proof for the applicability of the method of entropy analysis is given by the application to a real-life industrial process, namely the production of copper from ores and secondary materials presented in this article. The main tasks in the course of this analysis are to find a valid representation of the process and to gather the required data describing this process. The representation of the process of copper production was derived from the technical and engineering literature on this subject and modelled along the set-up of the *Norddeutsche Affinerie (NA)* copper plant in Hamburg. The multiple data sources yielded a description of the process that was partly imprecise and inconsistent. This problem was solved by an iterative data-reconciliation process (Gößling, 2001). The actual entropy production was then calculated from the physical and chemical properties of the material and energy flows by employing the well-known relations from thermodynamics.

The statement that *entropy analysis and exergy analysis are basically equivalent*, following from theoretical considerations, can be backed up by calculating the entropy production from published exergy analyses of equivalent processes (i.e., (Ayres et al., 2004, Kolenda et al., 1992, Alvarado et al, 1999 and the article by R.U. Ayres in this book) and comparing these values to the results from the case study mentioned above.

2. THEORETICAL BACKGROUND

For a system that goes through an arbitrary reversible cycle the quantity $\delta Q/T$, with δQ being the infinitesimal heat exchanged with the environment at temperature T, obeys

$$\oint \frac{\delta Q}{T} = 0, \tag{1}$$

where the closed integration path corresponds to a closed path of system changes. This finding gave rise to Rudolf Clausius' definition of the state function entropy (derived from the Greek word *τροπη* = transformation) S for *reversible processes* by

$$dS = \frac{\delta Q}{T} \qquad \text{or} \qquad S_B - S_A = \int_A^B \frac{\delta Q}{T}, \tag{2}$$

and for *irreversible processes* by

$$dS \geq \frac{\delta Q}{T} \qquad \text{or} \qquad S_B - S_A \geq \int_A^B \frac{\delta Q}{T}. \tag{3}$$

The infinitesimal change of entropy dS can be rewritten in terms of two contributions: one that is due to exchange of matter and energy with the exterior, d_eS, and one that is due to internal irreversible processes, d_iS:

$$dS = d_eS + d_iS \qquad \text{with} \qquad \oint dS = \oint d_eS + \oint d_iS = 0\,. \tag{4}$$

The observation of the limited convertibility of heat into work and the thermodynamical analysis of this effect can be summarised in a statement known as the second law of thermodynamics:

> *"It is impossible to construct an engine which will work in a complete cycle, and convert all the heat it absorbs from a reservoir into work."*

Applying the entropy concept to cyclic processes, another valid formulation of the second law can be derived as

"The sum of the entropy of a system and its exterior cannot decrease."

Generalising the idea of reversibility to arbitrary cycles, irreversibilities can be identified with $d_iS > 0$. For systems only exchanging energy with the exterior (closed systems) we then have

$$\oint d_eS = \oint \frac{\delta Q}{T} \leq 0. \qquad (5)$$

This has an important implication: *A closed system returning to its initial state has to discard its internally produced entropy through the expulsion of heat to the exterior.* This statement can be generalised to *open systems* (systems which are exchanging energy and matter with the exterior) as follows below. An open system, in general, is not in equilibrium, demanding a description of its thermodynamic state in terms of local variables and flows. Still, the above conclusion holds for open systems that maintain their thermodynamic state: the internally produced entropy has to be exported to the exterior in the form of matter or heat flows. The validity of the second law of thermodynamics is not restricted to purely physical systems and applies to all scales of (material) systems, from microscopic particles over biological systems to the universe itself.

Generally, every naturally occurring process is irreversible. Reversibility is only approached in the limit of infinite slowness of processes. This also implies that the efficiency of a process in terms of reversibility is, in essence, a function of the speed of the process in relation to the inherent relaxation times of the system. The derivation of the maximal efficiency of heat engines by Sadi Carnot and Èmile Clapeyron explicitly demanded quasi-static processes and infinitely small temperature gradients (Kondepudi & Prigogine, 1998). Thus, the deviation from these conditions along the thermodynamic path of a process determines its irreversibility and is apparent in the production of entropy.

2.1 Entropy production in living and non-living dissipative structures

A living being can be described as an open thermodynamic system far from equilibrium. Assuming constant pressure and temperature, the amount of free enthalpy to be imported to maintain a stationary state d_eG is determined by

$$\frac{d_eG}{dt} = T\frac{d_iS}{dt} > 0. \qquad (6)$$

The export of entropy is facilitated by exchange of heat and matter with the environment. It is assumed that the living being has a temperature of $T_L = T_0 + \Delta T$, with T_0 being the temperature of the environment. The rate of heat exchange with the environment through conduction is denoted by q_C Additionally, it absorbs radiation q_A from the environment and emits radiation q_E. For photosynthetically-active beings, the radiation absorbed from the sun is an important factor for their functioning. Since the absorption is, in general, very selective, it is appropriate to assume several radiation components q_S^i of temperature T_S^i. The matter exchanged with the environment consists of chemical components k with molar entropy s_k and mole number N_k. The entropy export is then given by (Ebeling et al., 1990)

$$-\frac{d_eS}{dt} = qc\left(\frac{1}{T_O} - \frac{1}{T_L}\right) + \frac{4}{3}\frac{q_E}{T_L} - \frac{4}{3}\frac{q_A}{T_O} - \sum_i \frac{4}{3}\frac{q_S^i}{T_S^i} - \sum_k s_k \frac{d_eN_k}{dt} \geq \frac{d_iS}{dt} > 0. \quad (7)$$

The entropy production will have the general form

$$P \equiv \frac{d_iS}{dt} = \frac{1}{T_L}\frac{\delta W_{irr}}{dt} - \frac{1}{T_L}\sum_k \mu_k \frac{d_iN_k}{dt}, \quad (8)$$

with δW_{irr} being the irreversible work performed (friction, dissipation etc.) within the system and μ_k being the chemical potential of species k. Equation (7) is sometimes called ‘the fourth law of thermodynamics for living systems’ (Ebeling et al., 1990) and determines the thermodynamically necessary conditions for life in general. The equality in (7) only holds for stationary states. For phases of growth, like embryo-genesis, adolescence, recovery from injury and others, the stronger condition applies.

$$-\frac{d_eS}{dt} > \frac{d_iS}{dt} > 0 \quad (9)$$

These findings for living beings can easily be applied to other dissipative structures, like the technosphere for example. It, too, maintains a metabolism with its environment and has to discard its internally produced entropy to the surroundings.

It is evident that the production of entropy and its export to the environment is an important factor for the stability of complex dissipative structures. If several such structures coexist in the same local environment, it is also evident that they will not only compete for the sources of free energy (the ‘resources’), but also for the possibility to export entropy to environmental ‘sinks’. In general, the local environment itself will also have a limited ability to export entropy to a meta-environment. For a meta-environment with entropy S, having sub-environments with entropy S'_j, which again have sub-sub-environments with entropy S''_{jk} and so forth, the stability condition (7) becomes

$$\frac{d_iS}{dt} + \sum_j \frac{d_iS'_j}{dt} + \sum_{jk} \frac{d_iS''_{jk}}{dt} + \ldots \leq -\frac{d_eS}{dt}. \quad (10)$$

Naturally, an increase in the entropy production of one of the sub-systems will reduce the available capacity for entropy export of the other sub-systems. The entropy export rate of the meta-environment will generally depend on internal and external parameters. The ability to export entropy might therefore very well be affected by the activity of one or more of the subsystems. As observed in many examples of dissipative structures, the system's answer to an overcritical change in internal or external flows and forces is to 'seek' new patterns of internal structure that enable an enhanced entropy export. This transition appears in a way that fluctuations in the internal material and energy flows begin to increase until a new configuration is found that corresponds to a stable state. Dissipative structures are always non-linear systems, which allows for small variations in one of the parameters to have large effects on the whole system. It is therefore easily conceivable that even a slight increase in the entropy production or metabolism of one of the sub-systems might have detrimental effects on the meta-environment and the other sub-systems. However, to exactly quantify the critical parameters of a complex dissipative system remains difficult, if not impossible in many cases.

2.2 The thermodynamic system Earth

The only appreciable source of free energy available to the 'living system' Earth is the radiation field of the sun (the flow of thermal energy from the Earth's core is comparatively small). It supplies the Earth with necessary free energy to keep its distance from thermodynamic equilibrium, a necessary prerequisite for the development of life. The sun's radiation deposits some of its exergy on Earth and the Earth itself discards its internally produced entropy to space via heat radiation, see figure 7-1.

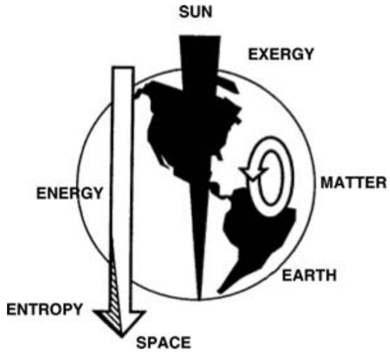

Figure 7-1. The sun delivers exergy (or free energy) to the Earth. The Earth's entropy production is discarded into space via heat radiation (from Malaska & Kaivo-oja, 1997).

If we imagined the Earth suddenly enclosed in an impenetrable sphere, it would start evolving into thermodynamical equilibrium with its surroundings until all physical, chemical and biological processes had come to a halt. Even if we made the sphere out of glass and let the sun shine through, most of the life on Earth would soon cease to exist, since the entropy produced within the sphere could not be properly disposed of. The long-wave radiation would be kept back by the glass, which would lead to a heating of the inside until a new equilibrium at a higher thermal level had been reached.

This prompts the question, what makes life on Earth possible? From the theory on dissipative structures, as outlined above, we can identify at least three properties of the thermodynamic system 'Earth' that led to the development of living systems on its surface:

– The Earth is an open system
– It is supplied by a sufficient amount of free energy (by the sun)
– It is able to export the internally produced entropy into its surroundings

In view of the topic of this article, the last point is of particular importance. The importance lies in the fact that the ability to export entropy is limited. Thus, the meta-environment 'Earth' places some restrictions on the entropy production of its sub-environments. This has led Werner Ebeling to the formulation of the 'commandment' for humans to minimise their entropy production (Ebeling & Feistel, 1994). In its current state, the Earth is only able to export a certain amount of entropy (as long as we do not want internal parameters such as temperature and climate to change drastically). Therefore, the amount of entropy that humans may contribute to the overall export is also limited. Thus, if we are concerned about the well-being of the human race, we should bear in mind that there is a limit to how wasteful we can be with the Earth's natural resources. It is rather difficult to support these statements with hard facts, since there are no calculations for how much entropy is actually produced by humankind. However, some approximations (see, e.g., (Stahl, 1996)) are in favour of the hypothesis that humans and their economic system have reached this upper limit already.

The approximate entropy production density of the Earth can be derived from some simple considerations. Assuming a constant solar irradiation on Earth $\dot{Q}_S$ with temperature T_S and a constant mean temperature T_E of the Earth (the temperature as seen from outer space using the emitted radiation as a measure), the imported and exported entropy flows are

$$\dot{S}_{in} = \frac{4}{3}\frac{\dot{Q}_S(1-A)}{T_S}F_{abs} \quad \text{and} \quad \dot{S}_{out} = \frac{4}{3}\frac{\dot{Q}_S(1-A)}{T_E}F_{abs}, \tag{11}$$

with F_{abs} being the absorbing area of the Earth's surface area F_E, as shown in figure 7-2, and A being the albedo of the Earth. It is also assumed that the Earth accumulates no energy, which is a good approximation for time scales of up to a decade or even longer.

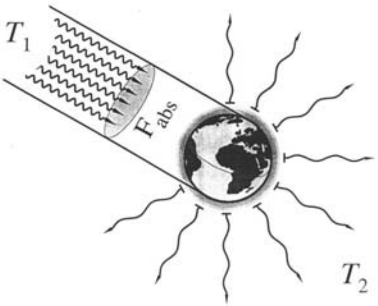

Figure 7-2. Earth's entropy export mechanism through radiation.

The total entropy export density can then be expressed as

$$-\frac{1}{F_E}\frac{d_eS}{dt}=\frac{4}{3}\dot{Q}_S(1-A)\frac{1}{4}\left(\frac{1}{T_E}-\frac{1}{T_S}\right)\approx 1.2\ W/(K{\cdot}m^2) \tag{12}$$

where the commonly accepted values for $A \approx 0.3$, $\dot{Q}_S \approx 1367\ W/m^2$, $T_E \approx 254$ K and $T_S \approx 5700$K were used. In analogy to the above 'fourth law of thermodynamics for living systems' (7), this sets a limit for the entropy production density:

$$\frac{1}{F_E}\frac{d_iS}{dt} \leq 1.2\ W/(K{\cdot}m^2) \tag{13}$$

Since this value is determined by the Earth's temperature, it cannot easily be changed or controlled and therefore represents a real limit to growth on our planet, at least in the material and energetic sense. It should be noted though that it is not the overall amount of entropy production that is limited, but rather the *rate* of production[5]. Thus, a slower growth process is, in principle, not limited at all by equation (13).

The consequences for the system Earth of violating the above-mentioned necessary condition for living systems are not foreseeable. In view of the findings for simpler dissipative systems, it can only be assumed that drastic changes in the internal structure and turbulent intermediate states would be some of these consequences.

How does this limit for the entropy production density relate to human activities? The actual contribution to the overall entropy production rate from humans can only roughly be approximated by considering the energetic throughput of the human subsystem. The physiological activity of every human implicates an entropy production rate of about 0.5 W/K. The additional entropy production stemming from the associated economic activity varies largely with the level of industrialisation as is apparent from table 7-1 (Stahl, 1996).

Table 7-1. Entropy production rate associated with physiological and economic activities of human beings, data taken from (Stahl, 1996).

Entropy production rate		
Physiological		0.5 W/K
Economic	average	10 W/K
	USA	30 W/K
	Germany	20 W/K
	India	2 W/K

The total entropy production of 6 billion people is then $P_{tot} \approx 63\,\mathrm{GW/K}$. Compared to a total entropy production of the Earth of 600,000 GW/K, this means that human activity currently contributes at least 0.01% to the total entropy production. Related to the entropy export density, each human 'occupies' between 2 m^2 (India) and 25 m^2 (USA) of the Earth's surface area. Looking at some densely-populated regions, this is reflected in the necessity of these regions to export massive amounts of entropy into their surroundings.

3. RESOURCES AND USE

3.1 Definition of the term resource

There is a variety of meanings of the term *resource* throughout the literature, depending on the context and the scientific subject. In this article, the term *resource* is to be understood as the least common denominator of the most common definitions, namely:

> "Resources are the flows and reservoirs of matter and energy that can sustain or benefit living systems".

This definition excludes the information resources used in physical resource theory, since these are difficult to quantify. The term *living system* has to be understood in the broader sense, including our economic system as a whole, since it is composed of humans and their technological 'extensions'. It also implies that the question of whether a physical object or component can be viewed as a resource is dependent upon whether it can be utilised by a living system or not. Therefore, natural deposits not yet recognised as resources in this sense might fit this description with the emergence of new technologies or differently adapted life-forms. Another consequence of this rather functional definition is that so-called wastes of a system might be considered a resource, if only the necessary means to utilise it are given or developed. Thus, every component of the natural environment that is not in thermodynamic equilibrium with the wastes of a given system can potentially become a resource for that particular system.

3.2 Entropy production as a measure for resource use

As was detailed in chapter 2, every dissipative structure lives on a gradient between incoming and outgoing flows of matter and energy. The incoming flows can be regarded as the resources of that system. The available gradient is decreased by the system's activity and simultaneously restored by an internal or external entropy pump. Decreasing the gradient is thus equivalent to using the resource. On the other hand, this decrease is exactly measured by the associated entropy production.

Hence, *entropy* production is the one common feature of all processes and it is directly linked to the accompanying degradation of resources. Therefore, it is straightforward to use it as a measure for resource use.

The ability to perform work is also called the *exergy* of a system (Szargut et al., 1988, Kotas, 1984). The definition of exergy is based on the assumption that the maximum amount of work extractable from any system is defined by the process of bringing it to physical and chemical equilibrium with 'the environment' (for more details see chapter 3.3). The decrease of the ability to perform work is equivalent to the decrease in exergy, which in turn is proportional to the entropy produced within the system. Thus, one could argue that exergy loss is really the correct measure for resource use and not entropy production. However, the calculation of the exergy loss by first obtaining the entropy production is much more straightforward and saves one from the difficulties associated with the definition of exergy (see chapter 3.3 for a discussion). Furthermore, exergy loss and entropy production are connected by the simple Gouy-Stodola relation,

$$\Delta E = -T_0 \Delta S,$$

where only the temperature of the environment has to be known. Consequently, it seems most plausible, from a physicist's point of view, to adopt entropy production as the right measure for resource use as understood in this context.

3.3 Exergy

The other measure of resource use mentioned above is the loss of exergy in a system. The method used is often called *exergy analysis* and was developed by Rant and others (Rant, 1956). The exergy of a flow of matter can be defined as follows (taken from (Brodyansky et al., 1994), slightly modified):

> *The exergy of a flow of matter is the quantity of work which can be extracted from it by reversible interactions with the environment until complete equilibrium (with the environment) is reached.*

Exergy analysis is not only a method to determine the resource use, but is also intended to yield a measure for the efficiency of processes -(Ayres & Martinàs, 1994, Ayres et al., 1996). The definition of exergy also includes a definition of a so-called *reference environment*. In this reference environment the chemical and physical state of each chemical element is defined. This includes the chemical compound in which it appears (e.g., carbon as CO_2), as well as its concentration and the temperature and pressure of the reference environment. The total exergy flow ϵ associated with a flow of matter is then the sum of a potential, a kinetic, a thermal, a mechanical and a chemical contribution. Each contribution reflects a single aspect of the equilibration process (Rosen, 1999):

$$\varepsilon = \varepsilon_{pot} + \varepsilon_{kin} + \varepsilon_{th} + \varepsilon_{mech} + \varepsilon_{chem}$$

The potential and the kinetic exergy of a stream are equal to its potential and kinetic energy. The thermal contribution $\varepsilon_{\mathrm{th}}$ is the amount of work extractable by reversible processes when bringing the material flow to thermal equilibrium with the reference environment without changing either its composition or its other thermodynamic parameters[6]. The mechanical contribution $\varepsilon_{\mathrm{mech}}$ is defined similarly for the work obtainable from reversible equilibration of pressure differences. The sum of $\varepsilon_{\mathrm{th}}$ and $\varepsilon_{\mathrm{mech}}$ is also called *physical exergy* and denoted $\varepsilon_{\mathrm{ph}}$ It can be derived from the specific enthalpy h and the specific entropy s of the stream:

$$\varepsilon_{ph} = \varepsilon_{th} + \varepsilon_{mech} = \dot{m}\left[h - h_0 - T_0(s - s_0)\right],$$

where the subscript 0 denotes the values in the reference state and $\dot{m}$ is the mass flow of the stream.

The chemical contribution can be obtained from considering the necessary chemical reactions leading from the component mixture of the material flow to the component mixture of the reference state, including their concentration in the reference environment. Using the chemical potential μ_{k0} of component k in the matter flow at temperature T_0 and pressure p_0, and the chemical potential μ_{k00} of the same component in the reference environment, the chemical exergy of a flow of matter can be expressed via

$$\varepsilon_{ch} = \dot{m}\sum_k \left(\mu_{k0} - \mu_{k00}\right)x_k,$$

where x_k is the mass fraction of component k and $\dot{m}$ is the total mass flow.

The exergy ε_s^q of a heat flow q across a surface region s on the boundary of the analysed system is given by

$$\varepsilon_s^q = \left(1 - \frac{T_0}{T_S}\right)q,$$

where T_s is the (constant) temperature of the surface region.

The exergy balance of a steady-state system with incoming exergy flows ε_{i}, exiting exergy flows ε_{e}, heat exergy flows $\varepsilon_{\mathrm{s}}^{\mathrm{q}}$ and mechanical work rate performed on the system then reads

$$\sum_i \varepsilon_i - \sum_e \varepsilon_e + \sum_s \varepsilon_s^q - \dot{W} - \dot{I} = 0,$$

where $\dot{I}$ denotes the *exergy consumption rate*. The *Gouy-Stodola* relation relates exergy consumption rate and entropy production rate $\dot{S}$ via

$$\dot{I} = T_0 \dot{S}\,. \tag{14}$$

Despite all the efforts made, the correct definition of a reference environment remains a controversial subject (Brodyansky et al., 1994; Gool, 1992). As long as only the differences in exergy are computed, this problem is not relevant, since the reference state cancels out in the equations. On the other hand, for determining the exergy consumption within a system, the exergy content of the streams is not really needed, since the exergy consumption can be derived from the entropy production via the Gouy-Stodola relation. It is thus sufficient to know the internally produced entropy, which can be calculated from basic thermodynamic properties without the need for a speculative reference environment.

It has to be noted though, that the exergy analysis gives a new view on the efficiency of processes, since it can compare absolute values of the above-mentioned available work. For a wide range of applications, especially in the chemical process industries and in the field of power conversion, this method is widely applied and delivers valuable information to the designing engineer.

Each measure of resource use has its own advantages and range of applicability. Depending on the questions asked, each measure will either supply a valid answer or not. The entropy analysis combines several aspects of the other three mentioned approaches: it includes energetic and non-energetic resources, it describes the resource use of processes based on the laws of thermodynamics and it quantifies the devaluation of matter and energy flows within a production system. The latter property includes the devaluation of natural resources. In addition, the entropy production as gained from an entropy balance is directly linked to an eco-systemic view of the human population, and can easily be incorporated into more complex theories of the interaction between humanity and the environment.

4. THE METHOD OF ENTROPY ANALYSIS

When trying to assess the resource use of a process, or a network of processes by analysing its entropy production, there are a few prerequisites. These include fixing the boundary of the system to be analysed, obtaining and reconciling the data for the network of material and energy flows, setting up the actual entropy balance and allocating the entropy production of sub-processes to the products. A detailed discussion of these steps is given in (Gößling, 2001).

4.1 Setting up the entropy balance

The first thing to do when setting up an entropy balance is to define the system's boundaries. It is desirable to find boundaries that are meaningful in the framework of life-cycle analysis. The ideal case would be to analyse the full life- cycle. However, for pragmatical reasons, the choice for the system boundaries will mostly depend on the data available and their inherent system boundaries. As an example, see figure 7-3 for a 'black-box-process'. Note that for convenience, the boundary (dashed line) was shifted away from the physical boundary of the system such that all heat flows enter and leave the system at ambient temperature T_0, while the temperature of the material flows is assumed to remain unchanged by this choice. Physically this means the irreversible process of heat transfer between the system and the environment is fully included in the entropy balance. In figure 7-3 the material flows m have been subdivided into incoming ones (m_i) and outgoing ones (m_o) for clarity. Mathematically, they are distinguished by their sign (incoming flows are positive). The energy flowing into and out of the system is denoted by e and subdivided into flows of radiation e_s, heat e_q, and enthalpy of the mass flows h (not shown in figure 7-3).

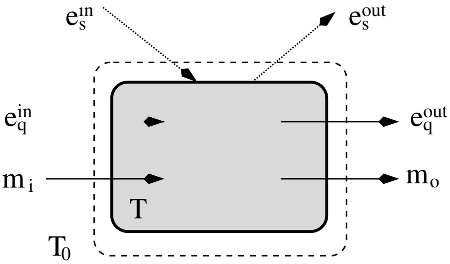

Figure 7-3. Typical set-up of system boundary for a single process.

To reduce the number of variables in the entropy balance, it is appropriate to assume a unique temperature T_s^{in} for all radiation entering the system, but different temperatures $T_{s,n}^{out}$ for radiation leaving the system (due to non-uniform temperature levels along the physical boundary of the system). Then the total entropy change of the system dS during an infinitesimal time interval dt can be expressed as

$$dS = \underbrace{\left(\sum_j m_j s_j - \frac{e_q^{out}}{T_O} + \frac{e_q^{in}}{T_O} - \sum_n \frac{4}{3} \frac{e_{s,n}^{out}}{T_{s,n}^{out}} + \frac{4}{3} \frac{e_s^{in}}{T_s^{in}} \right) dt}_{d_eS} + d_iS. \qquad (15)$$

As usual, the total entropy change is divided into an external part d_eS and an internal part d_iS. The only part generally accessible to measurement is the externally exchanged entropy d_eS. On the other hand, the actually interesting quantity, regarding the system's efficiency, is d_iS, the entropy produced within the system due to irreversible processes. For a steady-state system ($dS = 0$), the two contributions have to cancel each other out and the entropy production is found to be:

$$d_iS = \left(\frac{e_q^{out}}{T_O} - \frac{e_q^{in}}{T_O} + \sum_j \frac{4}{3}\frac{e_{s,n}^{out}}{T_{s,n}^{out}} - \frac{4}{3}\frac{e_s^{in}}{T_s^{in}} - \sum_j m_j s_j \right) dt, \tag{16}$$

such that the internal entropy production can be obtained from measuring the ‘metabolism’ of the system. In general, the industrial processes under investigation will not be steady-state processes. However, if for non-steady-state processes one chooses a time interval $\Delta t = t_1 - t_0$ such that the system runs through a complete cycle and initial and final state are equal (typically true for batch processes), then (using equation 15) $\Delta S = \int_0^1 dS$ vanishes and the internal entropy production $\Delta_i S$ can again be calculated from the matter and energy flows exchanged with the environment. In many cases one of the leaving material flows m_p can be defined as the main product flow. If then ΔM_p denotes the amount of m_p produced in the time interval Δt, the ratio $\Delta_i S / \Delta M_p$ defines the *specific entropy production* of the process.

4.2 The heat and radiation balance of a single node

For most real-life processes it is appropriate to assume that no physical work is performed on or by the system. If one knows the electrical energy e_q^{el} dissipated (i.e., transformed into heat) within the system, the net heat exchanged with the environment can be obtained from

$$e_q^{in} - e_q^{out} = e_q^{el} - e_s^{in} + e_s^{out} + \sum_j m_j h_j. \tag{17}$$

The heat flows can be calculated once the radiation heat flows have been determined. The radiation heat flows $e_s^{in,out}$ can be calculated from the Stefan-Boltzmann law, when the temperatures of both the outer physical boundary of the process and of the environment are known. Assuming the process vessels to emit black-body radiation, the net radiation heat emitted is

$$e_s = e_s^{out} - e_s^{in} = \sum_n A_n \sigma \left(T_n^4 - T_0^4 \right), \tag{18}$$

with σ being the Boltzmann constant, A_n being the partial surface areas with uniform temperature T_n, and T_0 being the temperature of the environment. The heat exchanged with the environment $e_q^{in,out}$ is composed of two distinctive parts: conduction and radiation. The convective part is already included in the enthalpy content of the material flows leaving and entering the system. The entropy content of the energy flows is determined by their temperature. The entropy content of heat flow q absorbed at temperature T is $S_q = q/T$. The entropy of a flow of black-body radiation q_S of temperature T_S is $S_S = 4/3(q_S/T_S)$

The surface area of the process vessels in the metallurgical industries is typically of the order of of 100 – 200 m^2 and the temperature between 323 K and 473 K. Therefore, the radiation emitted is typically of the order 3 to 40 GJ per day. The total heat loss to the environment on the other hand is between 350 and 800 GJ per day so that the heat radiation loss has been neglected in cases where the vessel shell temperature was below 373 K. Neglecting the heat radiation practically means treating the associated energy loss as a normal heat flow, since now the radiation part in (17) is zero and the heat flows $e_q^{in,out}$ are determined only from the electrical energy dissipation and the enthalpy balance. Thus, the energy balance is still satisfied.

4.3 The specific entropy of material flows

The specific entropy of the j-th flow, s_j, can be obtained from the molar entropy of the components, $\overline{s}_k$ (derived from the tabulated values of the molar heat capacity), plus a mixing term which is dependent on the mole fraction y_k^j of component k in flow j and the total mole number n_j of all components in j:

$$s_j = \frac{1}{m_j}\left\{\sum_k n_j y_k^j \overline{s}_k - R\sum_k n_j y_k^j \ln y_k^j\right\}, with \tag{19}$$

$$\overline{s}_k(p,T) = \overline{s}_k(p,T_0) + \int_{T_0}^{T} \frac{c_p^k(T')}{T'}dT'. \tag{20}$$

Since x_k^j and m_j are the variables of our material balance, equation (19) should also be expressed in these variables:

$$\begin{gathered} n_j = \sum_k n_k^j,\ n_k^j = \frac{x_k^j m_j}{M_k} \quad and \quad y_k^j = \frac{x_k^j}{M_k \sum_{k'} x_{k'}^j / M_{k'}} \\ \Rightarrow s_j = \sum_k x_k^j \frac{\overline{s}_k}{M_k} - R\sum_k \frac{x_k^j}{M_k}\ln\left(\frac{x_k^j}{M_k \sum_{k'} x_k^j / M_{k'}}\right). \end{gathered} \tag{21}$$

Having calculated all material and energetic entropy flows for a network of processes via equations (17), (18), and (21), one can set up the balance equation (16) for each node of the network and for the whole network itself. Comparing the single node values for d_iS, one can identify the basic process with the largest entropy production, and thus the greatest resource use. The entropy production of the whole process network can be compared with alternative ways of producing the same product, e.g. from recycled material, as done below.

5. APPLICATION TO COPPER PRODUCTION

As a detailed example of how the method of entropy balancing can be applied to industrial processes, the production of copper cathodes from sulphide ore concentrates has been chosen. The processes analysed comprise the metallurgical steps of smelting and refining.

5.1 Production path and system boundaries

There are several possible pathways for copper production from sulphide ore concentrates. Though they all follow a common scheme (oxidation of ore concentrates, converting of matte, refining of blister copper), there are significant variations in the actual techniques used. In this analysis, the production is modelled on the actual set-up at the Norddeutsche Affinerie (NA) in Hamburg, Germany. However, it is just a model and should be understood as such. The numbers given for input and output of materials and energy are typical for the processes at the NA, but not necessarily a one-to-one representation. The real data can deviate from the model by about 10 to 20%.

The complete production path assumed for this analysis is given in figure 7-4. The parts analysed are: Outokumpu flash smelter, Peirce-Smith converter, rotary anode furnace and electrolytic refinement (ISA technology). The other parts (air liquefaction plant, sulphuric acid plant, slag treatment processes and others) are processes not directly involved in the purification of the copper content of the raw materials, but rather side processes and as such are neglected in this work[7]. Once the entropy production associated with the four core processes is determined, this number can serve as a lower boundary for comparison with other production paths, for example the production from secondary materials (scrap, electronic waste, etc.).

The system boundary of each process is taken to be the actual physical boundary of the process itself with the exception for heat flows noted in chapter 4. This means only the entropy produced within the process and at its surface is taken into account.

5.2 Process description

Acquired in the above-mentioned way, the detailed process descriptions as used for the entropy balance are given below (sections 5.2.1 to 5.2.4) along with the assumptions necessary for a complete description.

The process network consists of four nodes (basic processes): **flash smelter, converter, anode furnace** and **electrolysis**, which are referred to by the letters F, C, A and E respectively. When later evaluating the process network in terms of its recycling capabilities, and calculating the associated entropy production (see chapter 5.7), some of the flows are of specific importance, since they will change in magnitude and composition when recycling material (scrap) enters the network. These flows are:

- ore concentrate entering F (m_{co})
- converter slag from C to F (m_{csf})
- converter slag transferred from C to A (m_{csa})
- matte (m_{mt})
- blister copper (m_{bc})
- anode copper (m_{ac})
- anode slag (m_{as})
- cathode copper (m_{cc})
- anode reverts from E (m_{ar})
- scrap copper entering A (m_{sca})

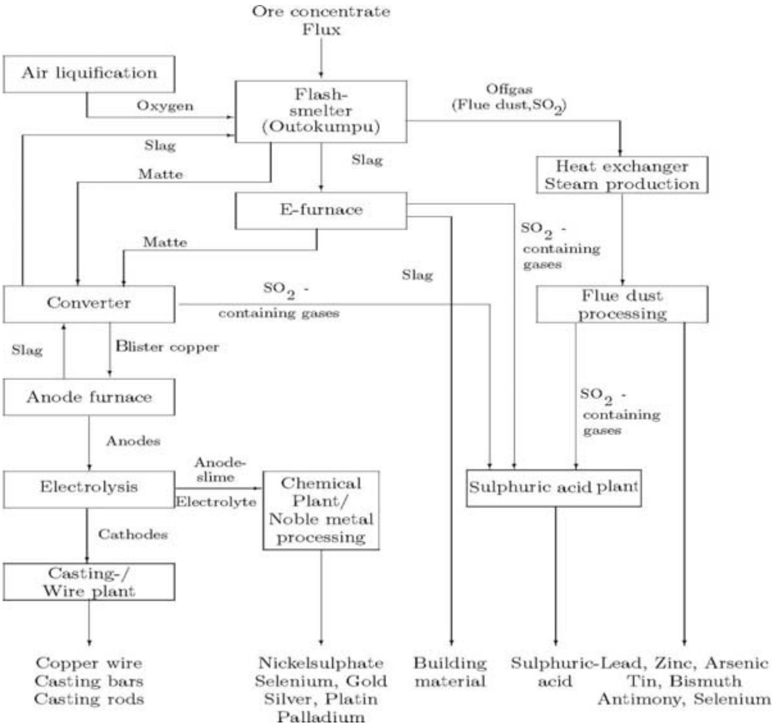

Figure 7-4. Schematic overview of copper production from ore concentrates. Sources: (Bartholomé & Ullmann, 1985, Krüger et al., 1995, NA)

The total entropy production of a node X (for a given set of flows entering and leaving the node) is denoted by S_X and the specific entropy production associated with the production of one of the flows m_y is denoted by $\overline{S}_y$. If the node X has only one product flow m_y, the specific entropy production is simply $\overline{S}_y = S_X/|m_y|$.

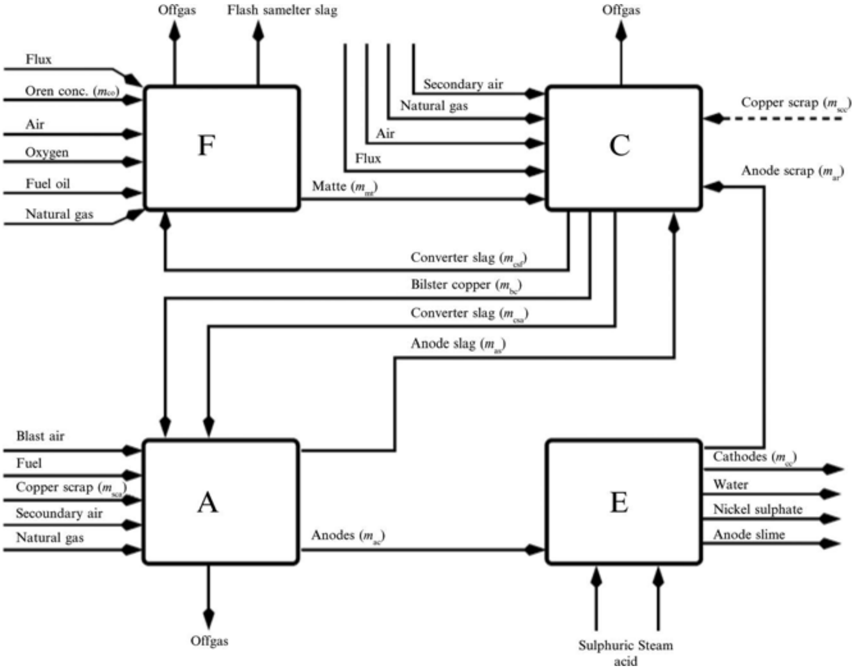

Figure 7-5. The material flows of the four main processes: flash smelter (F), converter (C), anode furnace (A) and electrolysis (E). Some flows have been named for easier reference.

5.2.1 Flash smelting

The flash smelter under consideration in this study is of the Outokumpu type, as described for example in Davenport & Partelpoeg (1987). The flash smelter is charged with sulphide ore concentrate, flux material (mainly sand) and oxygen-enriched air, plus slag from the converter process (see section 5.2.2). The oxidation of the concentrate delivers enough surplus heat to melt the reaction products (matte and slag), which are collected in the settler below the reaction shaft. The hot offgas is collected, cooled, de-dusted and then sent to the sulphuric acid plant for further processing. The dust is recycled to the flash smelter. The material and energy balance is given in the appendix, table 7-7.

5.2.2 Converting

The converter used at the NA is of the Peirce-Smith type as described in (Biswas, 1994). The matte transferred from the flash smelter is loaded into the furnace via ladles, together with flux material (mainly SiO_2 in the form of sand), copper scrap (anode scrap from the electrolytic refinery, rejected anodes from the anode furnace and others) and a small amount of copper-rich slag from the anode furnace. It is then blown with oxygen-enriched air in order to oxidise the sulphur content to SO_2. The process proceeds in two stages: the *slag blowing* stage in the beginning, when most of the slag is formed, and the *copper blowing* phase when most of the sulphur is removed from the system. During charging and skimming large amounts of ambient (secondary) air can enter the process. The final products are blister copper, slag and offgas rich in SO_2. The detailed material balance for one ton of blister copper is given in the appendix, table 7-12.

5.2.3 Fire refining

The last pyrometallurgical stage of producing high grade copper, the fire refining stage, is usually performed in the anode furnace, which largely resembles a Peirce-Smith converter, see (Biswas, 1994). The still liquid blister copper from the converter is transferred to the anode furnace via ladles, is then blown with oxygen to reduce the sulphur content to below 10 ppm[8] and subsequently with natural gas[9] to reduce the oxygen level to below 1000 ppm. The latter stage is also called *poling*. Additionally, the anode furnace is used in some locations to remelt some of the rejected anodes and anode scrap from the electrolysis. The refined copper is cast into moulds to produce anodes, which are then processed in the last refining stage, the electrolytic refinery. Some of the copper oxidises during the oxidation phase and settles in the slag layer, along with other impurities, mainly iron, which were transferred into the furnace due to imprecise skimming of the blister copper at the converter. The total mass and energy balance is given in the appendix, table 7-16.

5.2.4 Electrolytic refining

The anodes coming from the anode furnace (after being cooled down) are transferred to the tankhouse where they are installed in electrolysis tanks (divided into individual cells) for the last refinement stage.

Not all of the anodes dissolve during the electrolysis, since they extend above the electrolyte level. Approximately 16% of the anodes go directly back to the anode furnace or the converter for remelting. The impurities in the anodes partly dissolve in the electrolyte and partly form slime on the anode surface, which then collects at the bottom of the tank. The impurities collecting in the electrolyte are extracted from a small bleedstream. In the simplified model used here, $NiSO_4$ is the only impurity treated in this way. The total input and output balance for the production of one ton of cathodes is given in the appendix, table 7-20.

5.3 Entropy balance of the four processes

The detailed compositions and magnitudes of the material flows were derived by using mass balance equations and by applying the iteration process described in (Gößling, 2001). The entropy balance of each of the four sub-processes (flash smelting, converting, fire refining and electrolytic refining) is then derived from equation (16), integrated over an appropriate time interval[10]. The heat and radiation flows in (16) are deduced from the heat balance equation (17) and equation (18).

The specific entropy of the material flows was calculated from the molar entropy and enthalpy given in standard reference books (CRC, 1996, Barin, 1989) via equation (21), or from parametric expressions for the molar heat capacity as given in (Linstrom & Mallard, 2001), which were then plugged into equation (20). The results for the entropy balance are given in the appendix, see tables 7-7, 7-12, 7-16, 7-20. The entropy production through heat transfer as given in the tables comprises heat conduction *and* heat radiation. All results are given without error margins but an error analysis and an approximate error margin is presented in the next chapter.

As mentioned above, the real measure for resource use is the produced entropy within a process. In this sense, it is not the absolute values of in- and outgoing entropy that are of interest, but rather the difference between total input and total output of entropies. In table 7-2 the overall entropy production for the production of one ton of copper cathodes is given.

Table 7-2. Entropy production of all four processes for the production of one ton of cathodes.

Process	**Entropy production**	**Entropy coefficient η_e**
Flash smelter	$(1.92 \cdot 10^7 \pm 10\%)$ J/K	0.069
Converter	$(2.14 \cdot 10^7 \pm 25\%)$ J/K	0.080
Anode furnace	$(0.83 \cdot 10^7 \pm 10\%)$ J/K	0.006
Electrolysis	$(0.44 \cdot 10^7 \pm 10\%)$ J/K	0.002
Sum	**$(5.33 \cdot 10^7 \pm 16\%)$ J/K**	

The error margins were derived as discussed in chapter 5.4. For the meaning of the entropy coefficient see chapter 5.5.

5.4 Error analysis

The error margins of the magnitude and composition of the material flows making up the production network analysed in this study are mostly unknown. The data given in the standard literature on extractive copper metallurgy are also unsuitable to deduce the uncertainties, since they usually stems from single measurements performed under unknown conditions and are in all cases given without any reference to their accuracy. However, at every copper plant the magnitude and composition of flows is usually known with an error margin well below 10% (cf. (Gößling, 2001)). Thus, the conservative guess for the error margins applying to the calculation in this study is 10%, except for the error of the flow of natural gas into the converter process, which is assumed to be 60% due to largely deviating values either found in the literature (Krüger et al., 1995, Krüger & Rombach, 1998, Kippenberger et al., 1998) or given by metallurgical engineers (Velten, 2001, Kopke, 2001).

The high uncertainty in the natural gas flow of the converter implicates the same uncertainty for the heat flow output of the converter, thus yielding a relative error of the entropy production of the converter of 25%. The entropy production of all other units has an error of approximately 10%. This results in an overall error of the total entropy production of all production stages of 16%.

5.5 Interpretation of results

First it should be noted that this entropy analysis only comprises four core processes of one possible copper production chain. Thus, generalisations for the whole copper industry are not possible. These four processes, however, are quite typical for many production sites around the world and are among the most modern techniques in use.

The principal character of the copper production as a concentration and refining process can be seen when looking at the amount of entropy per mole of copper in the main copper bearing material flows, S_{Cu}:

$$S_{C_u} = \frac{S}{\eta_{C_u}}. \tag{22}$$

Here S is the respective entropy flow associated with a material flow and n_{Cu} is the included molar flow of copper. While the value for S_{Cu} for the ore concentrate is approximately 167.6 J/K, it decreases to 33.2 J/K in the final copper cathodes, which demonstrates the concentration process quite well. The decrease of this quantity is the direct consequence of the increasing copper concentration but not just a re-parameterisation of the same, since it takes the mixing of the different components into account. Also, it has the same units as the entropy production, enabling the definition of a dimensionless parameter, the *entropy coefficient* η_e, which describes the entropical degree of perfection of the process. It is simply defined as the total copper entropy decrease in the process divided by the total entropy production of this process. For a process X (X = F, C, A or E) with main copper bearing input flow m^i and main copper bearing output flow m^o the definition for η_e is given by

$$\eta_e := \frac{\Delta S_{Cu} n_{Cu}^o}{S_x} \; with \; \Delta S_{Cu} = S_{Cu}^i - S_{Cu}^o, \tag{23}$$

where S_X denotes the entropy production rate of process X for the given magnitudes of m^i and m^o.

The values for η_e for all four analysed processes are given in table 7-2. It is most obvious that, although the converter has a large total entropy production, it also has a large entropy coefficient and is thus 'more perfect' than the other processes. Anode furnace and electrolysis are decreasing the copper entropy only slightly, but are producing a large amount of 'overhead' entropy and have thus a lower entropy coefficient. Still, one has to bear in mind that the 'service' of the electrolysis is not only to make the copper purer but by this to enhance its conductivity, which again saves entropy production when used as electrical cables or wires[11].

The large entropy production values for the flash smelter and the converter are easily explained by the conversion of chemical energy stored in the sulphides into thermal energy stored in the products, mainly the offgas. This is an intrinsic property of the process and can hardly be changed without changing the whole process set-up[12]. Actually, the excess heat is needed in order to melt the products so as to be able to process them in the following process steps.

Nevertheless, the entropy production is not only determined by the amount of energy transferred to the products, but also by the temperature level at which this transfer takes place. This comes into play when the entropy production due to dissipation of energy to the offgas is considered. In particular the converter process allows in a large amount of secondary air, which is not needed for the conversion process itself. As a consequence, the final temperature of the offgas is lower than would be achieved by limiting the overall air intake. Thus, comparatively more entropy is produced. This fact can also be proven analytically by analysing the mass dependence of heat transfer entropy production. *Thus, from an entropic standpoint, it is advisable to limit the influx of secondary air into the process.*

Another major contribution to the entropy production of all four processes is the combustion of fossil fuels. This is especially true for the converter and the anode furnace and is unfortunately not visible for the electrolysis, since the combustion process (for producing the needed electricity) is outside the system. The Peirce-Smith converter process is, in principle, energetically self-sustaining, since the oxidation reactions are strongly exothermic. Still, since it is operated as a batch process, there are start-up procedures necessary that consume large amounts of fossil fuel. This also is an intrinsic property of the process and cannot be changed easily. Yet there are numerous efforts made to design a continuous process that does not have these disadvantages and should therefore have a lower entropy production. One should note that this use of fossil fuel would also be noticeable in an ordinary energy balance and is known well to most metallurgists.

5.6 Conclusions and recommendations for the primary production

The entropy analysis applied to the copper production from ore concentrates pinpoints the process stages with the highest resource use and indicates several possible optimisation approaches.

1. The major source of entropy production, and hence the process with the highest resource use, is the *converter* (Peirce-Smith type). The main contributions come from the exergetic oxidation reactions and the mixing of hot process gases with ambient air. The influx of ambient air can, in principle, be decreased by appropriate engineering measures. Though the converter process is the one with the highest entropy production, it is also the major concentration process along the production path, making it a rather efficient process.
2. For the *flash smelter*, the process design is already minimising the influx of secondary air. Its main entropy source is the oxidation process and the subsequent dissipation to the reaction products. This could only be changed if it was possible to find an efficient reaction path at lower temperatures as, for example, via electrochemical reactions. Although this is currently not feasible, the expected entropy production for this alternative process is considerably smaller.

3. The *anode furnace's* main entropy source is the dissipation of heat to the ambient air, which could be reduced by re-designing the offgas handling system and improving the insulation.
4. The *electrolysis'* main entropy production is through dissipation of electrical energy to the environment in the form of heat. This is already visible from an energy analysis, but could be confirmed by this entropy analysis. Increasing the efficiency of this process is probably only possible by further increasing the electrolyte conductivity and providing good electrical contacts within the circuitry. Enhancing the cathode current efficiency is probably not an option at the NA, since it is already at around 98%.
5. All process steps would benefit from increased insulation of furnaces and offgas systems, which would decrease the energy requirements for heat loss compensation.

Though some inefficiencies cannot be eliminated without fundamentally changing the process chain, there are other enhancements which are achievable through better design of the already-installed techniques. The entropy analysis, combined with an energy analysis and economical considerations, can be of help in finding the most promising targets for optimisation approaches.

5.7 Secondary copper production

The recycling of copper plays an important role in the world's copper consumption. In the year 2000, worldwide production of refined copper was 14.9 million tons of which 2.0 million tons were produced from secondary materials (recycled material and internal reverts), representing a share of 14%. In some countries, this share was as high as 62% (IPPC, 2000). There is a great variety of materials available for copper recycling, ranging from low-grade materials like dusts and ashes with a copper content of 1-2%, to high grade scraps with a copper content of more than 99%. The diversity of the sources for secondary copper is reflected in the diverse list of processes employed for recycling. The primary copper smelters very often have the facilities to also process large amounts of secondary material. The NA, for example, produces around 30% of its refined copper output from secondary sources (NA Website, 2001). In the case of a process set-up as described in chapter 5.2, the secondary material can be fed into the primary production network at two places: the converter and the anode furnace. The large amount of excess heat in the primary converter facilitates two effects: the fuel-free melting of solid scraps and the complete breakdown of organic material, as is present in printed circuit boards and cable insulation. The latter effect combined with the reducing conditions in the offgas stream inhibits the production of dioxins, a rather unpleasant side-effect of the recycling of such material in purely secondary copper plants. The anode furnace is suited to melt and refine high-grade scraps with a copper content greater than 90%.

5.7.1 Recycling of pure copper scrap in the anode furnace

The most simple scenario for recycling in a primary production network is to feed high-grade copper scrap, such as copper granules from cable comminution, directly into the anode furnace. Actually, this is already included in the analysis in chapter 5.2.3, since one of the inputs to the anode furnace is pure copper scrap (Cu > 99%). Thus, the only task left in this case is to calculate the fraction of the total entropy production attributable to the processing of this scrap. This leads us to the well-known allocation problem typical for environmental impact assessments. Here we have two different outputs from the process network: copper cathodes from primary production (i.e., from ore concentrate) and cathodes produced from secondary production (i.e., from scrap). Of course, the two products are physically indistinguishable and appear in the same form of copper cathodes at the end of the electrolysis process. But still, each copper atom took either of the two routes and should therefore be allocated a corresponding portion of the total entropy production. In fact, the problem is even more complicated, due to the several reflows inside the network, which theoretically could let some of the copper atoms cycle through the whole network more than once. However, these feedback effects will be rather small and are therefore neglected here.

All four processes purify the inputs, and the use of resources is directly linked to the quantity and quality of the main copper bearing flow entering the processes. Hence, the most intuitive choice for the allocation factor is the mass fraction of the copper-bearing input streams. For the anode furnace as described in chapter 5.2.3, this factor would be m_{SCA}/M_A, where M_A is the total input of copper-bearing flows to the anode furnace: $M_A = m_{bc} + m_{csa} + m_{sca}$, see figure 7-5.

Using the values calculated in chapter 5.2, the entropy production in the *anode furnace* attributable to the processing of scrap is then 0.0133/1.052 ≈ 1.3% of the total entropy production S_A. As described above, some portion of the copper input is oxidised and finds its way into the anode furnace slag. This is also true for the scrap copper input. This slag is recycled to the converter and thus some portion of the converter's entropy production has to be allocated to the processing of copper scrap. To distinguish the material flow originating from scrap, the notation of a * superscript is introduced. The aforementioned fraction is then directly proportional to m_{as}^*/M_C, with m_{as}^* being the flow of anode furnace slag originating from scrap[13] M_C being the total mass of all copper bearing inputs to the converter. Plugging in all the values from chapter 5.2, one finds that approximately 0.02% of the *converter's* entropy production has to be attributed to the processing of scrap. A similar calculation yields 0.005% as the respective fraction of the *flash furnace's* entropy production.

Following the same line of thought, the *electrolytic refinery* contribution to the overall entropy production is then $(m_{ac}^*/M_A)S_E$, where $M_E = m_{ac}$, since the only copper bearing input to the electrolysis is anode copper. Since anode copper from scrap should behave no different from regular anode copper, the ratio of cathode copper from scrap to anode copper from scrap should equal the ratio of the total cathode and anode quantities r, i.e. $m_{cc}^*/m_{ac}^* = m_{cc}/m_{ac} \equiv r$. Adding the single contributions of the four processes, and relating the result to the output of cathodes produced from scrap m_{cc}^*, one finds the entropy production attributable to the processing of scrap, S^*_{cc} and the specific entropy production for cathodes from scrap S^*_{cc} in this scenario to be:

$$S^*_{cc} = \frac{m^*_{csf}}{M_F} S_F + \frac{m^*_{as}}{M_C} S_C + \frac{m^*_{sca}}{M_A} S_A + \frac{m^*_{ac}}{M_E} S_E \ \ and \ \ \overline{S}^*_{cc} = \frac{m_{ac}}{m^*_{ac}\, m_{cc}} S^*_{cc} . \qquad (24)$$

Plugging in the values from chapter 5.2 and 5.3, one finds the specific entropy production for cathodes produced from scrap input to the anode furnace to be $1.29 \cdot 10^7$ J/Kt. How much each process contributes is shown in table 7-3. It is noteworthy that the electrolysis now contributes roughly 34% to the overall entropy production, while it was only 9% in the primary case. The anode furnace in this example serves mainly as a melting furnace and thus its entropy production should be related to this service. For melting and solidifying the scrap copper, the minimal entropy production is determined by the heat transfer to the scrap and the final transfer to the environment in the cooling phase (assuming that this heat is not transferred to some other unit). The associated entropy production for melting and cooling is then approximately $2.94 \cdot 10^6$ J/K per ton of cathodes compared to the actual $8.1 \cdot 10^6$ J/K observed. This indicates that this scenario is a rather unsuitable choice for recycling high-grade scrap. When there is no fire-refining necessary, it is probably advisable to use a more specialised melting device, like the shaft furnace.

Table 7-3. Entropy production for cathode copper from scrap per one ton of cathodes.

Process	**Entropy production**
Anode furnace	$(0.81 \bullet 10^7 \pm 10\%)$ J/K
Converter	$(0.03 \bullet 10^7 \pm 25\%)$ J/K
Flash smelter	$(0.01 \bullet 10^7 \pm 10\%)$ J/K
Electrolysis	$(0.44 \bullet 10^7 \pm 10\%)$ J/K
Sum	$\mathbf{(1.29 \bullet 10^7 \pm 16\%)}$ **J/K**

The scrap was assumed to have a copper content of 100% and to be fed into the anode furnace. Since these results are derived from the same data as the results for the production from ore concentrate, the same error margins as in chapter 5.4 apply.

5.7.2 Recycling of PVC-contaminated copper scrap in the anode furnace

The second scenario for copper recycling is the feed of copper scrap from cable comminution to the anode furnace. Here it is assumed that this scrap input has a variable PVC fraction x, where x typically lies in the range of 0.01 to 0.20. If the total mass is taken to be constant, then the specific entropy production for cathodes in this scenario depending on the PVC content of the scrap can be investigated. Again, it is assumed that all other processes are not affected by the composition of the scrap input, which is quite reasonable when looking at the mass ratio of copper scrap to total copper bearing input to the anode furnace: $m_{sca}/(m_{sca} + m_{bc} + m_{csa}) \approx$ 1.3%. The oxidation of PVC inside the furnace is taken to be complete, thus neglecting the possibility of dioxin formation. The heat of combustion of PVC will substitute some part of the fuel oil input needed for heating the furnace. Since the entropy production for combustion of PVC at standard conditions (neglecting all heat transfers) is slightly lower than for fuel oil with the same net heating value, the anode furnace's entropy production will also slightly decrease with increasing *x*:

$$S_A(x) = S_A(0) + \Delta S_{PVC}(x) \quad with \quad \Delta S_{PVC}(0) = -x \cdot 0{,}4 \cdot 10^3 J/K \tag{25}$$

The specific entropy production for anodes produced from scrap is found to be (Gößling, 2001)

$$\overline{S}^*_{ac}(x) = \frac{m_{sca}/M_A}{m_{sca}(1-x)r_A}\left(S_A(0) + \Delta S_{PVC}(x)\right), \tag{26}$$

where r_A denotes the ratio of total copper input to anode copper output. From chapter 5.2 we take the values for the production of one ton of anodes when $x = 0$: $m_{sca} \approx 13.33$ kg, $M_A \approx 1052.0$ kg, $S_A(0) \approx 0.69 \cdot 10^7$ J/K and $r_A \approx 0.97$ and then (neglecting $\Delta S_{PVC}(x)$) we find

$$\overline{S}^*_{ac}(x) = \frac{0.69 \cdot 10^7 J/K}{1.02(1-x)} \tag{27}$$

For $x = 0$ (no PVC in scrap), the specific entropy production in the anode furnace is $0.67 \cdot 10^7$ J/K. For small *x*, $\overline{S}^*_{ac}(x)$ is slowly increasing but diverges to infinity when *x* approaches 1. This is understandable when one notes that in the limiting case of $x = 1$ the anode furnace would mainly be used for incinerating PVC with only a small output of anode copper from scrap. The reasoning that was applied to the case of pure copper scrap above can now be applied to this scenario to yield the contributions to the entropy production from the other processes (converter, flash smelter and electrolysis). When calculating $\overline{S}^*_{cc}(x)$ in this scenario, the contribution from the electrolysis remains constant, i.e., independent of *x* at $0.44\,10^7$ J/K per ton of cathodes. The contributions from the converter and the flash smelter are still relatively small, since the reflow of slags originating from scrap is small. The dependence of $\overline{S}^*_{cc}(x)$ and the contributions from the different units is shown in figure 7-6. It is evident that the anode furnace and the electrolysis make up most of the entropy production in this scenario and should therefore be the primary target for any optimisation approach.

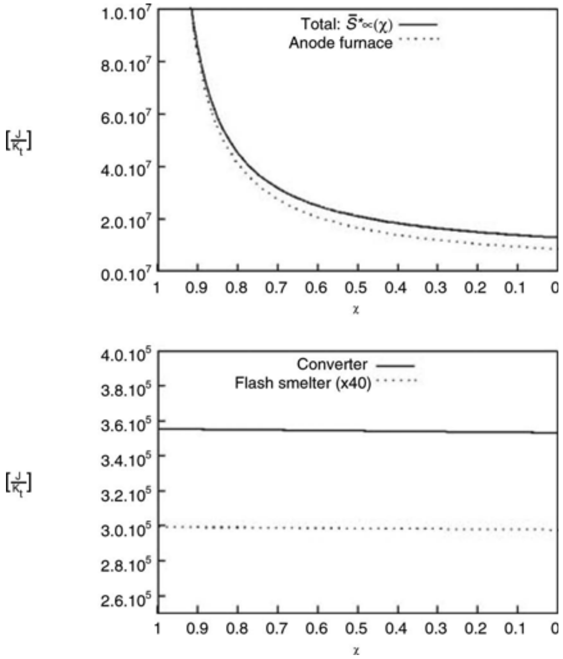

Figure 7-6. The solid line in the upper plot shows the specific entropy production for cathode copper produced from scrap input to the anode furnace, $\overline{S}^*_{cc}(x)$, with varying PVC content x. The dotted line is the contribution from the anode furnace alone. The lower plot shows the contribution from the converter (solid line), and the flash smelter (dotted line), which has been magnified by a factor of 40. The contribution from the electrolysis is constant (0.44.107 J/K) for varying x and is not shown in the plots.

5.7.3 Recycling of SiO_2- and PVC-contaminated copper scrap in the converter

A third possibility to recycle copper scrap using the primary process network is feeding it into the converter. Again, the easiest way to obtain the entropy production for cathodes produced in this manner is to *perturb* the already solved system from chapter 5.2 by changing the mass flow of reverted anodes from the electrolytic refinery, m_{ar}. The model for the electrolysis in chapter 5.2 included that about 16% of the anodes entering the electrolysis are sent back to the converter due to limitations in the mechanical set-up of the electrolytic cells. An easy way to accommodate for another recycling route is then simply to assume a smaller percentage of anodes recycled to the converter and compensate for the input loss at the converter by feeding additional copper scrap into it. Keeping all other flows in the network fixed, this means an increased output of cathodes m_{cc}. When $r{:}=m_{ac}/m_{cc}$ denotes the fraction of anodes refined into cathodes in the electrolysis, the fraction recycled to the converter is approximately[14] $(1 - r)$. For the unperturbed network the fraction of refined anodes is denoted by r_0. The specific entropy production in the electrolysis is then also a function of r, since it is defined by $S_E/m_{cc} = S_E/m_{ac}r$. It is further assumed that the additional scrap input to the converter is composed of copper, silicon dioxide and PVC with mass fractions α (Cu), β (SiO_2) and $\gamma = 1-\alpha-\beta$ (PVC) respectively, which roughly reflects the components of wastes from printed circuit boards (cf. (Langner, 1996)).

Adding all the contributions from F, C, A and E, we obtain the specific entropy production for cathode copper produced from scrap input to the converter:

$$\overline{S}^*_{cc} = \frac{1}{r}\frac{m_{bc}}{m_{ac}} \left(\frac{\beta c}{\alpha}\frac{S_F^0}{\left(M_F^0+\beta\frac{r-r_0}{\alpha}m_{ac}\right)} + \frac{c}{\alpha}\frac{\left(S_C^0+(1-\beta-\alpha)\frac{r-r_0}{\alpha}m_{ac}\Delta\overline{S}_C\right)}{\left(M_C^0+\frac{1-\alpha}{\alpha}(r-r_0)m_{ac}\right)} + \frac{S_A^0}{M_A^0}+\frac{S_E^0}{m_{bc}}\right), \tag{28}$$

where the 0 superscript denotes the values for the undisturbed network (as solved in section 5.3) and $\Delta\overline{S}_c \approx 17.8\ MJ/Kt$, which can be derived from the reaction enthalpy and entropy of the PVC combustion.

It is interesting to see how $\overline{S}^*_{cc}(x)$ behaves for different scrap compositions. One would intuitively expect that the specific entropy production should be smaller for a higher scrap quality, i.e., a larger value for α. This is confirmed by looking at the plot in figure 7-7.

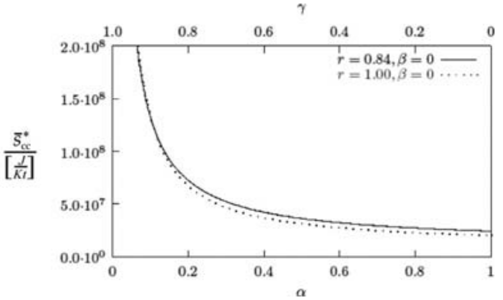

Figure 7-7. Specific entropy production for the production of cathode copper from scrap fed into the converter with varying compositions. The lower x-axis shows the copper content, the upper x-axis shows the corresponding PVC content. The SiO_2 content is zero in this case. The solid line represents an electrolysis transfer ratio of 0.84 (anode input to cathode output). The dotted line is the same plot for a ratio of 1.

With $\beta = 0$ in these plots, we have recreated the scrap quality from chapter 5.7.1, only now the scrap is fed into the converter. For pure copper scrap ($\alpha = 1$) the recycling via the converter path produces almost twice as much entropy per ton of cathodes as via the anode furnace path (see table 7-4).

Table 7-4. Entropy production for the production of one ton of cathode copper from scrap, using two different recycling paths and pure copper scrap (100% Cu) as input. The first column refers to scrap input to the anode furnace (A) as calculated in the previous chapter, and the second column refers to scrap input to the converter (C).

Process step	**Scrap into A**	**Scrap into C**
Flash smelter	0.07 MJ/K	0.00 MJ/K
Converter	0.35 MJ/K	12.07 MJ/K
Anode furnace	8.13 MJ/K	7.99 MJ/K
Electrolysis	4.40 MJ/K	4.53 MJ/K
Sum	**12.89 MJ/K**	**24.60 MJ/K**

This makes the anode furnace the superior furnace for high-grade copper scrap[15]. For low-grade scraps the difference is less pronounced, such that for $\alpha = 0.1$ and $\gamma = 0.9$ the ratio decreases to 1.5.

For $\alpha = 0.3$, $\beta = 0.4$, and $\gamma = 0.3$ we have a scrap composition comparable to the ore concentrate input in the primary production. The specific entropy production for the converter path (with a realistic value of $r = 0.9$) is then 53.7 MJ/K, which is almost identical to the primary production with 53.3 MJ/K. Thus, the processing of low-grade copper scraps (Cu ≈30%) has the same resource use associated with it, as the production from ore concentrates. This finding confirms the result from an energy analysis done by Krüger et al. (Krüger & Rombach, 1998, Krüger et al., 1995).

In conclusion, it can be stated that processing of medium- to high-grade copper scrap in either the anode furnace or the converter uses significantly less resources than the primary production from ore concentrates. The anode furnace is thereby the favourable choice for high-grade scraps, if no specialised melting device is available. The copper content of the scrap influences the result greatly, which has to be taken into account when evaluating recycling scenarios.

6. COMPARISON WITH ALTERNATIVE APPROACHES

The results from the entropy analysis can be compared with the results from other approaches only within limits. As mentioned in the introduction, the only really related measure of resource use is the exergy destruction. The concepts of MIPS and CED measure a different quantity, and thus a comparison can only be done qualitatively. A complication arises from the fact that the data on exergy analyses in the literature is given without error margins, with no exception. Thus, a scientifically sound comparison is impossible. In this study, error margins have been established for the entropy production of a specific industrial set-up for producing pure copper from ore concentrates, see chapter 5.4. Nothing is known, however, about the precision of the results from other approaches or about the underlying data leading to these results. This has to be borne in mind, when reading the following comparison.

6.1 Exergy

Kolenda et al performed an exergy analysis (Kolenda et al., 1992) on a primary copper plant using two different process set-ups. Their values for exergy consumption have been converted into entropy production rates using equation (14). Set-up A consists in a blast furnace as the main smelting aggregate producing copper matte, a converter producing blister copper and an anode furnace producing anode copper. The slag from the furnaces is not treated in this set-up. Set-up B comprises a flash smelting furnace producing blister copper, an electric furnace processing the flash smelter's slag (thereby producing a small amount of a Cu-Fe-Pb alloy, which is further treated in a converter), and an anode furnace producing anode copper. The electrolytic refinement stage was not included.

The flash smelter mentioned in the analysis from Kolenda et al., must be of a different type than the one analysed in this study, since it produces blister copper and not matte. In addition, the other devices are not directly comparable to the ones analysed in this study. Nevertheless, the principal inputs and outputs of the process chains are the same and thus it is interesting to compare the **exergy analysis** carried out in this paper with the entropy balance from chapter 5, see table 7-5.

Table 7-5. Specific entropy production of two different set-ups for the production of anode copper compared to the analysis from this thesis.

Set-Up A		Set-Up B	This study	
Blast furnace	39.2 MJ/Kt		Flash smelter	(19.1 ±10%) MJ/Kt
Converter	17.1 MJ/Kt		Converter	(21.4 ±25%) MJ/Kt
Anode furnace	11.0 MJ/Kt		Anode furnace	(6.9 ±10%) MJ/Kt
Total	67.3 MJ/Kt	38.2 MJ/Kt		(47.4 ±17%) MJ/Kt

Exergy consumption has been converted into entropy production using equation (14). The results for the sub-processes of set-up B from (Kolenda et al., 1992) were inconsistent with the results for the whole process and thus only the grand total is given. For a scientifically sound comparison, the error margins of the analysis from (Kolenda et al., 1992) would have to be known. If the same error margin as for this study is assumed, the results are in agreement within one standard deviation.

Set-up A is probably closer to the set-up used in this study, since the blast furnace produces matte from concentrates, and the converter and the anode furnace perform the same functions as the corresponding devices from chapter 5. For set-up A the entropy production (converted from the exergy data) was broken down into contributions from the different sub-processes, as given in table 7-5. The first noteworthy fact is the fairly good agreement in the results, considering the large uncertainty in the data basis. As mentioned in chapter 5.2.2, the literature on the converter process yields greatly varying values for its consumption of natural gas. Taking the lowest value found in the literature, this alone could amount to a decrease of the converter's specific entropy production of about 6 MJ/Kt. Thus, the rough agreement of the results from (Kolenda et al., 1992) with the results from the entropy balance must be considered satisfactory. *A real comparison between* *processes can only be made if the data basis is sufficiently accurate, the system boundaries for the processes to be compared are equivalent and the error margins of the analyses are known.*

The results as given in table 7-5 show the relation of exergy analysis and entropy balance insofar as they both yield a comparable value for the degradation of resources. The analysis by Kolenda et al. even goes a step further. In an additional analysis (not referenced in table 7-5), they calculate the *cumulative exergy destruction* by including the contributions from the preliminary stages of production. These preliminary stages include the processes necessary to supply the different feeds and energy carriers (ore concentrate, fossil fuels, coke, electricity, etc.). This alters the comparative results between set-up A and set-up B significantly and makes A the favourable choice in terms of resource use. The higher resource use of set-up B is hidden in the non-cumulative analysis, behind the higher consumption of electrical energy with its large *entropy rucksack. This again proves the necessity for a cradle-to-grave analysis in order to arrive at valid statements about the resource use of processes.*

Another exergy analysis was performed by Ayres & Masini (Ayres et al., 2004). There are two production paths analysed in this paper: a) via roasting and smelting of sulphide ores and b) via solvent extraction/electro-winning of oxide and sulphide ores. For sulphide ores the process steps include: concentration, roasting, smelting and desulphurisation, and electrolytic refining. The latter two units correspond roughly to the process set-up used in the entropy balance undertaken in this study. Ayres & Masini found that the exergy destruction due to smelting, desulphurisation, and electrolytic refining is 41314.4 MJ per ton of cathodes, corresponding to an entropy production of 138.4 MJ/Kt (via equation 14). This has to be compared with 53.3 MJ/Kt from the entropy balance in chapter 5. The difference between these values cannot be explained without knowing the metallurgical set-up and the mass flows of the analysis used by Ayres & Masini in more detail. However, in view of the findings of Kolenda et al, and the results from the entropy balance, this value seems to be much too high. It is interesting to note that the ore concentration unit in (Ayres et al., 2004) has an associated entropy production of 99.1 MJ/Kt - comparable to the metallurgical part. This again calls for an inclusion of the pre-metallurgical phases of mining and beneficiation in any analysis of copper production.

Alvarado et al. have compared the exergy destruction of two different smelting technologies (Alvarado et al., 1999): the reverberatory furnace (RF) and the Teniente converter (TC). Both of the furnaces produce matte from sulphide ore concentrates and are operated at the same copper smelting plant in Chile. This analysis is a good example of how an evaluation of industrial processes based on the second law of thermodynamics can point out the more efficient technology. The results were given in terms of exergy loss per ton of processed concentrate and have been rescaled to the production of one ton of matte. The converted results are given in table 7-6 together with the results for the equivalent furnace in this study, the Outokumpu furnace (OO).

Table 7-6. Entropy production of reverberatory furnace (RF), Teniente converter (TC) and Outokumpu flash smelter (OO) for the production of matte.

Furnace type	**Specific entropy production**
Reverberatory furnace	22.3 MJ/Kt
Teniente Converter	6.0 MJ/Kt
Outokumpu flash smelter	(10.8 ± 10%) MJ/Kt

The values for RF and TC were derived from an exergy analysis performed by Alvarado et al (Alvarado et al, 1999). the values for OO are from this study, chapter 5

It is obvious that the outdated RF technology is significantly less efficient than the other two more modern techniques. It has to be noted that the matte quality of the three processes is not the same, making a direct comparison difficult. The RF matte has a copper content of about 40% to 60%, while the OO matte usually contains at least 60% copper and the TC matte reaches grades well above 70%. This even enhances the differences in the respective efficiencies apparent in table 7-6. Another disadvantage of the RF might also contribute to the high entropy production: it produces large amounts of very dilute offgases, inappropriate for further processing in a sulphuric acid plant. The OO furnace produces the least amount of offgases with a medium SO_2 content followed by the TC furnace with a quite high SO_2 offgas concentration. Thus, the entropy production reflects very well the overall efficiency of the processes.

In summary, it can be concluded that exergy analysis and entropy balancing yield comparable results for the total resource use. The absolute differences, however, are still large and the reasons behind this should be investigated more closely. A large fraction of the disagreements can probably be explained by considering the generally poor data quality and the many different technologies found in the metallurgical sector.

Another factor of uncertainty arises from the unknown definitions of the reference environments used in the different exergy analyses and how they affect the results. This also highlights one of the shortcomings of the method of exergy analysis, namely the need for a correctly defined reference environment. When focusing on resource use, there is basically no need for such a reference base, since only changes in the thermodynamical state of the flows of matter and energy are relevant. These can be obtained much more easily from an entropy balance. The absolute values of in- and outgoing exergy flows do become meaningful when they are used for defining exergetic efficiencies. On the other hand, it remains to be shown whether these efficiencies yield more insight into the process and its potential for optimisation than the detailed entropy analysis.

In addition, it is recommended that authors of respective studies should specify the *uncertainties* of their raw data and final results in a more systematic way. This will require cooperative contributions from the copper mining and producing companies, in particular more accurate *monitoring* of the mass and energy flows in the copper production chain. This especially applies to mass flows not directly affecting the economic performance of the production system, like secondary (infiltration) air and offgas amounts.

7. CONCLUSION AND OUTLOOK

7.1 Discussion of results

The results from the application of entropy analysis to basic examples and the industry-scale case study, have shown that entropy production is indeed a valid measure for the general resource use, giving a *complete picture of the associated degradation of flows of matter and energy.* This makes the entropy production an important parameter in the environmental assessment of industrial processes. Since entropy production is a highly aggregated measure, it has to be augmented by other parameters and indicators, besides resource use, in order to yield insight into the overall ecological impact of a process. Tools that aid in the assessment of technology are for example *Environmental Impact Assessment, Risk Assessment, Toxicological Assessment,* and others.

The entropy production also serves as a measure for the *resource use efficiency* of processes, when it is related to the products or services of this process. An increase in this efficiency then signals a better adaptation of the production system to the available resource streams. For the primary copper production system, a few recommendations could be made as to how the resource use efficiency can be increased markedly (decreasing the amount of secondary air and increasing the thermal insulation of the devices). It also saves resources when the necessary cooling of systems is done in a way that enhances the re-usability of the captured heat, e.g., by water cooling. At present, most of the heat leaves the analysed system with the offgas stream.

The application to secondary copper production (from recycled materials) was an example of how the resources used, measured by entropy production, can be allocated to multiple products of the production system. It was shown (chapter 5.7), as expected, that the secondary production from high-grade scraps uses significantly less resources, than the production from ore concentrates. The favourable choice for the entry point of high-grade scraps into a primary copper plant, in the absence of special smelting devices like shaft furnaces, is the anode furnace[16]. The processing of low-grade scraps (copper content below 30%), however, uses approximately the same amount of resources as the production from ore concentrates. For scraps of very low grade, the resource use increases greatly. Considering the vanishing natural deposits of copper ore, this clearly indicates the necessity of high-grade recycling, keeping the copper content of the scraps as high as possible[17].

The only measure directly comparable with entropy production is the exergy loss of a process. It was found (chapter 6) that the results from exergy and entropy analysis have the same order of magnitude, but differ by up to 100% and more. The reasons for this difference are probably the poor data quality for most of these analyses and the differences in the actual industrial set-up investigated. From theory, the two methods, exergy and entropy analysis, should yield the same results. In theory and in application it could be shown that the entropy analysis can be performed without further prerequisites, if only the detailed material and energy balance is given. Only a table with thermodynamic properties of the relevant substances is needed. In contrast to the exergy analysis, there is no need to decide on a specific reference environment. Only the temperature, and in some cases the pressure, of the environment have to be known.

Taking these results into consideration, the inclusion of the method of entropy analysis into the framework of life-cycle analysis, or any other tool for ecological impact assessment, should be straightforward.

7.2 Remaining problems and further research tasks

The real problems arising in the course of an entropy analysis are actually problems outside the thermodynamic context. It has to be stressed that a detailed material and energy balance (including the specification of uncertainties and error margins) is a crucial ingredient of *every* ecological assessment. This is especially true if the use of resources is to be analysed. Therefore, it seems to be desirable to investigate the possibility of how the entropy analysis can be included in the design stage of industrial processes. One necessary part surely is the inclusion of sufficiently accurate *monitoring* (on the per cent level) of all relevant mass and energy flows of these processes.

The standard simulation and design tools for engineers mostly have the necessary thermodynamic databases and algorithms available to include an entropy analysis. Using the entropy production to optimise the process would then not only have ecological benefits but also economic ones.

Another interesting question is how to include entropy production into the framework of economics. Entropy production and the derived measure of resource use efficiency link ecological and economic aspects of industrial processes and thus help in finding an integral view on the technosphere. Applying entropy production analysis (and other impact assessment tools) to the whole life-cycle of a product, could eventually lead to a shift in the economic focus from short-term to long-term considerations. It seems that entropy production is the only measure for physical resource use and it should therefore find its way into an ecologically-orientated description of the economy. A first approach could be to relate the entropy production of a given process or product to its value added in the economic sense. Thus, one would create a thermodynamics-based relation between resource use and creation of value, where entropy production would play the role of a general “cost” in the sense of lost utilisation possibilities.

A common objection to a *closed loop economy* is the impossibility of complete recycling. Although this objection is not quite true[18], it is correct that complete recycling (of a given material) would have prohibitively high financial and energetic costs and is thus *practically* impossible. Also, recycling most often means ‘downcycling’, meaning the recycled material has a lower purity or decreased usability. In order to find a level of recycling that is economically and ecologically justifiable, one could employ the entropy production as a measure for the associated costs. One could then evaluate scenarios for recycling, taking the loss of usability of recycled materials into account, and compare them on the basis of their *entropic costs*. This could lead to an optimisation of incentive systems and organisation structures for recycling. Additionally, if the assessment of entropy production as a measure for resource use would be an integral part of the whole production process, it would also influence the design phase, automatically leading to a product design which is well suited for recycling. These statements are worthy of a more detailed investigation and should be backed up by appropriate case-studies.

APPENDIX: TABLES

Table 7-7. Mass and entropy balance of the flash smelter (Outokumpu process).

Input		**S [J/K]**	**Output**		**S [J/K]**
Ore concentrate	2.14 t	$1.65 \cdot 10^6$	Matte (1460 K)	1.00 t	$1.90 \cdot 10^6$
Flux material	0.14 t	$8.95 \cdot 10^4$	Slag (1500 K)	1.18 t	$2.85 \cdot 10^6$
Dust	0.10 t	$7.57 \cdot 10^4$	Dust (1500 K)	0.10 t	} $1.65 \cdot 10^7$
Converter slag (1500 K)	0.27 t	$6.36 \cdot 10^5$	Offgas (1570 K)	1592 Nm^3	
Air	1275 Nm^3	} $1.19 \cdot 10^7$	Heat	1085 MJ	} $4.06 \cdot 10^6$
Oxygen	293 kg		Radiation	15 MJ	
Fuel oil	38 kg	$1.17 \cdot 10^5$			
Natural gas	5.4 Nm^3	$3.99 \cdot 10^4$			
Electrical energy	14 kWh				
			Entropy production [J/K]		**$1.08 \cdot 10^7$**

Temperature of material flow given in parenthesis if differing from T_0=298.15 K. Original data from (Biswas, 1994, Davenport & Partelpoeg, 1987, Willebrandt, 1993, Krüger et al., 1995, Krüger & Rombach, 1998, Velten, 2001, Kopke, 2001, Cobre 91, Rombach, 2001) were modified to create a consistent network of material flows by using the iterative process described in (Gößling, 2001).

Table 7-8. Calculated composition of ore concentrate

Component	$CuFeS_2$	SiO_2	C	Al_2O_3	ZnS	PbS	H2O	As_2S_3	Ni	CaO
Fraction [%]	84.42	7.40	2.30	2.24	2.12	0.35	0.30	0.30	0.05	0.52

Table 7-9. Composition of dust from flash smelter.

Component	$CuFeS_2$	$CuSO_4$	CuO	SiO_2	Fe_3O_4	ZnO	PbO
Fraction [%]	13.93	35.76	17.72	4.37	18.57	6.12	3.53

Table 7-10. Composition of matte as a product of the Outokumpu process.

Component	$Cu_2S \cdot \frac{1}{2} FeS$	CuO	FeO	ZnO	PbO	Ni
Fraction [%]	95.05	1.85	1.21	1.25	0.54	0.10

Table 7-11. Composition of Outokumpu process slag

Component	Cu_2S	SiO_2	$(FeO)_2[SiO_2]$	As_2S_3	Fe_3O_4	Al_2O_3	CaO	ZnO
Fraction [%]	2.51	9.40	71.32	0.44	8.17	4.08	1.02	3.06

Table 7-12. Mass and entropy balance of the converter process (Peirce-Smith converter).

Input		**S [J/K]**	**Output**		**S [J/K]**
Matte (1460 K)	1.46 t	$2.78\cdot10^{6}$	Blister copper (1470 K)	1 t	$1.40\cdot10^{6}$
Flux	0.17 t	$1.43\cdot10^{5}$	Slag (1470 K)	0.43 t	$1.02\cdot10^{6}$
Anode slag	0.06 t	$7.69\cdot10^{4}$	Offgas (1023 K)	3073 Nm^3	$3.65\cdot10^{7}$
Scrap copper	0.16 t	$7.07\cdot10^{4}$	Offgas from start-up	591 Nm^3	$4.66\cdot10^{6}$
Air (23.5% O2)	992 Nm^3	$7.80\cdot10^{6}$	Radiation	90 MJ	} $5.72\cdot10^{6}$
Secondary air	2626 Nm^3	$2.06\cdot10^{7}$	Heat	1635 MJ	
Natural gas	56.5 Nm^3	$6.02\cdot10^{4}$			
Electrical energy	20 kWh				
			Entropy production [J/K]		**$1.77\cdot10^{7}$**

Temperature of material flow given in parenthesis if differing from T0=298.15 K. Original data from (Biswas, 1994, Willebrandt, 1993, Krüger et al., 1995, Krüger & Rombach, 1998, Velten, 2001, Kopke, 2001, Cobre 91, Kippenberger et al., 1998, Goto, 1979, Rombach, 2001, MacCain & Floyd, 1994) were modified to create a consistent network of material flows by using the iterative process described in (Gößling, 2001).

Table 7-13. Composition of converter offgas during slag blowing and copper blowing stages.

Component	SO_2	O_2	N_2	Ar	
Slag blow	5	15	79	1	25% of offgas
Copper blow	9.5	11.5	78	1	75% of offgas

Table 7-14. Composition of blister copper.

Component	Cu	Cu_2S	Cu_2O	PbO	Cu_3As	Ni
Fraction [%]	94.42	0.50	4.50	0.10	0.38	0.10

Table 7-15. Calculated and normalised composition of converter slag.

Component	SiO_2	$(FeO)_2[SiO_2]$	Fe_3O_4	Cu_2S	FeS	ZnO	PbO
Fraction [%]	6.8	65.7	16.7	5.56	1.54	2.6	1.1

Table 7-16. Mass and entropy balance of the anode furnace.

Input		**S [J/K]**	**Output**		**S [J/K]**
Blister copper (1470 K)	1.01 t	$1.51\cdot10^{6}$	Anodes (1470 K)	1t	$1.37\cdot10^{6}$
Converter slag (1500 K)	0.03 t	$6.96\cdot10^{4}$	Slag (1470 K)	0.07 t	$1.87\cdot10^{5}$
Fuel oil	0.03 t	$1.07\cdot10^{5}$	Offgas (860 K)	1168 Nm^3	$1.08\cdot10^{7}$
Scrap copper	0.01 t	$6.96\cdot10^{3}$	Radiation+Heat	1550 MJ	$5.20\cdot10^{6}$
Blast air	1.3 Nm^3	$1.05\cdot10^{4}$			
Secondary air	1127 Nm^3	$8.84\cdot10^{6}$			
Natural gas	6.7 Nm^3	$4.93\cdot10^{4}$			
Electrical energy	16 kWh				
			Entropy production [J/K]		**$0.69\cdot10^{7}$**

Temperature of material flow given in parenthesis if differing from T0=298.15 K. Original data from (Biswas, 1994, Willebrandt, 1993, Krüger et al., 1995, Krüger & Rombach, 1998, Velten, 2001, Kopke, 2001, Cobre 91, Kippenberger et al., 1998, Rombach, 2001, MacCain & Floyd, 1994) were modified to create a consistent network of material flows by using the iterative process described in (Gößling, 2001).

Table 7-17. Composition of anodes.

Component	Cu	Cu_3As	PbO	Ni	O
Fraction [%]	99.27	0.39	0.15	0.15	0.04

Table 7-18. Composition of anode slag.

Component	Cu_2O	$(FeO)_2[SiO_2]$	SiO_2	Fe_3O_4	PbO	ZnO	O_2
Fraction [%]	45.04	27.32	8.0	6.94	3.24	1.24	8.21

Table 7-19. Composition of anode furnace offgas.

Component	N_2	O_2	CH_4	C_2H_6	Ar	CO	CO_2	H_2O
Fraction [%]	75.26	12.24	0.31	0.01	0.97	0.25	5.22	5.72

Table 7-20. Mass and entropy balance of the electrolysis.

Input		**S [J/K]**	**Output**		**S [J/K]**
Anodes	1.199 t	$6.33\cdot10^{5}$	Cathodes	1.0 t	$5.22\cdot10^{5}$
H2SO4	2.5 kg	$5.18\cdot10^{4}$	Anode scrap	0.192 t	$1.01\cdot10^{5}$
Steam (4bar, 150° C)	128 kg	$9.60\cdot10^{5}$	Anode slime	6.0 kg	$2.83\cdot10^{3}$
Electrical energy	300 kWh		Heat+Radiation	1438 MJ	$4.82\cdot10^{6}$
			Cond. water	128 kg	$4.97\cdot10^{5}$
			NiSO4	4.0 kg	$2.37\cdot10^{5}$
			Entropy production [J/K]		**$0.62\cdot10^{7}$**

Original data from (Biswas, 1994, Willebrandt, 1993, Krüger et al., 1995, Krüger & Rombach, 1998, Velten, 2001, Kopke, 2001, Cobre 91, Kippenberger et al., 1998, Rombach, 2001) was modified to create a consistent network of material flows by using the iterative process described in (Gößling, 2001).

Table 7-21. Assumed composition of anode slime. The noble metals had to be neglected due to unavailable data. They were thus eliminated from the whole process network.

Component	Cu_2S	$PbSO_4$	Cu_3As
Fraction [%]	0.83	34.16	65.01

NOTES

[1] The term *technosphere* describes the part of the biosphere (the life-bearing part of our planet) which is directly influenced and changed by humans and their artificial extensions.

[2] In most industrial processes an even stronger restriction holds. Since in these processes the conversion of matter into energy and vice versa can safely be neglected, mass and energy are conserved independently.

[3] It is assumed that the energy content of the Earth is constant. However, variations could arise from an increased fixation of solar radiation, e.g., by increased photosynthesis, from an increased release of formerly stored energy, e.g., by burning fossil fuels, or from changes in the atmospheric processes governing the energy and entropy export into space, e.g., the greenhouse effect.

[4] The exergy analysis approach actually tackles this problem in a way quite similar to the entropy analysis method.

[5] The term 'entropy production' is used in both meanings throughout this article. It should always be clear from the context whether the *rate* of production or the *amount* of production is meant.

[6] Note that the heat flow involved in this transition does not necessarily flow from the material flow to the reference environment, but might also flow the other way. The assumption of constant chemical composition over the whole temperature range of the thermal equilibration process is not always valid. Then the exergy associated with a flow of matter cannot easily be partitioned into the above-mentioned contributions.

[7] As a consequence, the analysis cannot serve as a basis for a life-cycle assessment, since too many production steps and auxiliary processes are missing.

[8] (Mass-) parts per million.

[9] Different agents are used in different plants. Natural gas is the choice at the NA.

[10] The time interval is intrinsically given by the time needed to produce one ton of the respective product of each sub-process. The magnitudes of the flows have been derived accordingly.

[11] The electrolysis produces 4.4 MJ/K per ton of cathodes. If these cathodes were manufactured into an electric cable with a cross-section of 1 mm^2, and a current of 1 A was run through it, it would take approximately one month before the same amount of entropy was saved due to the higher conductivity.

[12] One could, for example, dream up a process that runs at near ambient temperature using a technique similar to a fuel cell. The excess electrical energy could then be used to drive the subsequent processes.

[13] All flows are considered positive in this section, since they may appear as input flows and output flows simultaneously.

[14] Neglecting the copper loss in the anode slime, which is about 0.3%.

[15] The accuracy of this statement hinges very much on the accuracy of the entropy balance of the converter, which suffers from the inconsistent data on its fossil fuel consumption (see chapter 5.2.2). The entropy production for this recycling route could be up to 7 MJ/K lower than calculated above. Nevertheless, this would still leave it substantially higher than for the anode furnace route.

[16] This only applies to the resource use as measured by entropy production. Including more categories in the description, e.g., toxicity, will probably yield a different result.

[17] This has to be achieved without introducing other sources of high entropy production, of course.

[18] The recycling losses can, in principle, be made arbitrarily small.

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Chapter 8

DEMATERIALIZATION OF THE METALS TURNOVER

Some Reasons and Prospects

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1. DEMATERIALIZATION

Metals are one of the different categories of materials in the societal metabolism or materials turnover in which we extract materials from Nature, and then transform, use to produce services, recycle, lose or discard them, leading to an eventual return to nature. There is a widespread and growing concern that this materials turnover needs to be adapted to restrictions set by nature and society emanating from environmental and health impact and costs and efficient and just use of scarce resources.

In order to meet these demands, suggestions for a "dematerialization" of the material flows has been put forward, that is, lessening of the intake of materials to the technosphere while keeping or increasing the societal service produced, see, for instance, (Cleveland & Ruth 1999), for a review. A rough estimate of the necessary global dematerialization has led to dematerialization concepts like "Factor 10", aiming at a general reduction of the materials turnover by 90 percent in the industrial societies in order to simultaneously meet demands for increased economic affluence in developing countries as well as environmental or resource restrictions, (Schmidt-Bleek 1994; Reijndeers 1998; Holmberg & Karlsson 1998).

Dematerialization can be accomplished by slowing down the net materials throughput in society by enhancing the lifetimes of products or by increasing recycling of the used materials and products. Another way may be by introducing smarter and thus smaller constructions, which has happened for instance in the electronic sector through an ongoing miniaturization. An interesting question is thus whether a dematerialization of the turnover of metals is an efficient way of solving the perceived environmental and resource problems. Here, we will briefly highlight

A. von Gleich et al.(eds.), Sustainable Metals Management, 237-247.

and discuss some reasons and prospects for dematerialization of the metal flows in the light of some characteristics of metals in nature and society.

2. SOME IMPORTANT CHARACTERISTICS OF METALS

The *geological* abundance of metals varies tremendously as exemplified in Table 8-1; from the relative abundance of iron and some light metals, via the scarce base metals and ferro-alloying elements, to the very scarce, for instance, the precious metals. Today, the metals are extracted from rare concentrations of specific minerals containing the metal in question. However, while the abundant metals are generally making up and are thus abundant in common minerals, only very tiny fractions of the scarce metals are found in separate metal-bearing minerals and even less so in economically relevant concentrations. They are scattered in common minerals by atomic substitution (Skinner 1987). Furthermore, geologically, the metals often occur together in complex ores giving main, co-, and by-flows of various metals when mined.

Table 8-1. Some indicators on global anthropogenic flows of metals compared to the natural turnover. From Azar *et al.* 1996.

Metal	Concentration in soils [mg/kg]	Metals mining [kton/year]	In extracted fossil fuels [kton/year]	Mining + fossil fuels/ continental weathering[a]
Abundant				
Al	72 000	18 000	34 000	0.05
Fe	26 000	540 000	34 000	1.47
Scarce				
Zn	60	7 300	260	8.31
Cr	54	3 800	34	4.62
Cu	25	9 000	55	23.83
Ni	19	880	570	4.83
Pb	19	3 300	85	11.67
Cd	0.35	20	3.4	4.42
Hg	0.09	5.2	10	10.86

[a] Mobilization in continental weathering was calculated using average concentration in soils (column 1) and suspended sediment flux of $1.5 \cdot 10^{16}$ grams per year in rivers.

In living materials, in *biota*, while some of the metals are found in very specific functions, typically in enzymes, but in low concentrations, others metals are non-essential and thus have no specific role in organisms.

The metals, possibly with the exception of iron, comprise a small share of the total materials intake into the *technosphere* in the industrial societies, Table 8-2. The production and use of metals imply, nearly without exception, blending into alloys and complex products to achieve specific properties.

Although the turnover of most metals in the technosphere is small it is often even smaller in nature. The societal extraction of many metals is large compared to corresponding flows in Nature, for instance, measured in the form of weathering, Table 8-1. This can be seen as an overarching explanation to problems with metal resource availability on the intake side and the emissions of metals to and accumulation in specific environments giving, toxicity problems on the output side.

Table 8-2. Materials intake in an industrial society: USA 1990. Data from Wernick & Ausubel 1995.

Material group	Apparent consumption[a]	
	[Tg/year]	[Percent of total]
Energy	1961	38.2
Construction minerals	1921	37.4
Industrial minerals	249	4.9
Forestry products	260	5.1
Agriculture	629	12.3
Metals	112	2.2
- iron	100	1.9
- copper	2.2	0.04

[a] production + import – export

Not all that is extracted or mobilized in exploiting natural resources is valuable material used in society. Connected to the extraction of useful material is what has been called an ecological rucksack (Schmidt-Bleek 1994). Major global extractions from the lithosphere together with their rucksacks are summarized in Figure 8-1. The annual extraction of lithospheric materials amounts to around 20 and 60 Pg (or billion tonnes) without and with the rucksack, respectively.

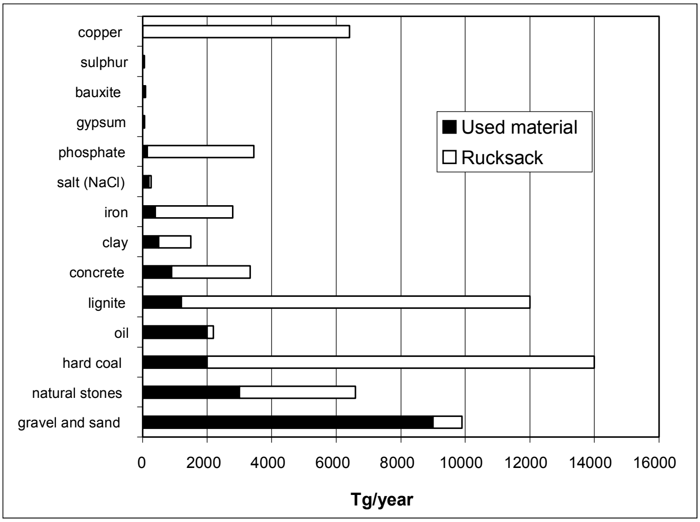

Figure 8-1. Global anthropogenic extraction of lithospheric materials in 1983 (Tg/year). Data from Schmidt-Bleek & Tischner 1995.

About half of this rucksack is due to extraction of raw materials for the supply of energy, especially the use of fossil coal. Some other high-volume non-metallic minerals are also important, for instance, minerals for phosphorus and for concrete production. However, some metals make a considerable contribution, for instance, iron, due to the large volumes used in society, and copper, due to its low grade in ores, giving rise to huge amounts of discarded useless materials. These rucksacks consist mainly in large dumps and other translocations of materials at the mine and may give rise to considerable but mainly local environmental effects.

Any dematerialization of the metals turnover in society will thus not significantly directly decrease the total societal intake of materials. However, a dematerialization of the metals, especially of the geologically scarce ones, will decrease mining activities and the ecological rucksack considerably more. Indirectly, also the demand for energy and other inputs to primary production will be lessened.

3. DEMATERIALIZATION AND EMISSIONS

To lessen the metal burden on the environment, the emissions need to be decreased. The emissions of metals to the environment consist of emissions from the system of producing metals and various goods and emissions in the use phase of the goods, consumption emissions. By lessening the need for new primary materials, dematerialization may contribute to decreasing the production emissions, besides decreasing the upstream materials mobilization and energy input.

In the modern industrial society, the focus of environmental regulations has been on production emissions and these have decreased considerably during the latest thirty years or so. The major emissions now tend to emanate from the consumption (Bergbäck, 1992). These emissions are connected to very specific uses. They occur during the use as wear and tear of, for instance, surface coatings on buildings and infrastructure, tap water systems, vehicle tyres and brake pads and wooden products containing metal-based preservatives, or they are the result of dissipative processes inherent to the specific use, such as metal spreading during the use of munitions (Guinée *et al.* 1999; Bergbäck *et al.* 2001). A prolongation of today's metals management practice will give continued and sometimes drastically increased concentrations of many metals in our environment (Guinée *et al.* 1999).

In many of these cases, a dematerialization in the form of increased recycling is either not feasible or does not decrease these emissions, as they occur during the use, and thus before and independent of the recycling. Dematerialization through thinner materials will also not influence surface corrosion and wear. Instead, in these cases "transmaterialization", i.e., substitution, to environmentally more benign metals or other materials is probably more feasible. For instance, copper leakage from the tap water system can largely be avoided by using plastic (polyethylene) pipes instead of ones made of copper. In some cases smarter constructions may decrease or totally avoid emissions from wear, for instance, the introduction of regenerative and non-frictional braking systems. In the post-consumption phase though, dematerialization by sorting out and recycling of metal containing products can help mitigate emissions from waste incineration and improper landfills.

Another question is the long-run environmental load and consequences of our metals management. Even with low direct emissions, in the long run, the metals are anyhow lost from further societal use and returned to nature. Any dematerialization will then not only introduce a delay, but will probably give rise to another geographical pattern of the final storage of the metals. Whether it is a better or worse pattern and long-term ecological outcome with an extensive dematerialization of the metal use is not evident. Recycling may tend to transfer a larger share of the turnover to more uncontrolled losses, compared to more controlled dumping in landfills.

4. DEMATERIALIZATION AND RESOURCE AVAILABILITY

Concentrated metal resources are valuable assets, but also limited and non-renewable. Their beneficial use thus implies potential technical/economic problems concerning availability and ethical problems concerning the distribution between people and regions (intragenerational justice) and the distribution in time (intergenerational justice).

Intragenerational justice puts restrictions on the distribution of the accumulated *per capita stock* of resources. It can be argued that the economic forces will take care of any scarcity through the price mechanisms, leading to an efficient and just distribution. It can also be argued that in the long run any scarce resource will be used up, and the prime focus should be to avoid future stress due to too rapid changes in the resource availability. Also, for the abundant metals, no long-term dramatic, sudden and large change in future availability can be expected. However, for some of the commonly used scarce metals, the easily extractable future resources per capita are much less then what has been used per capita so far during the build up of the industrialized countries, illustrated by lead in Table 8-3. The conclusion is that the historical pattern of accumulated use during the industrialization can not be extrapolated to the global scale. For these metals it is reasonable to aim at a decrease of the per capita accumulated stock in society, either through smarter, less metals-intensive use, or a turn to more abundant materials for fulfilling the demanded services.

Table 8-3. Global lead resources and lead use in Sweden during industrialization. Data from Karlsson 1999.

Resource/Use	Lead stock [Kilograms per capita]
Global reserves	7
Global reserve base	12
Global resources	140
Net intake into Sweden 1880-1980	290

The future development in the form of new technology and environmental restrictions may also imply increased demand for specific metals, for instance, introduced by the rapid development of new technologies within electronics. The need for considerable changes within the energy system also constitutes a specific situation. A mitigation of the climate change forced by the ongoing increase of the concentration of carbon dioxide in the atmosphere caused by the use of fossil fuels and the global net deforestation necessitates a decarbonization of the energy supply.

This may be brought about by an increased reliance on renewable energy supplies. Solar energy tapped by solar cells is among the promising alternatives with a large potential. A viable strategy also involves increased energy efficiency in various conversion facilities. In the transportation sector fuel cell, electric, or hybrid vehicles are possible substitutes for vehicles equipped with internal combustion engines, which dominate transportation today. With these alternatives also local pollution, for instance, in cities, may decrease as well.

However, many of these new technological applications use specific, often scarce, metals. A large-scale global application of such energy technologies will raise the demand for these specific metals considerably and may be heavily restricted by the availability of metal resources (Andersson *et al*. 1998; Andersson 2000; Andersson & Råde 2001; Råde & Andersson 2001). For examples from solar cell technologies, see Table 8-4. Many of these metals are geologically associated with other more common metals and are extracted only as by-flows to these common metals in today's mining (Ayres, 1997; Andersson, 2000). With the possible extraction determined by the demand and mining economics of these major metals, not only the totally available stock but also the possible rate of extraction of the by-flow metals might pose a severe limitation to the utilisation of these alternative technologies. Of course, in these cases, any dematerialization or substitution of the main metals in their use will further limit the rate. On the other hand, not using the by-flow metals or storing them for future use will require a long-term environmentally benign dumping or final storage of these metals.

Table 8-4. Requirements and indicators of some metals for the solar cells in four energy systems, each based on a specific thin-film technology supplying 100,000 TWh/year, that is, roughly the global energy use today. Data from Andersson *et al.* 1998.

Technology Material	Metal Requirements [g/m^2]	Total metal requirement/ today's reserves	Annual metal requirement^a/ refined metals
Grätzel			
Ru	0.1	7.5	88
Pt	0.05	0.83	2.4
CIGS			
In	2.9	650	110
Se	4.8	30	12
Ga	0.53	25	48
CdTe			
Cd	4.9	4.6	1.2
Te	4.7	110	120
a-SiGe			
Ge	0.22	51	21

^{a}Annual requirement in the build up of the system is calculated as 1% of the total material requirement.

5. DEMATERIALIZATION AND METAL LOSSES IN QUANTITY AND QUALITY

Non-extracted metal resources are of course not expected to vanish and are thus saved for future generations. To the extent that any losses are avoided, also the extraction or use *per se* will not decrease the availability of the metals! Rather, the extraction of metal resources is in this perspective not a loss, but an investment, at least in the short run, with an associated cost. Put in other words: the extraction process of limited metal resources is not in itself a wasting of these scarce resources. Instead, the real losses of resources are those losses from the technosphere that imply future costs for replacements. Intergenerational justice must thus be met by low *system losses* in quantity, not necessarily less extraction. For metals the major system losses tend to emanate from *lack of recycling,* as was concluded in a study on flows and stocks of heavy metals in Stockholm (Bergbäck *et al.* 2001), and as shown in Figure 8-2, illustrating the copper flows in Sweden. Large flows of copper recovered by the waste handling system are not recycled but ultimately deposited in landfills. Another historically large loss of copper has been ground laid cables for electricity distribution and telecommunication which, when taken out of service, are considered too costly to recover.

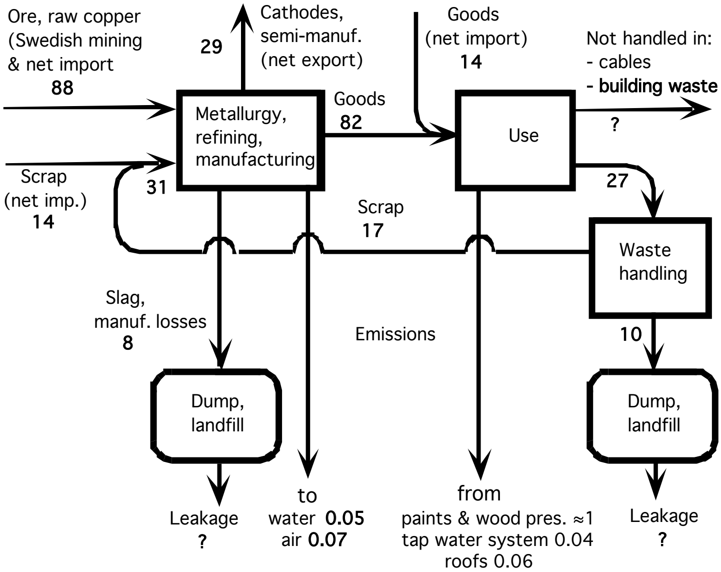

Figure 8-2. Flow of copper in the Swedish technosphere around 1990 (ktons/year). Based on Nilarp 1994.

If recovered for recycling, the metals are often recycled efficiently when it comes to quantity, as illustrated with the recycling and production system for lead batteries in Sweden (Karlsson, 1999). The quantitative losses from the recycling facilities and battery production parts of that system are small implying that the total system losses are dominated by lack of recovery of used batteries up to very high overall recovery rates, Figure 8-3.

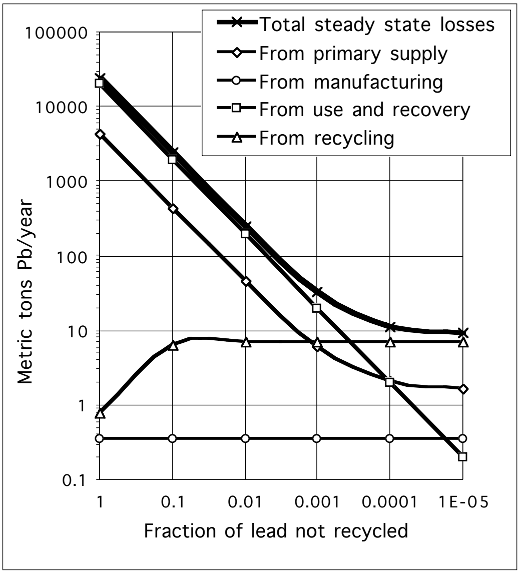

Figure 8-3. Steady state losses of lead from five subsystems of a modelled battery system for Sweden supplying batteries containing 20 000 tons of lead a year. The losses (y-axis) are shown as a function of the fraction of lead not recycled (x-axis). The model relies on lead flow balances data for the different parts of the actual Swedish production system. The recycling fraction is a model parameter, which can be varied. From Karlsson 1999.

However, when recycling metals there will possibly be a *down-cycling*, a qualitative degrading of the materials. Here down-cycling means that in a recycling process the outgoing material has a technical/economical restriction in possible reuse compared to the input materials. It is thus a quality indicator in connection to recycling or dematerialization. For metals, which due to their inherent properties have low vulnerability to structural wear even when intensively recycled, the down-cycling is mainly derived from mixing of various elements, either through inclusions of impurities accompanying the metal flows or through deliberate additions of various alloying elements. For instance, in lead battery manufacture in Sweden, only virgin lead has fulfilled the quality requirements set up by the manufacturers in the production of the lead paste, i.e., the chemically active materials in the battery. The recycled lead contained too high concentrations of impurities or alloying elements added to the lead in the production of battery grids or in other lead uses (Karlsson, 1999). Generally, the mixing of more precious metals into less precious metals, such as copper into iron and iron into aluminium, is most problematic.

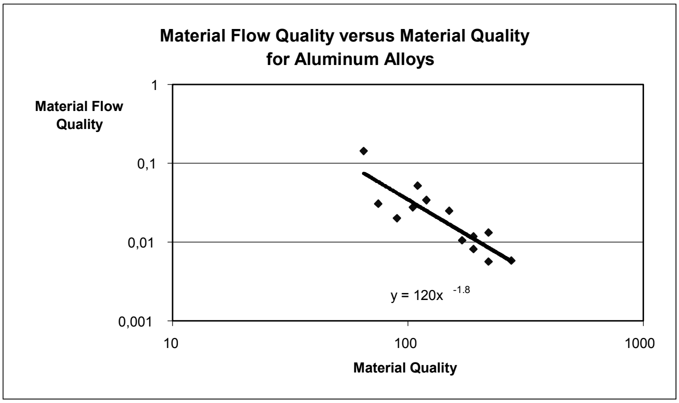

Figure 8-4. Material flow quality (measured as necessary dilution for recycling into all other alloys) versus material quality (measured as tensile strength) for aluminium alloys. From Holmberg *et al.* 2001

So far, to a large extent this quality problem has been hidden (or perceived as not acute) by the expansion in materials turnover and spreading of the industrial society and lack of extensive recycling. For the future, however, to achieve a dematerialization and a levelling out of the materials use, it will be necessary to develop and implement *materials flow quality* strategies (Holmberg *et al.* 2001). There is also a possible trade-off between dematerialization by increased quality in use achieved through increased and more diversified alloying and dematerialization by increased recycling made possible by avoidance of down-cycling, see an example in Figure 8-4 depicting aluminium alloys in Sweden. Unfortunately, so far there have been few materials flow studies addressing these pertinent questions devoted to quality rather than quantity.

6. CONCLUSIONS

Relying on the characteristics of metals in society and nature, we have in this discussion on metals and dematerialization indicated that:

- A dematerialization of the societal metals turnover will mainly lessen the upstream problems connected to production of primary metals: the large rucksacks and the large indirect flows such as energy associated with mining and primary production of metals.
- A dematerialization will not be effective in mitigating many of the problematic downstream emissions originating in connection with specific application of the metals in various consumer goods. Here transmaterialization or substitution is a more viable strategy.
- The scarcity and by-flow characteristics of many metals may pose severe restrictions on the possible large-scale global application of many emerging and

in other aspects environmentally benign technologies, especially in the energy sector.

- A dematerialization leading to an increased reliance on secondary instead of primary metals will require an increased focus on metals flow quality management to avoid down-cycling in the metals turnover.

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Chapter 9

SUSTAINABILITY STRATEGIES IN FIELD TRIAL

Results of the project 'Sustainable Metal Industry in Hamburg'

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The following will initially define the term sustainability, which forms the basis of this volume and the project 'Sustainable Metal Industry in Hamburg'[1]. The explanation of the objectives and the indicators at a very general level is kept as concise as possible. Much more important are the results of the sustainability strategies field trial conducted in co-operation with companies. Although there is an almost incalculable number of publications about the objectives of sustainability, about sustainability indicators as well as about agendas, plans and programmes, surprisingly little has been published that looks at empirical sustainability strategy field trials. Central to undertaking tangible steps in the direction of a sustainable metal industry remains the operationalisation of the sustainability concept, taking into account, on the one hand, the metals and how they are handled[2] and, on the other hand, the protagonist - the metal industry itself. Subsequently, there is a report on the empirical evidence gathered, within the framework of the project 'Sustainable Metal Industry in Hamburg', during an experiment to implement tangible sustainability strategies in one region. The main focus is on two aspects: reflections on the implementation and breadth of the sustainability strategies field trials *in cooperation with companies* and reflections on the possibilities and limitations of *'material flow management'* on metals and collateral material flows.

1. SUSTAINABILITY AND SUSTAINABILITY STRATEGIES

Sustainability is an objective with a high abstraction level and thus has great integration potential. The making tangible, the 'break down' into concrete feasible next steps is important if one wants to move closer to this goal, as is the compilation of indicators that can be used to evaluate projects and steps in the direction of a

A. von Gleich et al.(eds.), Sustainable Metals Management, 249-291.

sustainable economy. Sustainability is not a one for all time fixed goal. With regard to sustainability projects it is important to know whether and in what respect they are actually able to make a contribution to greater sustainability. Accurate orientation with regard to a ‘moveable target’ with a three-dimensional target area (ecological, economic and social sustainability) cannot imply more than that at least in the result the three ‘target vectors’ of the projects are pointing in the ‘right direction’.

Therefore, sustainability is *not* simply the extension of environmental policy or of Developing World policy under a new title. Although we encounter many of the issues in the sustainability concept, which have been under consideration for decades, they are and have been radically altered within the framework of this concept. Not a single issue, be it of a social, economic or ecological nature, emerges from the sustainability debate in the same form as when entered it.

The new issues in the sustainability debate centre on the following points:

- First the *long-term orientation and global orientation*. In our daily lives we do not often think about future developments over the next 30 or even 50 years on ‘spaceship Earth’.
- Second the *three-dimensionality of the goal*. Social, economic and ecological sustainability are of equal importance.
- Third the *orientation towards the carrying capacity* of the ecological, social and economic basis of sustainable development.

1.1 Sustainability as the Goal

Both in the public-political as well as in the scientific sustainability debate a defensive and an offensive understanding of sustainability can be discerned. In the defensive understanding, sustainability is a minimum condition for ‘future options’; to ensure that the limitations placed on the decisions of future generations are avoided as much as possible. From a ‘system theoretical perspective’ the formulation of the quote in the Brundlandt-Report: *“to meet the needs of the present without compromising the ability of future generations to meet their own needs”* [3] can be defined with regard to the defensive version of the sustainability goal as:

A sustainable path for the future is one that is able to reproduce its own requirements to exist and to at least prevent larger system collapses in the most important ‘support systems’ (i.e. ecological, social and economic sub-systems) of future societies. In this way future generations will have open to them decision-making options, which are as varied and as wide ranging as possible, not least with regard to the use and/or substitution of (non-renewable) resources.

Sustainability is, in accordance with this interpretation, a normative guiding principle that is immediately convincing and meets with general approval. But its formulation and design can now take place on a more functional level. The goal, therefore, sounds more abstract and the path to it appears rather technocratic. The depiction of a desirable future is largely avoided. But, this defensive functional sustainability goal is also characterised by social values. In the foreground stand the values of freedom (understood as ‘options at one’s disposal’) and intergenerational justice with a view to the inheritance that we leave behind for future generations both regarding material, social, institutional, cultural and ecological wealth as well as the corresponding damage, destruction and 'resources' that are no longer available.

A second fundamental element in this approach is the long-term and global perspective. The temporal and spatial dimensions are especially important for the weighting of problems and solutions. Very long-term up to irreversible effects have a greater weight than those that are short-term and more or less reversible. The same is true for extensive tending to global effects in comparison to those that impact a small, localised region. Particularly problematic are, all things considered, the creeping, slow developments that once they are taken seriously are so far developed that measures to counteract them come too late. Problems relating to the climate, bio-diversity and resources take this form. Thus the not directly perceivable but the long-term creeping problems and developments are the focus of defensive sustainability understanding i.e. those sustainability deficits for which the recognition and processing of scientific knowledge play a particularly important role.

An offensive sustainability understanding can be differentiated from the defensive sustainability understanding. It is imbued with all our wishes, hopes and utopias. It brings commitment and warmth to the 'sustainability movement' that is quite missing in the defensive and more techno-functional approach detailed above. However, this means that people with a positive intent, regardless of which movement they may come from, are all too quickly convinced that they 'have always' followed sustainability goals and they can carry on as before. In the offensive understanding of sustainability current and short-term intentions are much more integrated, starting with the eradication and/or narrowing of the income distribution gap within the industrial nations and to a much greater extent between 'North' and 'South', and ranging from the battle against the repression of indigenous cultures to greater equality between the sexes. Sustainable life and economies in this context is much more than a minimum condition, much more than the prevention of system collapses and the protection of carrying capacities. Sustainability in this case is much more positively cast and depicted. In this definition sustainability appears to supersede a very old metaphor: the 'good life' as already understood by Aristotle, but now without slavery and exploitation, and not at the cost of nature and animals, nor at the cost of people alive today, and neither at the cost of future generations.

1.2 Sustainability Criteria

Most of the national and international sustainability literature appears to be concerned with the objective of sustainability and with sustainability indicators[4]. Whether this is fruitful and justified on such a scale can in this instance be put to one side. In any case the setting of goals and the analysis of steps in the direction of sustainability are important whilst being extremely complex and correspondingly opaque. Within the framework of this project four fundamental elements were developed both with regard to these assumptions and the necessity of sustainability strategies that can only be touched on here. It concerns firstly the difference between varying types of sustainability problems (long-term, creeping, irreversible versus immediately discernible and acute) as well as the above-mentioned difference between a defensive and an offensive understanding of sustainability goals (maintenance of carrying capacities as a minimum condition for development capability versus the 'good life' as goal). Building on this, a raft of criteria is elaborated to evaluate sustainability paying particular attention to precaution. And finally – but still along the same differentiation lines of the problem – two varying types of sustainability strategies are depicted: control strategies and process strategies.

The criteria grid is composed of several levels (see table 9-1). Top-down, seven sub-objectives (goal-oriented criteria) are derived from the first level of the three-dimensional sustainability model. They are each supplemented on the second level by three criteria that are derived from very general system-theoretical thinking about 'system survivability in dynamic environments'[5] and by three criteria to put the precautinary principle into operation.

On the third level there are three criteria oriented toward carrying capacities and a further three criteria directed at impact models. Generated from the respective areas of operation, but in a counter bottom-up direction, additional criteria are derived in particular related to materials, processes and products[6].

The criteria on the second level are concerned with 'system management', especially various forms of system intervention and the resulting potential impact aspects. The objective on this level is ultimately an 'adequate' (object related) respectively 'adapted' system management in the sense of putting the precautionary principle into practice by taking the greatest possible cautiousness. The 'depth of intervention' criterion aims to define the opposite of this, i.e. the characteristic of extensive intervention with extremely wide-ranging consequences (up to global and irreversible).

Between the goal-oriented, theoretically derived criteria of the first two levels, on the one hand, and the carrying capacities and consequence-oriented criteria of the third level, not forgetting the individual aspects related criteria of the fourth level, on the other hand, some cover is created, but overall there is an immense gap that will only close at certain points. What remains is the problem of weighting. Weighting questions are value questions and therefore should be debated by society. A weighting in accordance with the spatial and temporal dimensions of the problems and/or consequences should be for the most part consensual. As is briefly illustrated below by the example of carrying capacity oriented criteria: The collapse of individual companies (being squeezed out of the market), the crash of individual social systems (marginalisation of some city districts), the crash of individual ecosystems (some ponds losing their ecological balance) would still be acceptable enroute to the sustainability objective if progress were being made in the other objective dimensions. Steps that equally benefit all three sustainability dimensions (real win-win-win steps) will remain the exception rather than the rule. But the bigger the endangered system and the more irreversible the damage, the more serious is the problem. A threatened collapse of an entire national economy or a whole social security system (e.g. health system, old-age provision) or the ecological imbalance of an entire sea should be avoided as a matter of principle. Thus global problems such as climate change are accorded a greater weighting than reversible and regional problems such as summer smog.

Table 9-1. Criteria Grid for an Integrated Sustainability Evaluation.

Four evaluation criteria levels	
I. Top Down	
1st Level (Objectives): Minimum conditions for a good life	a) Ecological, social and economic sustainability b) Derivate goals, e.g. Maintenance/increase of human, material and natural capital Sustainability optimised market functions Freedom, self-determination Justice (intra- and intergenerational) Health, quality of life Prevention of long-term contamination Maintenance of biodiversity
2nd Level (Processes): Development capability and precaution	a) System theoretical criteria for 'evolutionary capability', e.g. Reproductive capability Adaptability Effectiveness b) Precautionary criteria, e.g. Depth of intervention / error tolerance Entropic efficiency Consistency
3rd Level (concrete prerequisites): "Survival"	a) Carrying capacity criteria, e.g.: Macroeconomic stability, capability to reproduce human capital + natural capital Stability of regional company clusters Carrying capacity of social networks, social togetherness, democratic disposition Climate stability, critical loads Ecological footprint b) Impact model criteria, e.g.: Contributing to monopoly building Cancer-producing Acid rain Damaging to ozone layer
II. Bottom Up	
4th Level (Innovations): Small steps oriented to processes, products, materials and technology	Individual apects e.g.: Cumulative expenditure of energy Energy efficiency Noise reduction Pollution prevention Renewability Closing the loops (waste reuse) Recyclability Reparability Quantity and quality of jobs Job security

Similarly justice between the generations weighs stronger than within a generation and the long-term availability of non-renewable resources weighs greater than market price signals that currently suggest that recycling is unprofitable.

The spatial and temporal dimensions are depicted, as is generally known, as continua. There are no threshold values. With regard to certain problems, such as for example the maintenance of biodiversity, the spatial unit to which it refers to must be clarified. The dying out of species on the world stage is irrevocable and should with regard to the development chances of future generations absolutely be avoided. The same absoluteness is not applicable to the disappearance of species in certain regions. There is uncertainty regarding the question: how many regions we can so to speak 'accept as lost' without at the same time risking global extinction? The precautionary principle, which must be given special significance in sustainability strategies, forces us to be extremely cautious in this respect. With this in mind, it must be stated that at least for the problem areas 'loss of biodiversity' and 'accumulation of heavy metals', the differentiation between short-term, acute and regionally limited problems, on the one hand, and creeping long-term, global and irreversible problems, on the other hand, cannot be adhered to. Here the precautinary principle recommends avoidance as far as is possible.

As has already been mentioned, the debate about sustainability objectives and indicators can become as complex as you like. Unfortunately this often affects its practicability. The system of an objective, manageable, effective and as complete an evaluation grid as is feasible should be kept 'simple' if possible. This has been the aim here, in that on all levels the defensive understanding of necessity-oriented (i.e. the minimum conditions for sustainability) sustainability has been given priority. Thus the depiction of what is desirable, of a utopian 'sustainable economy' can be avoided to a great extent.

The criteria grid in table 9-1 is of course just an initial orientation attempt. More important than the concrete completion of fields is the structure of the grid, with its four evaluation levels as well as its combination of top-down and bottom-up approach.

1.3 Sustainability Evaluation

Usually criteria come in use within the framework of evaluation procedures and evaluation methods. Some ecological and economic evaluation methods are already comparatively well defined, however, in the social dimension much is still open. Cost-benefit-analysis (extended by the up until now neglected external costs), (eco)toxicological analysis, risk analysis and life-cycle-analysis are important, practical and established evaluation methods. Some methods such as (eco)toxicological analysis, risk analysis and life-cycle-analysis are already internationally standardised and regulated to a great extent. The (eco)toxicological analysis, risk analysis and the expanded cost-benefit-analysis also comprise aspects of all three sustainability dimensions. However, none of these methods are in themselves expressive enough with regard to the sustainability objective. A sustainability evaluation must in the norm revert to a methodology mix. The evaluation of the direction and results of sustainability projects is completed by a multiple iterative change in examination respectively evaluation perspectives.

1.3.1 Possibilities and limitations of life-cycle-analysis

When the subject – as in the sustainable metal industry project – is about materials and material flows the life-cycle-analysis is usually the dominant method. The life-cycle-analysis is extensively regulated and standardised, and at least takes account of the entire product life cycle. Very important observational work about the flow of material and energy streams has been conducted by the drawing up of inventories. However, the life-cycle-analysis focuses on the ecological effects. As the sole or just as the main evaluation method within the framework of sustainability strategies it is overstretched, even just looking at material flows.

The life-cycle-analysis lacks in particular:

- An approach to integrate the precautionary principle;
- an absolute measure for efficiency (system efficiency);
- a measure for the 'quality' (high-value) of recycling processes;
- a measure for resource consumption, or more precisely for the degree of resource debasement.

To at least overcome some of these shortcomings the development of entropy balancing as an addition to life-cycle-analysis was driven forward in connection with the project 'Sustainable Metal Industry' project. One of the interesting aspects of entropy balance is, without doubt, the bridging function role that the entropy concept plays between the scientific-physical point of view, on the one hand, and the economic point of view, on the other. Adding entropy balancing to life-cycle-analysis opens up an economic-social sustainability dimension in this evaluation method in that it seeks to understand the economic-social term 'consumption' as a scientific-physical concept.

1.3.2 Entropy Balances as an Extension of Life-Cycle-Analysis

In physical terms energy and materials cannot be destroyed. The conservative laws apply and with their help many of the gaps in the inventories of life-cycle-analysis could already be closed. Everything that enters into a system must remain somewhere. Either it accumulates within the system or it leaves it at some point. In a literal sense the application of the physical conservative laws for energy and materials means that there is no sustainability problem with regard to consumption. But here is where the 'qualitative' aspect of the second fundamental law of thermodynamics with regard to entropy comes into play. Although energy and materials cannot be destroyed their usefulness can be diminished or even wrecked. Higher order conditions, higher energy density and higher material concentrations, generally speaking conditions far from the thermodynamic equilibrium, are fundamentals for life and resources. With this in mind, when we consider the 'gradients' created by geological and biological evolution as the 'heritage of mankind', then their debasement as entropy production forms part of the core problem and evaluation concept of all sustainability oriented material flow management.

It concerns the quality changes that energy and materials are subjected to during their passage through the technosphere. Consumption in economic and technical terms means a diminishing of usefulness. The second law of thermodynamics can be successfully applied to many of the aspects of what we informally refer to as consumption. It can be used to describe the irreversibility and directionality of certain physical processes. Consumption in the sense of a diminishing of usefulness can thus to some extent be quantifiably measured as: entropy production[7].

A dissertation about copper production made a significant contribution in this regard within the framework of the research project 'Sustainable Metal Industry'. Using the example of copper production at the Hamburg Norddeutsche Affinerie plant (including an examination of the copper recycling process) it could be shown that although adding the entropy balance to the life-cycle-analysis was costly it was perfectly feasible[8]. As well as with life-cycle-analysis this approach permits efficiency potentials in companies to be traced as well as the weaknesses within whole processes to be identified and not only with regard to the absolute input-output-flows but also in respect of the connected debasement of energy and materials. More far reaching statements will only be possible in the future when additional competing (e.g. biological) copper concentration processes are balanced and these results can be related to the metallurgical procedures.

The move from input-output-flow observation to consumption observation i.e. to the loss of material quality is not only significant for metal *production*. It is strategically even more important for observing the *handling of metals in the technosphere* and especially for the evaluation of the *quality of recycling processes*. The German recycling and waste legislation refers constantly for example to 'high value' respectively 'high quality' recycling. A measure for this has, however, yet to be given. At present the economic connotation – i.e. the market value – sets the scene. However, the economic evaluation of recycling processes fails with regard to resource protection, as the completely unchecked deferment (externalisation) to future generations of the future rising cost of increasingly scarce respectively depleted resources still dominates. A 'diminishing of usefulness' must therefore be measured using other methods – e.g. with the help of the second law of thermo dynamics as entropy production.

This basic approach is illustrated in figure 9-1 below. The base level in the diagram represents the conditions of maximum entropy. If there were no concentration gradients on earth or in the earth's crust, if all metal ions were statistically evenly distributed across the earth's crust then we could and would have to mine for metal everywhere. Luckily this is not the case. Nature has carried out some preparatory work, which means that we can begin the production of a tonne of steel at a site where the concentration level of iron ore is on average over 50%. We must make use of energy and materials to mine the ore and to produce steel. However, we do not only produce steel but also the inseparably linked entropy that is represented in the diagram as entropy stream 1. If we were then to put the derived tonne of steel, for example without corrosion protection, in a corrosive environment (e.g. in sea water) within a short time the won level of 'order' would be completely dispersed in the direction of the above mentioned statistically even distribution in the sea water or in the sediment. We would have then simply squandered the heritage of mankind. For the most part we do not do this; instead we are able, at the end of the first usage cycle, to recycle the steel. Of course, recycling also requires the input of materials and energy and we must always expect dissipation losses. In the diagram, represented as entropy stream 2, a 90% steel recycling per cycle would certainly be a very good result, but unfortunately at present the losses are significantly higher. Additionally we are still far from being able to realise the ideal recycling at the same level of quality as outlined in the diagram. Due to the contamination by impurities (tramp elements) such as copper or tin, at least with regard to the recycling of 'old scrap' a steepening 'downcycling' in the steel life cycle occurs, as is indicated by the broken line. Definitive sustainability via the use of non-renewable raw materials is impossible; at most a 'respectable extension' of their consumption can be achieved. We will concentrate on this. It, therefore, concerns three areas: (1) high resource productivity (greatest possible use by society per generated tonne of steel), (2) effective recycling with the least possible dissipation losses and (3) the prevention of qualitative debasement (e.g. through pollutants). A worthwhile goal would be, for example, a 'tendential ecological amortisation' of the primary costs of metal production during the usage phase. If entropy stream 1 resulting from primary production is much bigger than the entropy streams 2-5 resulting from recycling then although the 'ecological rucksack' of the accumulated emissions, wastes and dissipation losses grows ever larger in absolute terms, with regard to the individual usage cycle it shrinks in size.

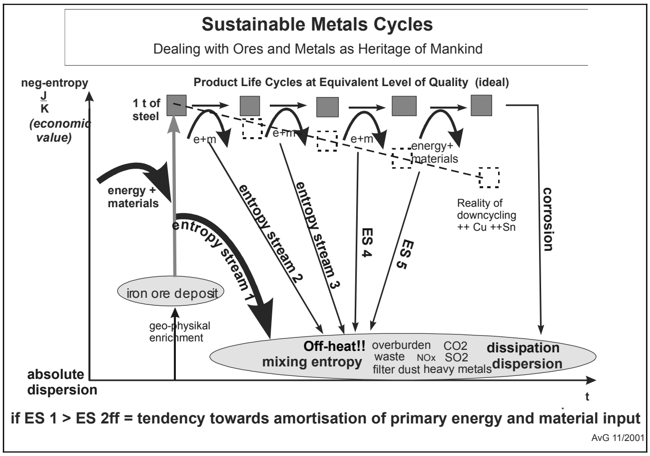

Figure 9-1. Entropy balance as an evaluation method for handling resources

This is certainly an interesting effect and in sustainability terms an attractive objective, even when we do not want to go so far as to speak of 'tendential ecological amortisation'[9].

In principle, therefore, entropy production should be related to the connected 'social uses'. This is anything but simple, first because the balancing of the entropy production requires more data than for the life-cycle-analysis and second because the 'ecological amortisation' objective aims to build a bridge between scientific facts and socio-ecological questions about social uses.

1.4 Sustainability Strategies – Control Strategy and Process Strategy

The metal industry's most far-reaching long-term sustainability problems are related to securing inputs (primary and secondary resources) as well as to nature's carrying capacities for its emissions and waste as part of its output (e. g. greenhouse effect). The most urgent sustainability problems at present apply to mid-term social, economic and ecological problems, current health and social problems, to justice between the generations currently alive (here and especially with a view to the North–South divide) as well as local and/or regional intrusions in ecosystems due to open-pit mining.

Both the strategy types – control and process strategy – reflect different system models as well as the differing understandings of the sustainability objective. In the defensive understanding of the sustainability model, the **control strategy** is oriented to preserving the minimum conditions of development and focuses strongly on carrying capacity questions. It is concerned with the 'preservation of options', and looks to a future where at least the larger system collapses are prevented (see figure 9-2).

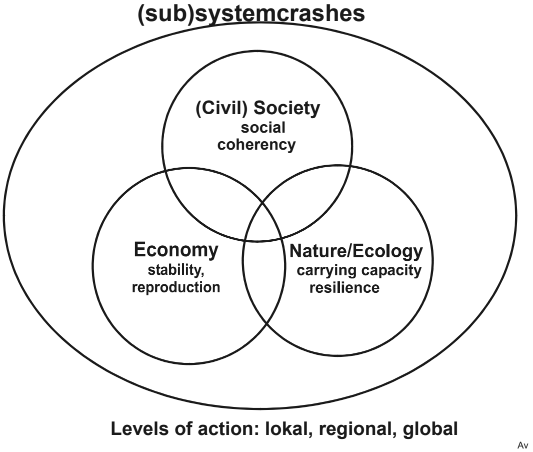

Figure 9-2. Sustainability as a way into the future avoiding (sub)systemcrashes

The control strategy is, therefore, concerned with the minimum conditions, with the essentials. Imperilment due to reaching or exceeding the limits of carrying capacities is, however – as we know from the greenhouse effect – mostly not immediately recognisable. Developments are likely to evolve slowly, with effects that are only expected in the future, but when they do appear they are usually irreversible. Scientific knowledge, therefore, plays a very important role in control strategy both for observing problems as well as for resolving problems.

Carrying capacities do not only determine ecological systems. Breaking points also exist in similar forms in the social and economic systems. Critical variables and therefore criteria for carrying capacities include the carrying capability of social networks such as social security systems, the social togetherness of a society that maybe linked to defined conditions such as the strength and range of social solidarity as well as macro-economic stability or the robustness of the democratic disposition of political units. In the economic sphere the capability of economic systems to reproduce their own natural and socio-cultural preconditions certainly plays a central role. This is particularly true in the case of the reproduction of so-called 'human capital' to guarantee family reproduction as well as education and qualifications. In all these areas minimum conditions must be fulfilled to ensure 'sustainable development'. However, there are few areas at present where such a carrying capacity can be formalised and quantified[10].

Within the control strategy framework, science has a comparatively important role with regard to the observation of creeping developments and the research into minimum conditions and carrying capacities. National and international institutions also play a leading role in the control strategy in that they are committed to 'taking precautionary measures against damage by their citizens'. It is well known that the United Nations took the initiative in a bid to tackle climate problems by setting up the Climate Change Convention; this has since been outflanked and expanded by national strategies and by the self-imposed pledges of economic players.

The control strategy has, however, to battle with specific problems. The main difficulties lie in the restrictions related to managing complex systems and the limited knowledge about carrying capacities. The unknown can be divided into the 'not yet known', on the one hand, and the 'not knowable', on the other hand. Research can convert the 'not yet known' into future knowledge. But there are also areas that are in principle not 'knowable' such as, for example, the precise and wide ranging what-if capability about the behaviour of complex dynamic systems. Regarding the objectives of a 'Sustainable Metal Industry' the holes in the 'not yet known' are evident, especially a propos the long-term availability of resources, on the input side (in this case energy and raw metal materials, but also atmospheric oxygen and water) as well as (moving into the not knowable) on the output side in the global and regional carrying capacities for the emissions and waste of the metal chain. The situation in terms of control strategy has a certain irony. It is, on the one hand, dependent on scientific knowledge and has, where it works, the advantage of a science-based political strategy. But on the other hand, the most interesting questions, namely those about the carrying capacity of various complex (sub) systems, very quickly come up against the limits of what is knowable. System models – as important elements of the same within the framework of strategies moving towards a sustainable metal industry – especially energy and material flow balances but also energy and material flow models on the various spatial levels (company, regional, national and global) can still provide an understanding of the fundamental links between the key components.

This type of strategy has a third but major problem in 'motivating' and mobilising its protagonists, both its main protagonists – scientists and state officials – and to an even greater extent other economic and civil society protagonists, due to the often creeping, not immediately perceptible nature of the problem, which is the main focus of control strategies. This problem is also attributable to its more instrumental and even technocratic approach. Scientists and state protagonists (member of the community of states respectively) on their own do not have the means to implement wide-ranging (precautionary) measures. This is one of the main reasons why control strategies in isolation are unable to resolve most sustainability deficits and must be combined with elements of process strategies.

In contrast to the defensive management strategies that focus on the essentials, on the minimum conditions and the maintenance of actionable options, the **process strategy** can be characterised as ‘offensive’. It is more concerned with the desirable, with the ‘good life’. The sustainability objective in this type of strategy includes all those goals that have for a long time ‘moved’ people: security, material wealth, physical and psychological well-being, cultural development opportunities, justice and freedom not only with a view to the future but also for generations currently alive. Instead of being (primarily) oriented toward carrying capacities that are essential for *survival,* desirable utopias are formulated, which go to make up the ‘*good life’.* The sustainability objective should have motivational power, for this it must have life breathed into it, or so to say imagined. Only with the mobilising power of ‘tangible utopias’ can the sustainability debate breach the current audience, which is still mainly limited to a few specialists (e.g. scientists such as climatologists, as well as political and economic protagonists). What should a ‘sustainable life’ in Germany or in Hamburg look like in fifty years time? Or sector specific, how do we envisage a sustainable construction and housing sector, sustainable mobility or a sustainable metal industry?

The protagonists of the process strategy are spread far and wide, and are not limited to the specialists that dominate control strategy. A large part of this strategy is public debate, the thrashing out of ideas at the proverbial ‘round table’. Targeted network and cooperation building, the establishment of institutional overlapping communication, negotiation, consensus finding and knowledge transfer processes are also possible building bricks for this procedure. The protagonists of the process strategy derive to a much greater extent from civil society i.e. from the associations and initiatives of ‘the people’. At the ‘round tables’, where time and again the common targeted goals and the next common steps are negotiated, committed citizens such as representatives of the unions, environmental groups, Third World groups, citizens’ rights groups and consumer organisations sit together with the representatives of state institutions, the scientific and business worlds. Also within the framework of the project ‘Sustainable Metal Industry’ that right from the start was geared towards strong cooperation with economic protagonists, with the companies of the region, the civil society protagonists played an important role, admittedly less in the individual company and inter-company field projects but in both the discussion platforms that were set up at the same time as the project, in the lecture series ‘Sustainable Metal Industry’ and in the ‘Forum Sustainable Economy Hamburg’ that emanated from the project advisory board and is based at Hamburg’s Chamber of Commerce.

2. POSSIBILITIES AND LIMITATIONS OF MATERIAL FLOW MANAGEMENT

In a further step – against the backdrop of the above-described differentiations – those elements of the sustainability strategies that deal explicitly with materials and material flows will now be more closely examined. It is the material flow management approach [11]and – within this framework concept – the more quantitative efficiency strategy and the more qualitative approach that forms a consistency strategy or 'industrial ecology' respectively.

The project 'Sustainable Metal Industry', as can be seen from its original title 'Efficiency Gains Achieved Through Cooperation to Optimise Material Flows in the Hamburg Region', was conceived in close connection with the approach of material flow management and within this framework of an efficiency strategy. The more we occupied ourselves with this strategy, in which the handling of materials and material flows were the focus of attention, the clearer the associated limitations of the sustainability aspects under examination became. The ecological view took centre stage, while the economic aspects of material flows also played a greater role as did health. Thus although all three sustainability dimensions were still integrated, the greatest weight was given to the environmental dimension and – with corresponding holes – to the economic and the social dimension.

2.1 Examples of Two Field Trials

The starting point: opportunities and limitations of material flow management projects in cooperation with companies will now be sketched out with the help of two field trials. Following on from this the concept of material flow management will be incorporated in our theoretical setting, and further possible developments will be discussed.

2.1.1 High Quality Abrasive Slurry Recycling

Abrasive slurry is a particularly problematic waste while also being a potential resource. Due to its disadvantageous geometry and the comparatively high proportion of contaminants, this iron metal component is mostly left out of the secondary steel recycling process so that here a relevant loss is notable. Cuttings and abrasive slurry that is covered with coolant lubricant must first have the oil removed and then be pressed and sintered, so that it is in the correct condition to be directly reused in the molten baths of electric steel works. Interestingly, in a regional context, a pilot plant to sinter abrasive slurry already existed, which was subsidised by Schleswig-Holstein's Environment Ministry. The plant operator was very keen to be able to actively communicate the sustainability advantages of his process in a local context with potential purchasers of sintered materials. The eco-balancing and modeling of the recycling outcome offered by the project, using the platform of the regional sustainability debate in the metal industry accompanying the project, was seen as a very good way of graphically explaining the outcome of closing the gaps in recycling abrasive slurry. With the help of modeling and balancing the process the ecological and resource conservation advantages of this process respectively are shown to good effect. Unfortunately the plant operator subsequently had to declare bankruptcy due to an earlier unfortunate financial problem. The difficulties were compounded in that he left behind a considerable amount of unprocessed abrasive slurry at his industrial works. This included very problematic "pollutants" that during the Elbe flood in 2002 resulted in negative national press headlines as the plant was located on the banks of the Elbe.

2.1.2 Minimum Quantity Lubrication

The sub-project on coolant lubricants was also initially significantly affected by waste disposal problems; and here too (similar to the abrasive slurry sub-project) the pressure of ecological problems due to earlier inappropriate waste disposal which, because of the consequent internalisation of previously external costs, appeared as a financial pressure due to rising handling and disposal costs (additional costs for special storage, emulsion maintenance, cleaning of parts and machines etc). In addition, occupational health and safety also played an important role. All three sustainability dimensions in the sub-project were hugely tasked. Therefore, a solution to the evident sustainability deficit in this sub-project was also not looked for in an improved waste handling or recycling process but in its substitution, i.e. in reducing and/or avoiding the problem respectively. The use of coolant lubricants was almost entirely avoided by minimum quantity lubrication. Only an infinitesimal amount of lubricant is yielded directly and evaporates during the process. That means, with regard to the function of coolant lubricants, that the cooling and removal of turnings must be achieved using another method.

The implementation of so-called minimum quantity lubrication in the metal cutting process resulted, on the one hand, in an efficiency increase (and by as much as a factor of 1000, when taking into account the problematic use of lubricant coolants). On the other hand, for the participating companies it involved huge technological and extensive organisational and technical innovation even if from a national point of view the introduction of minimum quantity lubrication can be described more as a diffusion of an already existing technology and procedure respectively[12].

A key condition for the practical success of this sub-project within the framework conditions set out for the SME manufacturer was the already long-standing cooperation with the Institute of Production Engineering at the University of Applied Sciences Hamburg, on the one hand, as well as with a number of regionally based metal processing SMEs and the Association of German Machine and Plant Manufacturers (VDMA), on the other hand. The activities within the orbit of the project were thus able to link in well with existing technology networks. On the back of previous successful cooperations and many personal contacts, the pioneer companies also ventured to restructure production relevant (bottleneck) aggregates. In the meantime many of the processing centres are now 'run dry'.

2.2 Efficiency Strategies and Material Flow Management

As in the above-described examples most of the material flow management projects to date have either looked at waste flows or targeted an improvement in the resource efficiency of internal company processes. Admittedly from the viewpoint of sustainability the much more far-reaching concept of an improvement in resource efficiency along the entire product line is desirable.

The eco-efficiency strategy can be understood as a reaction to the various restrictions of environmental policy in the 1970s and 1980s and an attempt to overcome them. An important foundation for the original conception of material flow management was without doubt the waste problem (see Spangenberg; Verheyen 1996, Strebel 1998). However, for a long time now it has not just been about the handling of waste or waste prevention (and even then looking at the entire value creation chain) but about an optimization of material flows along the whole value creation chain. Here, it is clear that the parallel breakthrough of the life cycle analysis concept with its view of the product life cycle 'from the cradle to the grave' helped to push this forward. A second important point was overcoming an approach focused on the protection of different environmental factors like water, air and soil. It was important to opt for an all encompassing view of environmental factors to avoid merely shifting the problem between them. In this respect the efficiency strategy and material flow management can also be seen as elements of the move from the end-of pipe policy to process and product integrated environmental protection. And finally the switch from a qualitative view focused on the (eco)toxicological effects of individual substances to a quantative observation of larger material flows played an important role in the career of the material stream management concept. The latter was a reaction to the restrictions and the immense unsolved scientific problems such as knowledge about the (eco)toxicological effects as a precondition of chemicals and materials policy, on the one hand, and to the findings that (eco)toxicologically comparatively harmless materials such as nitrogen, phosphorous or CO_2 and also water consumption and earthworks can lead to big environmental problems when they result in large flows on the other hand[13].

The greatest potential and success of the efficiency strategy and material flow management lies in the 'rationalisation', in the tracking down of efficiency potential and the optimisation of existing processes and products. Both approaches can be implemented in individual companies but their true sustainability oriented potential really comes to the fore when they form part of an intercompany value creation chain or an entire product life cycle[14].

A major objective of the efficiency strategy oriented toward a sustainable economy is the increase in resource efficiency or resource productivity respectively. This means producing the same amount or even more products and services with a smaller input of materials and energy. Boosting efficiency is common practice in everyday business life as it can immediately result in cost savings (rationalisation). The efficiency strategy aimed at achieving a sustainable economy rests on the theory that in everyday business life there are still untapped and/or undiscovered potential efficiencies, which could be put to better use if a greater effort were made. Targeted intra and intercompany analysis of material and energy flows and also an adjusted (flow) cost accounting[15] would uncover these potential efficiencies. Already the simple analytical linking of purchased input streams with the contrasting fees to handle waste flows clearly highlights the cost saving potential that was never seen before[16]. Storage and handling costs offer further interesting potential. The efficiency strategy opens up classic win-win situations with the realisation that whilst protecting the environment cost savings can be achieved (Huber, 2001: 309).

The efficiency strategy corresponds to an important element of corporate everyday logical – that of rationalisation. Thus its projects were relatively easy to integrate into company practice, as:

- ‘rationalisation’ procedures in the business world are known and established,
- in practice the changes affect individual processes and are thus technically easy to manage,
- they are often the responsibility of just one department or a recognisable number of people and are therefore organisationally easy to implement,
- they can be integrated into the process technology investment cycle and are therefore (if at all) accounted as “additional costs” of already planned investment (economic efficiency),
- as an incremental innovation their effects are easy to forecast (little risk) and easy to manage (performance control) and,
- they can often be realised in the short-term.

The first critical reactions to the concept of material flow management were more related to its technocratic connotations. Material flow management – that sounded initially like ‘planned economy’. This initial criticism may have been unjustified but the material flow management concept does contain a claim that with the help of this ‘instrument’ rationality with respect to material flows will finally break through. The accusation of a planned economic approach and the overestimation of the management possibilities in the real economy was countered with the ‘definition’ from the Enquête Commission, which much more realistically spoke of ‘influencing’ the material flow: “The management of the participating protagonists’ material flows is understood as the target-oriented, responsible, holistic and efficient influencing of material flows whereby the set targets stem from the ecological and economic areas, whilst taking into account social aspects. The objectives are developed at company level, in the material flow chain of participating protagonists or at state level[17]. Another definition reads as follows: “Material flow management targets the ecological and economically efficient influencing of material flows whilst taking into consideration social aspects. The point of departure is as comprehensive as possible material flow analysis that allows an evaluation of all the environmental factors. Building on this, strategies can be developed to achieve the set targets. In principle it involves lowering the material throughput across the entire economy and the reduction and substitution of environmentally dubious materials”[18]. If material flow management is to be successful, then material flow analysis cannot just be limited to the analysis of material flows but must from the beginning aim to represent the protagonists’ relationships or at least look at and understand them[19]. Even if time and again it looks as if the efficiency strategy is the main avenue to a sustainable economy it must be noted that this route also entails clear restrictions.

Although without doubt numerous – and in part quite considerable – unused potential efficiencies are identified not just within a company but particularly business-to-business, the decisive obstacles and restrictions, as seen by experience, are not due to the fact that these potential efficiencies lie undiscovered. Rather the chief restriction is the (in)ability of companies to make good use of this potential. A final decisive issue for the success of the efficiency strategy is seen time and again in the *innovative ability* of companies and or company networks.

Many efficiency improvements run along established technical routes and relate to established industrial arrangements (products and processes). The necessary expenditure on these routes for further efficiency improvements do grow exponentially with success, which means that the achievable *marginal utility* of further efficiency improvements is rapidly sinking. Really radical reductions in material and energy expenditure, in these cases can only be achieved if the route is changed i.e. through radical innovation. There is also the danger that the achievable efficiency gains through the growth effect or the rebound effect are negatively overcompensated. These unwanted side effects must be taken into consideration when comparing the effectiveness of the efficiency strategy with the negative trends. Looking at the danger of overstraining the ecological carrying capacities, only the absolute total emissions value is relevant and not merely individual product or process specific improvements.

The range of efficiency strategies is dependent on so-called *learning curves,* S- or life cycle curves that can be observed during the development of many different ecological and social systems. If the efficiency improvement of these systems is applied over time then a S-curve results. After a fundamental restructure (basic innovation or capturing a new ecological niche) rapid growth and improved system efficiency are relatively easy to achieve. Over time, however, these improvements diminish until they asymptotically near marginal utility.

In short the efficiency strategy has to battle with the following problems:

- A deep-rooted dependence on innovative ability
- Efficiency improvements along a technology or product line that trends to a structurally conservative approach
- An increasingly problematic cost-benefit-ratio along this route (shrinking marginal utility)
- Focusing only on partial areas of the systems while the overall system optimisation is not taken into consideration
- The rebound effect, which can nullify or outweigh the positive effects.

2.3 Consistency Strategy and Industrial Ecology

Within the framework of the efficiency strategy it is the quantities of material flows that take centre stage. Meanwhile the consistency strategy looks more closely at the quality of the material and material flows. In other contexts the consistency approach is also called eco-effectiveness[20]. The link between both strategies is a specific material flow management approach, via which a (mostly regional) networking of various material flows is targeted enabling the waste of one process to be used as the raw material for another process close by. The above approach is known as 'industrial symbiosis'[21]. With its orientation towards an attempt to integrate anthropogenic metabolism into 'nature's metabolism' the consistency strategy goes significantly further[22].

The *consistency strategy* aims to structure the quality and quantity of metabolism between the technosphere and the ecosphere so that the social metabolism is qualitatively and quantitatively compatible with the natural metabolism. This can, on the one hand, be achieved through a targeted and as extensive as possible reuse of recycled material in the technosphere (sealing with regard to the ecosphere, recycling, closed loops, closed systems) or, on the other hand, through a conscious opening up to the natural metabolism e.g. via a conversion to renewable energies and material sources, to a 'solar' economy based on the sun's energy and biomass in accordance with the corresponding 'sustainable' carrying capacities. The consistency strategy is dependent on much more radical innovations than the efficiency strategy. The consistency strategy is not only concerned with efficiency improvements in existing technologies and product lines, but also with a structural change driven by basic innovations in technology, products and organisational structures.

The advantages of the consistency strategy include:

- A high potential to protect the environment by optimising the entire system,
- Orientation towards the qualities and quantities of the natural metabolism,
- Orientation towards innovation abilities and fundamental innovations.

The disadvantages of the consistency strategy include:

- Difficulty in forecasting the effects of fundamental innovations and thus there is a high risk of failure.
- That its realisation usually has to fulfill multidimensional framework conditions, which include:
  Opportunities for creative interdepartmental work within and between companies.
  Trust-based cooperation with companies in the production chain.
  Greater organisational expenditure to convert systems.
  Dependence on windows of opportunity against a backdrop of differing investment cycles in the various companies.

The above-mentioned restrictions of the consistency strategy are, however, not just typical for this special strategy. They are also the restrictions, which it seems all innovations in the economy have to battle with, regardless of whether the targets are new markets, cost cutting or reducing ecological impacts. The consistency strategy has a specific standing within the current environmental innovation debate as it pushes forward the ecological modernisation discussion (Huber 2001: 314). It is, therefore, part of a series of similar approaches that today are increasingly integrated in a broad understanding of the term *Industrial Ecology*. Industrial ecology is oriented toward the structure of industrial production systems using ecosystems as the ideal, where particular attention is paid to the use of renewable material and energy sources in a highly efficient recycling economy and the rapid degradability (compostability) of the few remaining residues[23].

2.4 Limitations of Regional Material Flow Management and the Regional Networking of Material Flows

The 'regionalisation of material flows', a restricted if not closed regional material recycling system is often seen as a major objective of material flow management. This is even truer for the already mentioned model of 'industrial symbiosis'. The regional networking of material and energy flows in Denmark's Kalundborg served and still serves today as a much admired and much quoted model of such 'industrial symbiosis'[24]. Attempts to strategically implement this model have, however, to battle with much greater problems and restrictions than is the case for the significantly broader and more flexible efficiency strategy. Today, regional industrial complexes (clusters) are rarely (if at all) planned on the 'drawing board'. They are also much less likely to be newly set up on 'greenfield sites'. In most cases the opportunities for this are limited to already existing companies networking their own energy and material flows[25]. In a sub-project looking at 'high value abrasives recycling' such a regional networking within the framework of the project 'Sustainable Metal Industry' was at least partially successful.

2.4.1 Example: High Quality Blasting Abrasive Waste Recycling

Blasting abrasive waste is compared with abrasive slurry, at least with regard to its material composition, comparatively 'pure'. Its particular problem lies much more in its structure. The minuteness and the relatively large surface of the iron particles on the one hand lead to 'acute' toxicological problems due to the inhaled dust's ability to enter the lung, and on the other hand it can be the cause for an almost explosive oxidation process. To be able to recycle blasting abrasive waste it must be compacted otherwise it cannot be smelted. To date the resultant blasting abrasive waste of a partner company was packed in accordance with precautionary safety measures and transported to the Ruhrgebiet to be recycled. To begin with the sub-project only investigated whether or not a closer recycling location could be found. But then came the idea, in cooperation with the Institut für Werkstoffprüfung und Werkstofftechnik at Hamburg University of Applied Sciences, for a much higher quality form of recycling. As the abrasive waste was already in the form of powder, the recycling process should strive to reuse not only the valuable resource but also its particular structure. In fact a company in the region was found that manufactures friction linings based on powder metallurgy, and which expressed an interest in undertaking a pilot scheme. The suitability of blasting abrasive waste as an input material to powder metallurgically manufacture friction linings was successfully confirmed in the experimental run. Two not untypical factors then brought any further advance to a halt. First a quality management system in accordance with ISO 9000 was in place at the friction linings manufacturer, which among others supplies the aerospace industry. It remained unclear until the end in how far the use of 'waste' as raw material could be 'certified'. Further, doubts were raised regarding the supply dependence resulting from regional networking to obtain raw materials, as this meant that the company became dependent on the 'waste production' of another company. The articulated problems related, on the one hand, to quality and, on the other hand, to the 'supply reliability' of waste as a 'raw material'.

The sub-project came to a standstill. The anticipated cost advantages (free raw material) were clearly unable to outweigh these concerns.

Overall, the above outlined experiences seem to show that the goal of a regional tie-up of material recycling is unnecessarily restrictive. The smaller the region, the narrower the room to manoeuvre, the more unlikely a useful association of the occurring material flows. There are many indications that this type of tie-up only promises sustainable success in a considerably larger spatial dimension[26]. In the meantime, many empirical projects have also clearly shown that transport costs do not have such a high weighting in either ecological or economic terms that for this reason alone there should be a greater regionalisation of material flows. And finally, experience in the chemical industry, which has over many years optimised the linkage of its material flows via so-called 'coupled production', has demonstrated that such a tight networking of material flows can impede innovation. Every small alteration in such a highly efficient network system has far reaching consequences for the whole system[27].

2.5 Change in Perspective When Observing Materials and Material Flows

Comparatively independent of the possibly too narrow an option of 'learning from nature' and the ensuing too narrow a conception of material cycles is the impetus, with regard to the qualitative aspect of material flows, generated by the consistency strategy. This impetus is important for the project 'Sustainable Metal Industry' even when looking at metal material flows and their attendant material our focus was not on finding more environmentally friendly (more consistent) materials and processes. Material substitution did not come within the focus of the project. With the exception of a few auxiliary substances in the areas of surface cleaning, lubricating and coating, alternatives based on renewable resources are neither in the offing nor appear fundamentally necessary for a sustainable metal industry. Meanwhile, putting quality on a pedestal when looking at metal recycling is of extraordinary, but unfortunately at present almost completely underrated, significance.

Limitations of Quantitative Flow Analysis

To date, material flow analysis and the resultant material flow management has concentrated on input-output quantities or flow rates respectively, be it at the level of products (as inventories in life cycle analysis or as material input per service unit (MIPS) when determining their ecological rucksacks), of companies (with regard to environmental management and company material flow management and environmental controlling respectively) or at regional and national levels (as material flow analysis MFA or of material flow management at a corresponding spatial level). In general just the 'input' or flow rate respectively is measured and modeled, even though confusingly this is often referred to as 'consumption'.

Input-output and simple flow observations respectively concentrate on interfaces between the ecosphere and the technosphere. How much is taken from nature versus how much is returned to nature as emissions into air, water and earth (waste). As has already been mentioned in the discussion about the limitations of an efficiency strategy, the most far-reaching potential innovation oriented toward sustainability lies in the handling of materials and energy in the technosphere i.e. in process and product design. Strategies that concentrate on the interface between technosphere and ecosphere, especially emission, waste and resource policies are without doubt important elements of an integrated sustainability strategy. The decisive changes and innovations enroute to a sustainable economy do not involve transitions between technosphere and ecosphere but the handling of materials and energy within the technosphere. It is here that usage patterns and lifestyles can be seen, as can the development, formation and usage of products and processes (from process and product integrated environmental protection to an integrated product policy IPP), the technology policy as well as the conditions and range of innovations. If it is correct that small efficiency improvements along an established technology path alone are insufficient for far reaching steps in the direction of a sustainable economy, if it is about changing the path and to achieve an integrated examination of the technical (related to materials, processes and products), organisational (management systems) and institutional innovations (arrangements, governance) then light must be thrown on the topic of handling materials and energy in the technosphere.

Consumption as Loss of Quality

An example, which was considered in depth in the project Sustainable Metal Industry, is the enrichment of impurities in metal recycling, especially those impurities that with the existing and foreseeable available technology cannot be removed (this includes in particular copper and tin in steel and aluminium). These contaminants result in significant 'losses in usefulness' of the respective materials[28]. The pressure to overcome the currently dominant pure quantative flow observations of material flow modeling and material flow management, relates not only to illuminating the black box to, for example, harness far reaching potential efficiencies and innovations when 'handling energy and material in the technosphere' but also to the qualitative aspects of 'consumption'. Entropy production is able to deliver a practical measure in most cases.

With regard to this quality aspect, in future, there will have to be a change in focus and expansion of the observation, modeling and management of metal material flows from a concentration on the quantity of recycled metal to a greater consideration of the produced and in particular the quality of recycled metal.

2.6 Material Flow Models as a Basis of Information for Sustainability Strategies

Observations of metal flows and metal cycles over the entire product life cycle, of raw material demands, metal production, product manufacture, product use and disposal or recycling respectively play a central role when considering the questions thrown up by the project 'Sustainable Metal Industry' about problems, perspectives and projected solutions in the various spatial and temporal dimensions. Static and, provided that they are feasible, dynamic models of these material flows provide important information about:

- Development of resource ‘consumption’ and as the case may be resource availability.
- The accumulation of metal supplies in the technosphere, in which above all products and scrap metal make up the technical reserves (the so-called stocks).
- Accurate recycling rates.
- The size of dissipated losses in the environment and in other anthropogenic material flows as well as the ‘spots’ they come from.
- Weaknesses (especially high consumption and losses) and the thus very suitable areas to improve efficiency.
- Assessable effects of (possible) ‘material flow management’ measures.

Within the framework of our research project we were able, nonetheless, to make two contributions to the balancing and modeling of metal material flows. As a national model of the steel cycle was not available – we must after exhaustive research assume that one does not exist yet – we developed a simple model to be able to simulate the accumulation of the tramp element copper at various recycling ratios over a longer period of time. In addition, an important step was made with the entropy balance of copper production, using the example of Norddeutsche Affinerie, towards the integration of the qualitative and for the sustainability debate central consumption aspect.

2.7 The Role of Material Flow Models to Communicate Long-Term Problems – The Example Copper as a Tramp Element in the Steel Cycle

Apart from the dissipative losses of metals in the ecosphere, which are painful for two reasons – as a loss of valuable resources and as contamination of organisms and ecosystems – a second aspect of the ‘consumption’ of metals has come to the fore recently, namely the usability loss of certain metal qualities. Certain impurities, the so-called ‘tramp elements’ – the most well known of these are copper and tin in steel or aluminium – but also consciously and specifically added alloys, cannot be extracted from molten metal with the current technically and economically feasable tools. This leads to an accumulation of these impurities in the metal recycling process. The tendency to accumulate impurities when recycling metal, as a result of scrap metal inputs, is in contrast to the fact that the further developed technical practice requires ever greater purity and specifically defined alloy quality.

The distinction between immediately perceptible sustainability problems that affect people now and very far reaching but slowly worsening sustainability problems has been mentioned several times already. In connection with the debate about promising strategies, the practical problems of company cooperation will now be highlighted assuming that the aim is to move the gaze and attention towards those long-term problems that at present do not pose an imminent pressure. As mentioned previously, science has an important job in researching and clarifying the dynamics of those problems. We were able to achieve this in a sub-project of the project ‘Sustainable Metal Industry’ that looked at contamination in steel recycling with regard to the impurity copper. However, it was only possible because first we prepared sundry conditions.

The problem of contamination has been well known for a while. It is talked about in every metallurgical foundation lecture. In practice, it is mainly electro-steel works and secondary aluminium works, which mostly produce goods from scrap metal that have to face the problem. To date, they successfully 'resolve' the problem by either thinning with 'virgin materials' (to be able to maintain the threshold value for better quality material, which is financially more interesting) or via the targeted outward transfer of impure secondary materials in applications with lower purity requirements. The common practices thus push the problems into the future. This is anything but sustainable and a typical case of cost externalisation.

A first major prerequisite to clarify the real acuteness of the problem was an initial more or less 'snatched' (but obviously acceptable to all protagonists[29]) target scenario of a 'sustainable metal industry'. By 2050 they should be able to offset just the unavoidable dissipative losses i.e. work on the basis of approx. 90% recycling material. With this 'settlement' or with this 'scenario' respectively the currently practiced thinning strategy was taken out of the equation.

A rough model of domestic steel recycling in Germany was prepared to make clear the problem. It could then be shown (simulated) with the help of this model how the impurities in the national steel stock dramatically accumulate over time in the technosphere. Various scenarios could be crudely rehearsed and the expected effects of the different measures estimated. In the case before us it went so far that in a few worst-case scenarios it was even recommended to take certain very impure scrap metal completely out of the recycling process and 'deposit' it in a landfill site to be able to remain within the defined just tolerable limits for impurities in the overall steel flows.

Admittedly the model was still very rough and on this basis the possible scenarios were full of uncertainties. Much work can and must be invested here in future if one wants precise information. Despite this the national steel model had, even in its completely deficient form, an important, so to speak, 'didactic' function. The individual values, perhaps even its dimension, will definitely change when it is refined, but the model has shown significant connections and possible long-term dynamics about problems that have not yet been tackled[30]. During a workshop with the protagonists of the automobile related steel cycle, where this scenario was presented, it was clear to all participants that something must be done about the contaminates, if the objective of a sustainable metal industry based ostensibly on recycled material is to be achieved. As well as metallurgists and association representatives, protagonists from all steps in the steel recycling sector attended the workshop, including representatives from the automobile sector as chief consumers of deep drawing steel to representatives of vehicle dismantling companies, shredder and scrap metal firms to electric-steel works. The presentation at the beginning of the workshop of the to date only under laboratory conditions realisable potential to purify molten steel of contaminants in a high vacuum was important, because it underlined that within the foreseeable future no practical or economically realistic contingency is in sight that could 'technically' solve the problem at the 'end of the pipe'. And because all the major players were present it did not help the, until now, oh so popular game of pushing the responsibility and calls for action onto the other protagonists in the supply chain.

The major result of this workshop was the model supports the actualisation and clarification of the, until now, almost imperceptible creeping problem and the sudden awareness that the problem can only be resolved if all protagonists in the chain act together. Only on this basis can a rational debate begin about how much and what exactly each individual protagonist can and must contribute in future to achieve the common goal along each and every step.

3. REGIONAL SUSTAINABILITY STRATEGIES IN COOPERATION WITH COMPANIES

A sustainable economy is a comprehensive, complex and long-term goal. The path to a sustainable economy relates to a time period that only rarely plays a role in everyday business as well as in political and economic decisions. The positive objective of a sustainable economy cannot be formulated once and for all time. It is, therefore, easier to determine conditions and trends that are not sustainable. Particular attention should be paid to those sustainability deficits that are more creeping in nature, which do not trigger acute consternation but when they do break through are almost impossible to overcome, especially anthropogenic climate changes, biodiversity losses, the accumulation of persistent harmful substances and the long-term availability of energy and material resources[31].

Against this backdrop every sustainability strategy has to battle with two big problems: It must steer the focus to these long-term problem developments (generate dismay), and it must be able to demonstrate concrete steps that can be seen to make a reasonable contribution to resolving not only current problems but also long-term problems. This means dragging the future back into the present, to make current future problems while at the same time ensuring that, even though mostly only small steps towards a solution are possible at present, they are still held to be making a reasonable contribution to the resolution of the major long-term problems.

Not only the temporal dimension but also the spatial dimension of the sustainability deficits present practical difficulties. The project ‘Sustainable Metal Industry in Hamburg’ was set up as a regional project, quite literally in the sense of the maxim ‘global thinking – local and regional trading’. The most relevant sustainability deficits do not only reach far into the future, they are global in nature. As with regard to the longevity of problems there is the task to provide a reasonable timetable (actualisation while maintaining a long-term perspective) so a reasonable spatial area of operation is required for problem solving strategies. The regional area of operation was selected with regard to the project.

From the overarching perspectives of the value creation chains the deficits in the innovative and competitive capabilities of the metal industry in the metropolitan region of Hamburg appear relatively small in comparison with the economic, structural and competitiveness problems of the corresponding sectors in the developing and threshold countries from which Hamburg receives most of its processed raw materials and to which a proportion of the products flow.

Obviously, the social sustainability deficits in the Hamburg region's metal manufacturing and processing sector include the ongoing associated problems of industrial safety and public health protection. However, in the industrial nations huge advances have been made in this – and also in environmental protection – in the past decades. Therefore it is also true: that the main industrial safety and health protection problems in the metal industry no longer lie in the Hamburg region, they lie – as with the ore extraction and processing – in the developing and threshold countries that increasingly wish to take on these processing steps to secure national output. From this perspective even the above mentioned coolant lubricants problematic belongs more to the smaller and everything considered reversible problems even when in this example proposed solutions in all three sustainability dimensions could be furnished.

3.1 The Innovations Strategy – Competitiveness through Focusing on Sustainability

Both the triple-win strategies – improvement of 'resource efficiency' and 'raising consistency' – should where possible run in tandem or be combined. At first glance following these strategies appears to be the best route to implement the sustainability goals in the materials area, especially when it focuses on cooperation with companies. Both strategies, however, are dependent on the companies' innovative capabilities.

The innovation strategy concentrates on this aspect and opens up an, at heart, broad and far-reaching access to the companies. During the project, the main focus of its approach shifted more and more from its originally oriented flow management efficiency strategy toward the innovation strategy, from 'management of material flows' to 'management of the protagonist constellations'. 'Innovation and competitiveness capability through sustainability orientation' proves to be the most fruitful approach in company cooperation.

An important reason for the fruitfulness of the innovation strategy can be found in the altered market conditions and the associated jump in the significance of the public for corporate success. On the globalised, extremely competitive markets it is essential not just to offer lower prices but also to be qualitatively better than the competitor. It is about, optimally satisfying customer wishes and thus winning customer loyalty, retaining market share and capturing new markets when possible. Alongside cost competition, this *qualitative competition* plays an increasingly important role on almost all markets. For companies based in the Federal Republic of Germany, a high wage country with a high tax burden, high environmental standards, high energy prices and almost without its own cheap raw materials, the qualitative competition is more important than the price battle on most market segments. What is understood as "quality" is essentially determined by the customer. Given the comparable prices and comparable technical quality of many of the competitors a huge variety of additional aspects can play a decisive role in the buy decision: starting with the design and reliable delivery, moving on to the service and further on to the environmental and social performance of the company and thus its sustainability strategy.

Given the 'inertness' of the socio-economic systems, innovations appear to be more or less unlikely. But they are always taking place. Competition is the driving force to generate knowledge and innovation, to constantly improve and make more flexible. It is, therefore, understandable to put this efficient procedure to the service of achieving tangible sustainability-goals. When the topic is about the competitiveness and innovative capability of companies, the question arises, how can they be strengthened? Various scientific disciplines have developed a series of concepts that look at both "demands on companies" and at "demands on the institutional environment" (Hinterberger 1998: 86). It is clear that competitiveness is neither spontaneously emerging nor can it be attributed to a definite set of framework conditions or entrepreneurial actions. Rather it is due to a 'systemic quality', a joint interplay between company, state, intermediary institutions and society's ability to learn (Hinterberger 1998: 86). In the project this interplay is examined with the concept of 'regional innovative systems'. The innovative capability of company clusters is thus determined by the ability of a large number of very different protagonists to work successfully together within an innovation system. The so-called Porter-Hypothesis plays an important role, namely the theory that spatial proximity has a great significance for the functioning of 'regional innovation systems' and thus the world market success of many companies is 'home based', i.e. can be attributed to the conditions within the regional innovation system[32].

Retaining market share and 'conquering' new markets are important elements of the motivation of companies to cooperate about sustainability as part of an innovation strategy. It is more about 'lifting revenue' than about 'cutting costs', the latter is the focus of the efficiency strategy. Not to be underestimated is also in this regard the *modernisation impetus* that is generated by the company's development and implementation of a sustainability strategy. As with the introduction of a quality or environmental management system it positively impacts a company's fitness, if it is able to repeatedly question ingrained routines, organisations and responsibilities, to take up external stimuli and thus reposition the company.

Corporate value also plays an important role, especially for listed companies. The Chief Executive Officer of our partner company Norddeutsche Affinerie (NA) appears absolutely to have had an eye on the company's share price when he said during a presentation within the framework of the series of lectures 'Sustainable Metal Industry' in the context of our project that both the high environmental standards in Germany and continuing sustainability concerns as well as the social problems in the ore extracting countries were 'challenges for the Company'. Proudly he could illustrate, supported by key figures, that NA belongs to the leading copperworks in the world, not only in terms of market success but also, for example, in terms of labour conditions, plant availability or by the level of SO_2-emissions per tonne of pure copper. Alone the fact that given today's environmental standards a copperworks just three kilometres from Hamburg's city hall can operate, was highlighted by the CEO as remarkable. Just how much the sustainability topic 'future' affects the actual value of a company, how much "psychology" is lodged in the economy, how much expectations can, to some extent, be even more important than actual facts and figures, the stock market developments show us again and again.

The example of NA is, in this context, especially interesting because it partly contradicts a hypothesis that we have gained in other fields e.g. with regard to sustainability oriented product strategies. There it appears that sustainability concerns are extremely well tackled if the products or markets respectively have an especially close contact with the end customer, marked by very intense competition (in particular quality competition), therefore by markets that are intensively competitive, dominated by demand, very fragmented and extremely dynamic. Much of this is certainly true of the copper market, but copper is and remains far from end consumers a (fordist) mass product. The impetus for a sustainable economy is even more interesting in this case. It is without doubt competition driven but mainly from the engines of the stock market and the general public and thus impacts corporate value in particular.

Obviously the innovation strategy also has to battle problems. A few are already visible, others may not be apparent yet in this comparatively 'recent' approach. A central problem in improving innovative capability can lie in its tendency to be 'directionless'. If one 'only' wants to improve innovative capability there is no guarantee that this ability will be used just (or mainly) for innovations aimed at sustainability. But it is positive that within the cooperation at least model sketches were put into the regional innovation system, which were characterised by links between competitiveness and sustainability and were oriented toward a sustainable economy. These guiding principles were and are being further developed and in some cases also 'extended' or 'redrawn' by the participating protagonists, with their potential to influence. What also appears to be decisive for the innovation direction is the tangible constellation in the innovation system, on the one hand, who the protagonists are, what they propose and what influence they have and the models that give direction to the development and structure of corporate strategy, the processes and products, on the other hand.

3.2 The Region as Area of Operation

A key reason for choosing a regional area of operation lies in the access to major protagonists. The most important sustainability problems may be global in nature but much suggests that they cannot be resolved on a global level (alone). A global political operating level is just being set up and is at present very much occupied with crisis management. The decision to investigate the vista of a regional operating level in a three year model project was without doubt a decision for a tangible region, with protagonists, with whom in many cases there was already contact and to some extent working relations. The, for us, interesting constitutive element of the 'regional operating level' was neither the political borders of the federal state of Hamburg, nor any geographic or socio-economic demarcation of a congested urban area. The regional context of the project was seen as the 'protagonists' region of Hamburg, the 'spatial proximity' as foundation for protagonist relationships, as foundation for direct communication upon which trusting relations are built. Spatial proximity between the protagonists, direct communication and trust – so runs a fundamental work hypothesis – are the vital conditions for innovative capability, for the smooth running of a 'regional innovation system'.

Less the tangible space but more the spatial proximity, less the regional material flows but more the regional protagonists' relationships build the core of the regional reference. This was not the original plan. At the start of the project it was still open whether or by how much the regional orientation of the project should relate more to the protagonists' relationships or more to the material flows. In the original project design it was envisaged that the material flows between the various industrial protagonists would strengthen the material-technical basis for intercompany cooperation, so to speak as the 'hard link' for transactions and cooperations in the economic region. Most of the practical sub-projects, therefore, centred on regional material flows or on the regionalisation of material flows respectively. Only during the course of the project did it become increasingly clear just what a decisive strategic importance spatial proximity was for the protagonists' relationships. The shift in attention from regional material flow management to regional 'protagonist management' also had – but not just and not predominantly – something to do with the above mentioned limited possibilities of 'regional material flow management'. Even though a large part of the practical activities continued with a 'regional material flow management' approach, during the course of the project the emphasis shifted towards 'protagonist management' at least on the analytical level. In the material flow oriented projects the focus of attention shifted from material flows to the protagonists' relationships, which affect the former. Other, from the beginning, predominantly protagonist oriented activities, the series of lectures and the transformation of the project council into the 'Forum Sustainable Economy Hamburg' based at the Chamber of Commerce, gained importance. If the therewith associated systematic excessive demands did not from the beginning forbid it, then one could say that the focus of the project shifted from the examination of 'regional material flow management' to that of an investigation into 'regional innovation management'. Increasingly it was not the material flows at the core of the regional approach, but the business people and thus the protagonists' constellations in the regional innovation systems of Hamburg's metal industry.

3.3 Networking Successes

Particularly important in the regional context is the aspect that almost all real fundamental changes in company processes and products demand new forms of cooperation with external partners. Above all the flexible adaptation of complex products to varying customer wishes means that SMEs, in particular, need a stable, long-term *development network*, to which every partner makes equal ranking, (symmetric) specialist contributions, and by which the cooperation partners also submit absolutely to a close mutual dependence. Both in this commitment and also in the degree of essential interaction, these development networks are clearly differentiated from the increasingly to be found in the skilled trade sector *complementary networks* (alliance of equals enabling the completion of bigger orders in case of need) or the widespread *vertical networks* in the engineering industry, where the system leader delivers fully developed production specifications to its suppliers, which entail very little further coordination.

Here, special attention is also due to the "face-to-face" contacts. Fortunately, to some extent, this agenda could be integrated into an already extensively established network. This was, for example, the case with regard to supporting the regional diffusion of minimum quantity lubrication. The key protagonists of this ‘innovation system’, coming from a series of small and medium-sized engineering companies, the Hamburg-based management of the northern section of the German Engineering Federation (VDMA Nord) and the Professor of Manufacturing Engineering (including a well fitted laboratory) at the University of Applied Sciences, already knew each other and had previously discussed the problem of coolants.

Also the most important network success, the foundation of the ‘Forum Sustainable Economy Hamburg’ benefited from the fact that the region’s civil society protagonists had already successfully joined forces in the ‘Future Council’. The Future Council has been unable to date to permanently integrate representatives of the larger Hamburg-based manufacturing companies. Thus, as an interim measure it appeared that a grouping of industry representatives ‘alone’ would have more success in the attempt to give a voice to the Hamburg economy in the regional sustainability debate[33]. The Hamburg Senat had also shown with its manual ‘Environmental Goals for Hamburg’ that it is able to undertake the task of developing a sustainability strategy for the Land[34]. The only thing that was missing was the consolidation of the ‘third power’. The advisory board of our research project that from the beginning was formed by high ranking representatives from Hamburg’s industrial and science communities offered itself as a starting point. The forum has since been established. Meanwhile it is run without the support of the research project by the Chamber of Commerce and representatives of participating companies and holds events for the general public about sustainability related best-practice examples as evidenced by companies in the region.

3.4 Success Prerequisites for Cooperation with Companies in Sustainability Projects

In the following, using examples of companies that participated in the research project, general experiences made during the field trials will be outlined about what happened when the previously sketched sustainability strategies were implemented into practical cooperations with companies. The various sub-projects had the function of gradually approaching the central questions about company and intercompany sustainability topics, of developing and implementing practical solutions as well as documenting and reflecting the underlying cooperation processes. At the conception of the joint sustainability projects a comparatively complex set of motives on the part of the corporate protagonists was assumed. In addition, the projects should investigate models that exemplarily include the above mentioned temporal, spatial and protagonist related complexities and which can be applied to a tangible common resolvable problem.

Over the term of the project we have tried and tested a whole series of practical approaches. Ultimately the projects that made it through, apart from the already discussed practical projects: “Preventing Impurity Accumulation in Steel Recycling”, “High Quality Processing of Metal Sludge”, “High Quality Processing of Abrasive Waste”, “Minimal Quantity Lubrication in the Metal Cutting Process”, were the projects: “Material Flows in the Coatings Sector”, “Sustainability

Controlling", "Improving the Electronic Waste Recycling Process", "Leasing and Fleet-Management of Fork-Lifters" as well as "Recycling Oriented Modular Product Design". The spectrum ranged, therefore, from waste recycling to efficiency gains, from high quality recycling to the design of products and services. In addition there were also the 'fora', the series of lectures and the 'Forum Sustainable Economy Hamburg'.

3.4.1 Central Problems in the Approach Methods

Due to the type and quality of the sustainability deficits in the metal industry in Hamburg and beyond, there were three main difficulties in initiating and conducting the (regional) sustainability strategies in cooperation with companies.

First the **most serious and urgently acute sustainability problems** were not manifested in the region but in the developing and threshold countries. This did not mean that the economic protagonists of Hamburg's metal industry (especially the metal producers) had absolutely nothing to do with it or no influence on it. On the contrary, they are directly connected with this problem via their global material flow and value chains. And they also have some influence, there where they have 'weight' as a 'gravitation centre' of the international metal industry, at least with respect to their own global material flows. Their product responsibility, which stretches along the entire product line, demands that they tackle the problem and use their influence as much as is possible to alleviate the problems.

Second the **widest ranging i.e. the in effect irreversible and also mostly global sustainability problems** of the metal industry are at present almost unperceivable. Although we are talking about the most problematic, irreversible and global developments, at present – with the exception of the greenhouse effect – most protagonists do not see a contribution to their solution as urgent. This is particularly true for the securing of long term resource disposability; indeed both as far as the primary resources in the mineral ore deposits and the secondary resources, especially the quality of spent metal stocks and scrap metal, is concerned. The productive life of mineral ore sites are discussed periodically, but the real need to act – except for greater prospecting efforts in some cases – are not seen. Also the contamination of scrap metal and secondary metals by impurities is discussed time and again but at present this has not led to the drawing up of precautionary action plans. Nevertheless, on the output side the greenhouse effect has been perceived as a problem pertaining to the energy intensive metal sector. The metal producing industry in Germany has reacted by undertaking an obligation to reduce its energy consumption[35].

Third the quantity and quality of the dimension and range both of the currently perceived and the barely perceived long-term sustainability deficits of the metal industry stand in, an only with difficulty, bearable contrast **to the available regional operating and influencing possibilities**. The regional communications and operating area offers itself, on the one hand, as a very promising start while, at the same time, it appears much too small. The achievable successes appear to be wholly inadequate. Obviously, improvements in the processing of metal bearing waste or reducing coolant applications represent important practical successes. Also the raised awareness of the problem by major protagonists of the regional and national steel recycling sector with regard to the long-term accumulation of impurities or the creation of a regional protagonists' chain for an effective and as high-quality as possible processing of electronic waste are important and necessary steps on the path to a sustainable metal industry and belong to the practical successes of the project. But it is difficult to describe these successes with a view to the size of the task as 'fundamental' steps in the direction of a 'sustainable metal industry'.

3.4.2 Concrete points of departure and motives

Cooperations oriented towards a sustainable economy between science and companies and between companies among one another do not occur through persuasion, entreaty and certainly not by accusations. They are dependent on common interest or concern respectively. With the rather metaphorical differentiation between interest and concern it should be pointed out here that the motives of companies for such cooperations cannot be too narrowly defined from the beginning. Companies must make a profit: that is clear. Profits are, above all, the reason why the company is able to exist, their internal logic that they cannot ignore without consequences in the longer-term. Decisive with regard to the sustainability point of view is, of course, *how* they make their profit, whether they generate profits long-term at the cost of the other two sustainability dimensions or in harmony with them. How profits can be made and not just short-term but also long-term that is, in the era of globalisation and heightened competition, anything but clear and easy to document. There are almost innumerable starting points to achieve the comparatively clear objective of securing or increasing profits. There is, for example, the possibility of growing profits by cost cutting or by raising revenues. Apart from the short-term profit expectations, it is also important to secure corporate value and the company's market position over the longer-term. This can, among other things, be associated with the value and trust in a 'brand' or a stock exchange listing. Beyond this, the industry protagonists in the 'real business world' are guided by many more and further reaching motivations, as is usually supported by the blueprint 'homo economicus'.

Although, from whatever point of view, one would think it unlikely for a company to orientate itself to the goal of a 'sustainable economy' with the exception of speeches from a soapbox, it does happen. Against the backdrop of already existing (work) contacts, especially the scientific project partners based at the University for Applied Sciences in Hamburg and the Ökopol Institut Hamburg with various companies in the region's metal sector, it was not too difficult to find field trial partners for a joint project proposal. At this stage, however, not much more was asked than a very general statement of intent based on the project proposal that had been mostly drawn up by the scientific partners. The content focus was roughly sketched, but the firmness and in particular the possible range of the cooperation was still fairly unclear at this stage. In this respect, the digested and considered observations at the end of the project term about supportable and less supportable topics, trends, strategies and the associated range of each project looking at the sustainability goal belong to the core project results.

To date, as the starting point for sustainability related projects and cooperations with companies the following reference points, interests, motivations and strategies are discussed and also put into practice:

a) **Committed (entrepreneurs) individuals** or strongly (ethically) motivated company protagonists, who were already committed to the sustainability objective. Such points of contact are important. But those who build on this alone, place extreme limits on their possible cooperation partners. There are outstanding entrepreneurs with a strong commitment to a sustainable economy in the Hamburg region, e.g. Mr. Otto, who heads Otto-Versand and Mr. Winter, who co-founded and stamped his mark on the Green Business Companies Association BAUM e.V.

b) **Ethical sectors and markets,** in which the customers (or a significant proportion of customers) anyway demand sustainability related qualities both with regard to products and manufacturing processes. Such 'ethical consumption' whereby the dominant customer orientation is towards sustainability, environmental protection, health and social justice is evident for example in the area of explicit ecoproducts i.e. in the food sector or in general where biosectors have been successfully established or with a view to the North–South divide in the 'Fair-Trade' market. The approach for a 'regional identity' linking into regional marketing also belongs here. With a view to the objective of a 'sustainable metal industry' these points of contact offer only limited help because usually metal companies operate at a fairly wide distance from the end consumer. It deals mostly in the 'business to business' markets[36].

c) **Cost advantages through efficiency gains particularly on the basis of energy and material flow management.**
This is where the core of efficiency strategies apply, e.g. with the motto 'environmental protection pays well'. The efficiency strategy belongs, without doubt, to the most widespread, popular and apparently 'simplest' form of win-win-win strategies, via which all three dimensions of sustainability can benefit equally. Already at the corporate level, however, a serious narrowing of the observations and debate is evident. Anyone with proposals for cost cutting must be able to justify the mostly comparatively short-term expected monetary implications. It can be assumed that for all companies manifold potential cost cutting opportunities exist at all times and on very many levels. The decisive bottleneck is not whether the potential is there but the ability to realise it. Innovative capability is the prerequisite for the efficiency strategy's success.

If the corporate protagonists' motives are reduced to narrow and short-term 'economic interests' then the most interesting and potentially successful cooperation possibilities are already blocked before one has even started. In short, this means that cooperation with companies, on the one hand, has to take into account certain fundamental economic logic. However, that this fundamental logic fully 'determines' corporate behaviour is a myth. After a more precise look a significant room for manoeurve opens up. That companies must make a profit is absolutely clear, but how companies under the current competitive conditions (market saturation, globalisation etc) and political and social framework (state regulation, the power of the general public and civil society protagonists) can successfully generate long-term profits is today more unclear than ever before. Efficiency and material flow management strategies limit themselves all too quickly to energy, material and cost savings in terms of products and technology lines that are no longer in question. For longer-term company success, for securing market position and above all conquering new markets, innovation is, in most cases, very much more important.

For example, the vulnerability of companies to public debate (in the media unfolding 'scandals') as part of the globalisation and development of a 'civil society' with a strong media presence has increased enormously. Also much has changed on the markets over the past decades. Against the backdrop of saturated markets and, as part of globalisation, continuing intensifying competition, the power of the customer has grown and with it general opinion, which influences it. If more companies offer comparable products or services as regards technical–functional quality and price, additional qualities can become buy decisive, as well as in some cases the sustainability aspects of health, workers, environmental and consumer protection. A positive company image – and for brand companies in particular the brand – with the public is important for the success of the 'brand', for customer loyalty, for the share price and also for the prospect of the company attracting the best employees to work for it. The assumed perception of the company's responsibility along the entire product line, the precautionary efforts to avoid scandals is today more than 'image building', that one might as well halt. It can be decisive for the rise or fall of the company.

There are few starting points for the objective of a 'sustainable metal industry' in the areas of 'ethical markets' or 'regional products'. Thus our project was also dependent on 'committed individuals'. Without doubt a committed and influential promoter played an important role in every practical project[37]. Luckily in the sub-projects there was a whole series of people who took on this role, and who thus made possible the success of the project. In particular: The Environment Senator and the committed employees of the environmental authorities; two managing directors of the region's very well anchored industry associations (VDMA and Nordmetall), who are open to cooperation and innovation driven "new" topics; a university professor with recognised "problem solution competence" and a very wide-spread contact network; the CEO of the region's largest headquartered metalworks, who also occupies senior positions in Hamburg's self-governing industrial bodies, as well as the environmental representative of this company; the environmental representative of an industrial fork-lifter manufacturer and last but not least committed employees of the Chamber of Commerce.

The individual motives that have led them to become committed promoters of a stronger anchoring of the sustainability approach in the regional economy certainly differ. While some in the environmental bodies were clearly looking for an expanded or complementary positioning to the administration's own statement on the topic "Sustainable Hamburg", the industrial association employees and also the university staff, who were involved in the research transfer, were mainly interested in strengthening the regional cooperation network. For the "metal sector business leaders" the questions to be asked from a strategic point of view clearly relate to the company's image with the general public, to its vulnerability, the share price and future market opportunities. In addition, the question of the "modernity", and thus the attractiveness of the domestic region, plays an important role for large companies.

3.4.3 Access to Strategically Relevant Departments and Functions

The really essential access to improve a company's innovative ability and competitiveness through orientation at a sustainable economy is the access to the company's strategy, to its quality management and product development i.e. to those departments in which wide-ranging strategic decisions are made. Some of our experiences highlight that access to these departments after entering the company via the environment department – as is more usual with regard to the efficiency strategy – often remains blocked. However, the longer-term aspects of a company's *competitiveness and strategic ability* [38] can only be comprehensively reflected when the named strategic departments are also included. It is there that the already mentioned factors, which have rapidly gained significance in motivating companies to cooperate in sustainability projects over the past few years, are evident e.g. the reliance on quality and innovation, the radical orientation toward the customer, the company's public image ('brand' respectively), the avoidance of scandal, the share price etc. With the shift of the point of departure for cooperations from efficiency to innovation strategies, the cooperation and contact partner within the partner company also changes.

Initially, the environment representative or the environment department, if there is one, was often approached about the sustainability topic and given responsibility for the project. This is due, on the one hand, to the fact that still the 'environment' is seen above all as part of sustainability and, on the other hand, that the operational energy and material flow management is usually part of that department, especially if the company's environmental management system is established in accordance with EMAS or ISO 14000. The projects show, however, that getting into a company via the environment department can definitely end in a blind alley. The environment department often does not have the necessary influence and power within the company to push through really wide-ranging changes in other departments. As a rule the more strategically important departments such as the research, product development, quality management or strategic company management departments can only be reached via the innovation strategy. Even if the energy and material flow management remains part of the efficiency strategy, it will only have extensive influence if it is integrated via the company-wide controlling.

In contrast to our medium-term orientation towards markets and revenues – concrete advice about gradually improving the efficiency of sub-processes was found to be particularly well suited to initiating contact with a company during the project, as it created a basis of trust for further joint activities.

An example of such a "door opening activity" in the context of the project is the material flow take-up in the coatings section of a medium-sized apparatus engineering company that targeted a cost effective and environmentally-friendly waste separation strategy. Such measures mostly deal with clear win-win situations[39] that create visibly recognisable "successes" within the company[40].

Against the backdrop of a target that goes beyond "traditional" environmental protection and assesses the regional economic sustainability of a company in terms of innovative capability, flexibility and cooperativeness it is certainly important that from the beginning further aspects vis-à-vis "normal" operational environmental planning is taken into account:

- Concurrent with concrete solutions to "technical" problems is the early integration of the other production processes with regard to these activities.
- Non-technical and non-material processes are considered on an equal footing.
- Optimisation opportunities that have no ecological, but rather an exclusively economic impact e.g. the reduction of shut-downs or set-up times were equally examined.

  In the above mentioned example of the coatings division this expanded point of view led to the identification of additional relevant problem areas.
- High craftsmanship claims of the lacquerers and imprecisely defined (optical) quality standards resulted in a significantly "too high a quality" finished surface[41]. This mainly resulted in comparatively long preparation times, but also in the high consumption of indirect material.
- As the final customer and bigger system manufacturers could not be prevailed on to accept a uniform colour standard, a large amount of custom-mixed colours had to be disposed of[42].
- Due to the variable and mostly low utilisation of the coatings plant, it was not possible to determine an efficient amortisation rate for a simple technical improvement, such as the implementation of a HPLV spray gun[43]. The improvement investment was therefore not undertaken.

It is common that the solution to this type of problem, which is evident in similar forms in many SMEs, cannot be found directly in the production department but in an entirely different company department, in this case in the marketing department (setting the correct pricing structure and defining the adequate quality standards) or in the senior management team (possibility of optimising utilisation via the external marketing of coatings as services).

Company-wide decision and negotiating processes are required to achieve such optimisation potential. These are not normally found in the day-to-day sequence of operations and, for many, there is also no suitable in-house "site"[44]. The preparation of concrete optimisation projects thus offers the opportunity to initiate an informal in-house exchange forum about further improvement requirements or possibilities.

If sustainability strategies, in cooperation with companies, are to be carried out then two actions must been undertaken after the initial contact has been established: relevant points of contact for cooperations should be found and, building on this, projects formulated that can be successfully implemented within a clear timeframe. The first relevant points of contact are not usually directly attributable to the large and more long-term sustainability deficits. Although, we were able in several sub-projects to see that within the framework of an already existing cooperation, 'consciousness' can be raised, with the help of material flow models, about the mostly creeping and, therefore, future large and long-term sustainability problems and that 'concernment' can be caused. But most tangible cooperations apply to today's many problems, i.e. industrial and environmental protection, waste disposal problems, problematic cost development and handling problems with regard to certain material flows (e.g. coolants and coatings) and the goal of improving company management through more clarity about company and intercompany material flows. A determining factor is, however, that the company had the confidence that we were capable of contributing something really helpful to palliate the actual problem. In this respect the institutional background of the scientific project partners was definitely helpful. In cases where working relationships were not already established, it appears that the previous experience of the institutions' involved and thus the 'origins' of the protagonists of the University for Applied Sciences Hamburg, of the Engineering Office for Social and Environmental Balance (Ingenieurbüro für Sozial- und Umweltbilanzen SumBi) and the Institute for Environmental Strategies Hamburg (Institut für Ökologie und Politik Hamburg, Ökopol) built the confidence required. Outwardly, the cooperation relationships appear almost the same as the numerous other projects for which companies use external scientific-technical or management specialists[45].

The next significant step is the drawing up of sustainability projects that can be successfully implemented within a clear timeframe. There are more than enough problems in every company and the current, short-term ones are usually the most urgent. In addition, the company must be prepared and able, here and now, to do something to resolve those problems that at present are possibly not very acute, often rather complex and mostly of a long-term nature. In our experience the necessary capability to resolve problems is usually more linked to the current internal state and economic position of the company than the protagonists would like to admit. A well-managed company that is able to resolve its pressing current economic problems is usually also able to tackle the complex and longer-term questions. The latter is also true for a company's strategic orientation, its long-term competitiveness, for its market strategy and product development, for the financial strategy, staff development as well as for the product responsibility that has long been extended to cover the entire output chain, for securing the resource base and reducing the problematic long-term environmental and health effects of the metal industry. This covers the entire range of relevant topics and cooperation approaches. It has already been mentioned that we could proceed with a set of comparatively complex company 'interests' of which the most usual principal 'interests' such as for example 'cost savings' played a more secondary or even subordinate role.

4. FINAL REVIEW

Considering the notable project successes there remains an immense gap between what could be achieved in practice and the very demanding 'key' steps in the direction of sustainability or even management of complex innovation systems. In most cases the cooperations did not extend beyond the bilateral collaboration of a few companies, on the one hand, and the research institutes, on the other.

This enhanced the importance of the fora, the series of lectures 'Sustainable Metal Industry'[46] and the 'Forum Sustainable Economy Hamburg'. Both 'platforms' were characterised by a broad regional (specialist) general public orientation and not by an orientation (and domination) by individual companies and that they could initially develop at a certain 'distance' from day-to-day company business.

To the greatest moments of the project belong, within the framework of the series of lectures, on the one hand, the debate about the range of metallic resources sparked by the presentation of the President of the Federal Institute for Geosciences and Natural Resources (BGR) Hanover[47] and, on the other hand, the debate between the CEO of Norddeutsche Affinerie and representatives of the non-governmental organisation 'Save the Elbe' (Rettet die Elbe) about the serious ecological and social problems surrounding the Ok Tedi copper mine in Papua New Guinea. The first direct consequence of the latter debate was, at the invitation of NA, a joint delegation to Papua New Guinea to attain greater clarity about the social and ecological situation at the site and to discuss remedial or at least palliative measures with regional government and mine representatives[48].

The recipe for success of the project 'Sustainable Metal Industry Hamburg' appears to lie in the combination of two strategic approaches, on the one hand, a well prepared plan of material flow management that in essence focuses on long-term 'resource conservation and recycling' (and is thus increasingly 'emancipated' from the region) and, on the other hand, an innovation strategy that concentrates on the use and improvement of the advantages of the Hamburg metal industry's regional 'home base' and the regional protagonists' relationships (innovation systems).

NOTES

[1] The project was funded and implemented within the framework of the BMBF (Federal Ministry of Education and Research) funding initiative 'Model Projects for Regional Sustainable Economies' (www.nachhaltig.org). For more about the project see: www.nachhaltige-metallwirtschaft.de, Brahmer-Lohss et al. 2000 and 2001

[2] See also von Gleich 'Outlines…' in this volume.

[3] WCED 1987.

[4] See the listings e.g. in IISD 2004 and OECD 1999.

[5] Bossel 1999.

[6] All these 'derivatives', abstractions and selection procedures are naturally subjective. The least that can be demanded here is that it is done with disclosures, transparency and traceability.

[7] Within the above briefly sketched approach there is, however, a whole series of theoretical and practical problems to solve, e.g. with regard to evaluating alloys, the elements of which significantly raise its usability in comparison with pure metals during its serviceable life. Meanwhile, they render the recycling possibilities more difficult after the utilisation phase, as further blending with other alloys must be strictly (and expensively!) avoided. Only identical alloys can be recycled together to produce high value material.

[8] See Gößling-Reisemann in this volume.

[9] An amortisation in the sense of an increase through a return of investment as in the financial sector is obviously impossible here. But one can and should have much more far reaching objectives in mind. Biological evolution and natural ecosystems demonstrate that in 'open systems' levels of order (gradients) are not only extremely efficiently used and 'consumed' (e.g. also in the form of cascade utilisation) but are maintained as 'levels of order' that can be continually built upon and raised. The entire biological evolution of organisms and ecosystems shows how levels of order as a whole can be raised

(fed naturally through exergy supplied by the sun). This would be the correct target model for a 'sustainable economy'. Scientific-technical approaches in this direction guided by 'the model of the energy and material flows found in ecosystems' are currently being followed as part of the 'Industrial Ecology' concept.

[10] This in no way fundamentally differentiates socio-economic systems from ecological systems. The possibilities to determine 'critical loads' or 'carrying capacities' in ecological systems is actually also limited to two or three areas, e. g. to the input of acidifying and eutrophicating substances into the ecosystem. There is now also a third case with climate – the input of relevant greenhouse gases into the atmosphere.

[11] See the important stages of the material flow management debate in the German-speaking world: Claus, de Man, Völkle, Wiedemann 1994; Enquête-Commission 1994, 1998; Friege, Engelhardt, Henseling 1998; Sterr 1998, 1999. The Enquête-Commission 1994 and 1998 reports have in particular broadened the concept far beyond the scientific sphere. In the English-speaking world the debate is being piloted under the terms such as 'supply-chain-management' and more specifically 'substance-chain-management' – see http://www.uni-oldenburg.de/produktion/sonstiges/subchain/ 2004.

[12] An innovative new requirement, with regard to a broader framework, was the successfully realised attempt to implement relevant solutions for problematic alloys (in this case high grade steel) and especially problematic geometries.

[13] See Schmidt-Bleek 1993, 1994.

[14] Various target projections predicting by which factor resource productivity can be raised without having to worry about economic damage (factor 4, see von Weizsäcker; Lovins 1995) or by what factor the resource productivity in the industrial nations must be raised by if sustainability is to be achieved (factor 10, see Schmidt-Bleek 1998) have become well-known. The United Nations Environment Programme (UNEP) also sees a key problem in the demands made on resources: "A tenfold reduction in the resource consumption of the industrial nations is a necessary and long-term objective if adequate resources to meet the needs of the developing countries are to be made available" see UNEP 2000.

[15] Environmental cost accounting, material flow cost accounting

[16] The intra- and intercompany material flows were (and are still) not known at all by companies in most cases.

[17] Enquête Commission 1994, p 449.

[18] http://www.umweltdatenbank.de/lexikon/stoffstrommanagement.htm 2004.

[19] See Fels 2002.

[20] See Huber 2000, Clausen, Stahlmann 2000; Braungart; McDonough 2003.

[21] See Christensen 1998, Sterr 1998, 1999. Similar material is also presented under the title ‚zero emissions' see Kühr 2000.

[22] See Huber 1995; Huber 2001; Braungart, McDonough 2003.

[23] See as a starting point to the approach Industrial Ecology in particular the International Society for Industrial Ecology www.yale.edu/is4ie and its magazine Journal of Industrial Ecology'. Earlier terms such as 'Industrial Metabolism' and 'Metabolism of the Antroposphere' see Baccini, Brunner 1991 sowie Ayres, Simonis 1994 are also to be classified here.

[24] Christensen 1998.

[25] See for corresponding attempts and positive (limited) successes Sterr 1998, 1999; Großmann et al 1999 as well as the project conducted by the Fraunhofer Institut Systemtechnik und Innovationsforschung ISI Cooperation for environment considerate

resource exchange: Regional company networking to link-up energy and material recycling http://www.nachhaltig.org/isi/reg05fr.htm;

[26] In this respect for example the projects undertaken by Sterr and his colleages in the Heidelberg region that gradually expanded its catchment area is absolutely understandable.

[27] Baumgärtner 2000, Müller-Fürstenberg 1995.

[28] E.g. steel loses its deep-drawing quality as copper impurity levels increase, see details by Savov, Janke 1998 as well as Janke, Savov, Vogel in this volume.

[29] Astonishingly to date the 90% recycling quota for the meaning and purpose of this type of considered model has not been questioned in principle by either scientists or practitioners.

[30] At present another dissertation has been finished that directly pertains to the project results with regard to the development, implementation and function of such models within the framework of material flow management, see Gottschick 2004.

[31] The climate, biodiversity and resource problems were only discovered to be increasingly significant problems as a result of scientific research, which in turn influenced the topics of the Rio Conference in 1992.

[32] Porter 1991

[33] Here is not the place to discuss in detail all the reasons for the 'at present separate' foundation. Much still had to do with attributing blame. But also differing cultures, efficiency expectations and the needs of time management also played an important role here. In the meantime the converse route to integration has been taken; the Future Council has been incorporated into the Forum.

[34] See Umweltbehörde Hamburg 1999.

[35] The German steel industry had for example bound itself to reduce its absolute energy consumption by 22% by the year 2012 compared with the year 1990. Nevertheless, in the years 1990-2000 they already managed to achieve a reduction of 14.5%.

[36] By which absolutely no claim is made here that ethical aspects have no role to play in business to business markets. However, often they do not play a 'dominate' role. In saturated markets with intense competition, given comparable qualities with regard to 'hard' aspects such as technical quality and price 'soft' quality factors (additional uses and also ethical aspects) can also definitely be buy decisive in business-to-business markets.

[37] See Hafkesbrink 2003.

[38] With strategy capability is addressed here the ability to also concentrate on the longer term developments of the markets and still further to try to influence and/or structure them as far as possible.

[39] Respectively even win-win-win situations, if they also have, apart from helping the environment and easing cost burdens, other positive effects e.g. improving industrial safety or the health of employees.

[40] I.e. that they follow individual company economic logic and can be seen to be directly integrated into a SME's overall controlling structure, lowering manufacturing and material cost levels.

[41] So for example the inside casings of grinding gear are expensively coated even though this application of colour is already scratched off in testing. But "the customer wants an all round attractive product".

[42] Left-over paint of up to 45% of the total purchased amount is generally accepted with a shrug of the shoulders in manufacturing, "as sales/marketing promise everything to the customer". Price discounts for standard coatings or supplements for custom-made coatings are not achieved.

[43] With such a high-pressure low volume application technology the so-called "overspray" can simply and easily significantly reduce lost orders.

[44] In both some of the SME project partner companies and a few of the larger organisations there were no routine coordination talks between all of the technical departments of the company.

[45] It is impossible from the current project experience to make metareflections about how one sees the project partner (his role respectively) with regard to cooperation relationships. Thus, we can also only speculate on how our cooperation partners actually saw us and what were the motives of the partners in the cooperations respectively. If one abstracts the directly personal (e.g. sympathy and antipathy) aspects and emphasizes the 'functional' aspects, the following aspects in differing mixes and weightings appear to be significant. 1. the already mentioned scientific-technical and/or management competence (advisor) to resolve existing tangible problems and to realise unused opportunities in the company; 2. the access achieved via the project to a general regional debate about sustainability (in the metal industry) and a closely connected desire by the company to 'wave a flag' to the general public; and 3. we also believe now and then to have plainly felt the intellectual stimulus to move beyond the daily routine and also become involved in all embracing topics such as sustainability or with challenging scientific topics such as entropy balances. Thus the strive for 'excellence' in each ones individual role and task should not be underestimated.

[46] The lectures given in the series of lectures built the foundation for this volume.

[47] See Wellmer, Wagner in this volume.

[48] See Baumgardt in this volume.

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3

METALS MATERIALS FLOWS

Chapter 10

LIMITS OF METAL RECYCLING

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1. INTRODUCTION

The importance of recycling as a constituent of the metal supply is undisputed. Apart from the economic and ecological advantages of the application of secondary raw materials there is a set of factors, which limit expenditure and use of recycling. These are among other things the metal contents of the raw materials, the emergence of secondary wastes, the multiplicity of alloys, a rising number of composite materials and the effects of user-specific material treatment on the attainable metal quality.

For the presented non-ferrous metals aluminium, copper and zinc, the recycling is to be evaluated very differently, due to substantial differences in areas of application, resulting quantities and process technology. None of these metals alone could give representative results for an optimal recycling quota for metals.

This article deals with today's and future recycling potentials, equally the limits of recycling are discussed. Here above all the availability and quality of secondary raw materials, as well as technological development of material processing and remelting and economic factors with their various effect connections are to be considered. Additionally, the evaluation of recycling concepts is made more difficult by the often misleading use of descriptive terms.

2. AVAILABILITY OF SECONDARY RAW MATERIALS

The supply of metal production with secondary raw materials is influenced by various parameters, which are described in the following by the example of aluminium. These are in particular aspects of time and quality that limit the availability of secondary material. An exact analysis of the existing metal flow and

A. von Gleich et al.(eds.), Sustainable Metals Management, 295-312.

the used technologies leads to an additional problem in recycling, i.e., the definition of recycling quotas and recycled metal contents that are used to describe and evaluate recycling activities. This article introduces technical-metallurgically based solutions.

The difference between the produced and used aluminium quantity in Germany is substantial, as shown in the metal statistics. Questions arise as to how the high metal demand of the processing industry is covered and what role the recycling plays. According to figure 10-1 the recycled content of production would amount to only 18%, whereby only the secondary aluminium production on cast alloy base is related to the entire metal supply of semi-finished wrought products and castings (WBMS, 1999). Indispuably, this leads to false conclusions.

For the correct definition of the terms of recycling, first a qualitative and quantitative description of scrap flows from the areas of application of aluminium is important, as well as their connection to existing recycling paths. Therefore, aluminium materials have to be distinguished into two groups of alloys. With the cast alloys the content of alloying elements, above all silicon and copper, is rather high. In comparison, wrought alloys are lower alloyed, usually with magnesium and manganese. Therefore, they should be separated and, if possible, should arrive well-sorted in the recycling cycle. The material separation however is limited by application and collection. Figure 10-2 shows the German application of aluminium partitioned by casting and wrought alloys, which is dominated by the traffic sector (GDA, 1998). In each of these areas of application, with the exception of the packaging area, casting and wrought alloys which are often mixed, result after their use.

Looking at individual areas of application, a further distinction must be made: On the one hand closed loop recycling exists if scraps are supplied to a comparable reapplication, e.g., beverage cans and window frames. Open loop recycling is present if secondary raw materials after remelting are supplied for another use, usually in form of other alloys. Here in particular the secondary smelters (refiners) are mentioned, which produce cast alloys for the automobile industry, for example from a mixture of different old and new scraps.

Beside these idealised cases, a special area exists in regard to materials and distribution considerations. Wrought alloys are often converted to cast alloys and so achieve a materials modification. From a distribution standpoint, production scrap is not only internally used, but also externally and thus does not remain in a closed loop. Well-sorted wrought alloy scrap is recycled directly by the remelters into rolling and extrusion ingots, which then enter into both closed and open recycling loops. Mixed and contaminated scrap is recycled exclusively by the refiners into cast alloys and usually goes into open recycling loops (Rombach, 1998).

While the product is in use, the metal is considered to be material stock. The entire stock quantity for aluminium is estimated at 700 Million tonnes worldwide. The distribution of the metal concerns spatial, material and time-based aspects. The depot characteristics of aluminium can be described on the basis of selected products, product groups or sections or types of use (tab. 10-1). For packaging material for example, a high spatial variation exists with small product size and high distribution at the same time. The material purity can be high (menu plate, beverage can), middle (cover caps, painted foils) or low (multi-layer foils, vaporised coated bags). The retention time for aluminium packaging is small, with an average life time of half a year (Bauer, 2000).

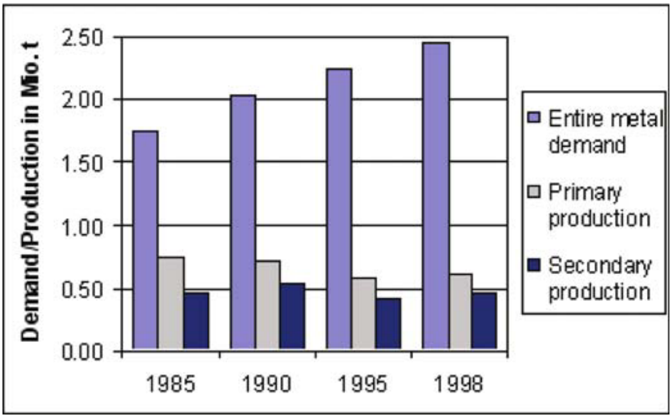


Figure 10-1. Development of entire metal demand, primary and secondary production of aluminium in Germany (WBMS, 1999).

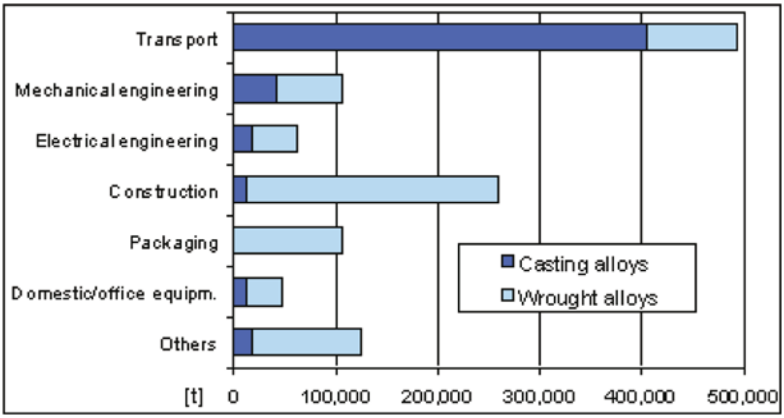


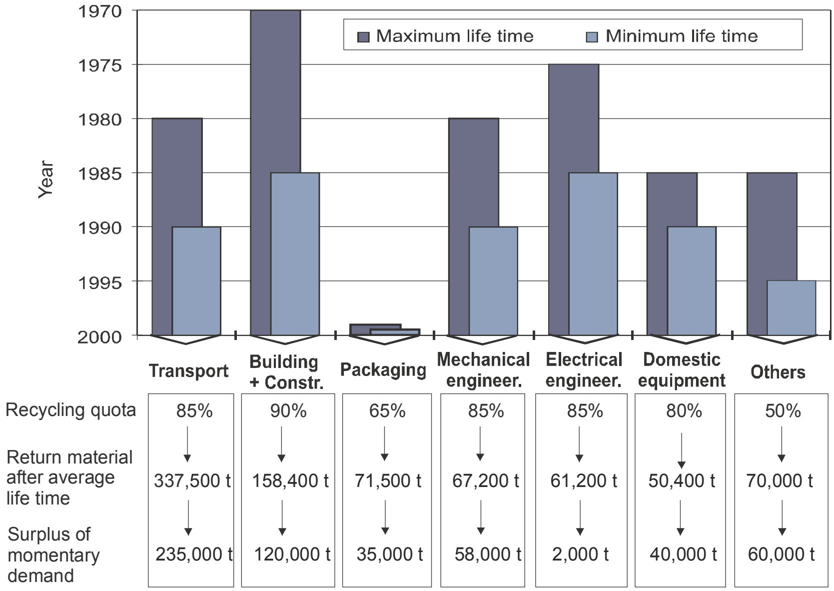
Figure 10-2. Use of aluminium casting and - wrought alloys 1997 (GDA, 1998).

Table 10-1. Depot characteristics of aluminium products in selected use areas (Bauer, 2000).

Depot characteristics		**Packa-ging**	**Transport** train/plane/car		**Con-struction**	**General engineering**	**Electrical engineering**
Spatial	Size	small	high	middle	high	middle	middle
	Distrib.	high	small	high	middle	middle	high
Materially	Purity	varied	high	small	high	middle	varied
Time-based	Retent-ion time	small	high	middle	high	high	varied

The time-based aspect is illustrated in figure 10-3, which shows production periods, lifetime, recycling quotas, return flow quantities of aluminium scrap and the resulting difference to the present requirement in different applications. Today, for example, returned scrap from mechanical engineering applications, that were produced between 1980 and 1990 thus had a lifetime of 10 to 20 years. By the temporal shift of scrap return and production, the difference between scrap availability and metal demand increases. This is further expanded by the high growth rates in particular aluminium applications.

The determination of the scrap amount is based on the stock quantities of individual applications and their recycling quotas. The recycled metal content, i.e., the share of secondary material of products, resulting from this estimation would amount to 60% assuming total scrap collection. One reason for the difference to the actual value of 18%, specified previously, is the determination of the recycling quota. Following some definitions for metal recycling (Wolf 1999, Wolf 2000), the recycling quota consists in the collection quota and the technical recycling quota. This separation clarifies the different levels of the recycling and permits a resource-oriented view.



	Transport	Building + Constr.	Packaging	Mechanical engineer.	Electrical engineer.	Domestic equipment	Others
Recycling quota	85%	90%	65%	85%	85%	80%	50%
Return material after average life time	337,500 t	158,400 t	71,500 t	67,200 t	61,200 t	50,400 t	70,000 t
Surplus of momentary demand	235,000 t	120,000 t	35,000 t	58,000 t	2,000 t	40,000 t	60,000 t

Figure 10-3. Recycling quotas and return quantities for Germany, resulting from different lifetimes for different applications under the assumption of complete collection.

- The collection quota (CQ) determines the quantity of available secondary material that is registered in collection systems, related to the used product quantity.
- Technical recycling quota (RQt) represents the quantity of collected material that, after recycling, is actually available for utilisation as secondary metal, i.e., it concerns the yield of the technical process.

$$RQ_t = \frac{\text{amount of remelted aluminium}}{\text{amount of secondary aluminium collected}} \cdot 100\%$$

The technical recycling quota consists again in two portions: the processing quota (PQ), which indicates how much metallic aluminium from the collection is supplied for melting and second the smelting yield (SY), which indicates how much aluminium is won as liquid metal. Also taken into account are the return flows from salt cake (SR) and dross treatment (DR), see fig. 10-4.

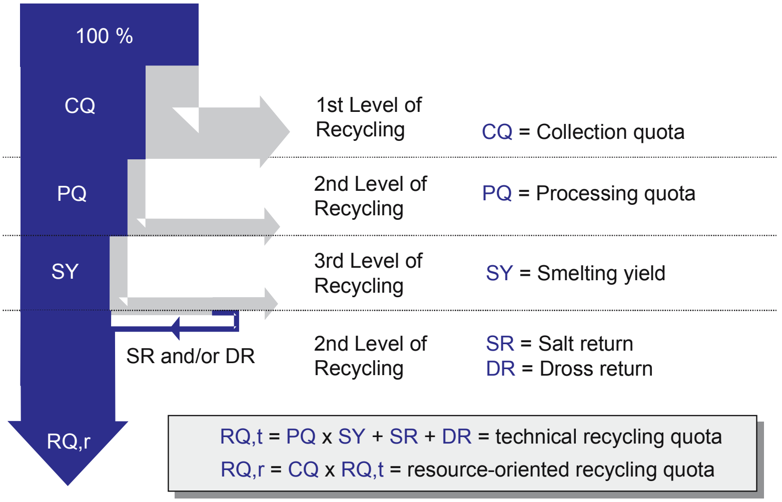


Figure 10-4. Definition of the recycling quotas for collection, processing and smelting (Wolf, 1999).

Using the example of German packaging recycling, the different levels can be illustrated. In 1997, consumption of light packaging material (LPM) consisting of plastics, tinplate, combined materials and aluminium, amounted to 1,778,198 t (Wolf, 2000). 1,582,596 t of the used packaging were collected, which corresponds to a collection quota of 89%. At the same time 389,525 t of non-packaging material were also collected. In the sorting plants plastics, tinplate and combined materials are separated and an aluminium fraction (LPM Al40) is supplied for further utilisation in mechanical processing, composite processing and pyrolysis. The appropriate recycling quota is calculated corresponding to figure 10-5. The technical recycling quota reaches values of 68,4% and the resource-oriented recycling quota

61,7%. For the different areas of aluminium use, the determined quotas vary significantly (Wolf, 2000). The range of collection quotas reaches from approx. 25% for the aluminium content of urban waste to almost 100% of the scrap quantity from the building sector (fig. 10-6). It hence becomes the crucial parameter for the success of a recycling concept regarding the most possible efficient utilisation of secondary raw materials.

Considering the collection of secondary raw materials in figure 10-3 accordingly, the theoretical recycled content decreases from 60 to 46%. Thus the recycling quota defines the retrievable metal content of the used materials or components.

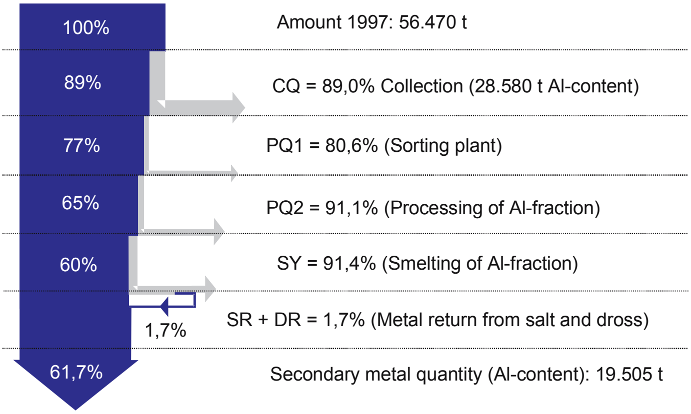


Figure 10-5. Determination of the recycling quotas for aluminium light packaging material (Wolf, 2000).

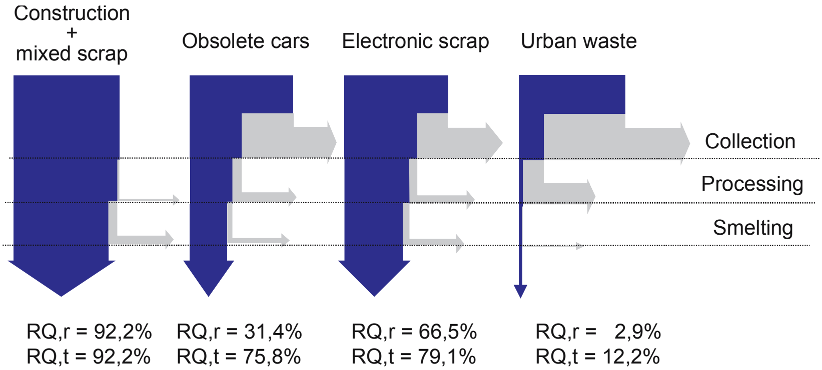


Figure 10-6. Technical and resource-oriented recycling quotas for aluminium products (Wolf, 2000).

In contrast to the resource-oriented recycling quota, the recycled metal content of a given product is the share of secondary metal that is used for processing. The recycled metal content usually lies below the recycling quota, since with rising application more primary metal must be produced than corresponds to the losses during the use phase. However, the recycled metal content is unsuitable as a standard of valuation for recycling success, since it represents a regional value, which can be misinterpreted depending on the existing open scrap market and the rising metal demand.

3. QUALITY INFLUENCE OF SECONDARY RAW MATERIALS ON THE RECYCLING

Apart from availability, the quality of the raw material is of crucial importance for the recycling, i.e., their condition and above all their alloy composition.

Aluminium:

Refining of aluminium is only possible within very small limits (table 10-2). Elements such as iron, manganese, silicon, magnesium, copper and zinc remain predominantly dissolved or precipitated in the metal phase. For this reason, during primary aluminium production the refining is done before reduction. For recycling, this means an exact separation of the scrap before melting with regard to type of alloy and purity. If not, only a dilution with primary metal or blending of different melts remains as a possibility for alloy adjustment.

Table 10-2. Possible melt treatment of aluminium

Kind of refining	Effect
Use of melting salt	Removal of oxides
Chlorination	Removal of alkalia and earth alkalia
Gas treatment	Removal of H, Li, Na, Mg, Ca, Sr, oxides, carbides and nitrides
Salt refining	Removal of Li, Na, Ca, Sr and oxides
Inter-metallic precipitation	Removal of Fe, Mn, Si
Vacuum distillation	Removal of Li, Zn, Mg, Na
Addition of primary aluminium	Dilution of accompanying elements
Addition of alloys	Blending, dilution of single accompanying elements

As a consequence, two furnace types became generally accepted. Well-sorted scrap and new scrap are usually melted in large volume reverberatory furnaces, whereas mixed new and old scrap, dross and turnings are melted in smaller, flexible salt bath rotary furnaces. Despite rising return quantities from production and use, the intensified recycling of wrought alloy scraps at the remelters cause a lack of blending material for the refiners. Their operations are thus becoming more costly through the necessarily increased use of primary metal. Accordingly, the scrap input of the German aluminium refiners (fig. 10-7) shows decreasing shares of new scrap in the years 1975–1999, while the share of old scrap increased (VDS, 2000).

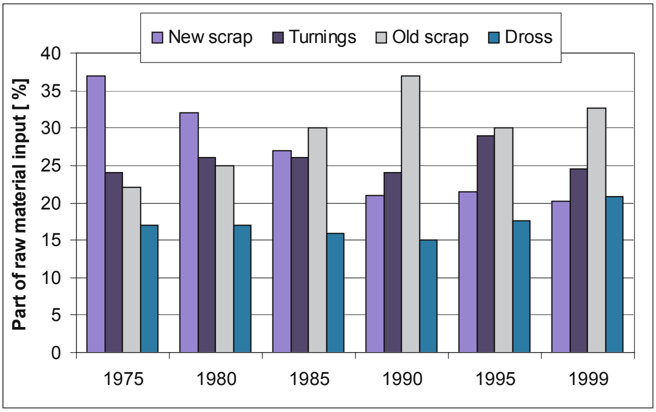


Figure 10-7. Development of the scrap supply of the German refiners from 1975 to 1999 (VDS, 2000).

For aluminium, the scrap balance of 1997 in figure 10-8 clarifies the aspects of scrap availability. First a small export surplus is detectable that consists of old scrap, processing scrap and turnings. For secondary aluminium production about 400,000 t scrap (Al-content) were used, of which about 70,000 t well-sorted wrought alloys were remelted. Further wrought alloys were remelted in the casthouses of the primary smelters (174,900 t) and the semi-finishing plants (190,000 t) (BAW 1998, BAW 1999). The amount of production scrap of 920,000 t was directly reused in the semi-finishing manufacturing as cycle material and was thus not registered statistically. With regard to the shown scrap use, the imported quantity of 168,000 t secondary aluminium and the scrap share of foreign primary metal the real recycled metal content of total German production results to 37%. This is a material balanced average value of the individual areas of application.

The interaction among product areas can be quantified by the existing scrap flows (fig. 10-9). An alloy cascade results, where the recycling activities increase the alloy content of the entire stock. Unalloyed aluminium forms the starting point of this material flow and therefore has the smallest recycled content. Lowering of the alloy status, i.e., a reversal of the usual supplying direction into figure 10-9 is only possible with expenditures comparable to the primary metal production.

Finally, the success of recycling activities can only be evaluated by the metal quantity recovered and thus by primary metal savings in the total aluminium system. It has to be considered that aluminium recycling needs only about 10% of the energy expenditure of the primary smelting. Beyond that, well-sorted collection and special processing work against an enrichment of alloying elements in the recycling cycle and thus promote the maximal utilisation of secondary raw materials.

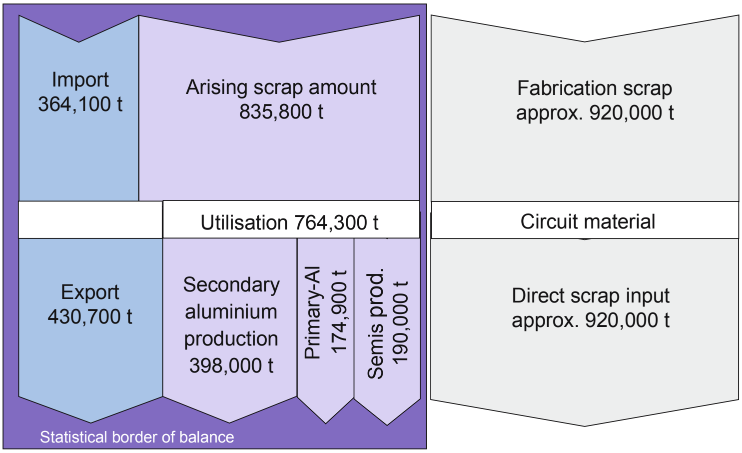


Figure 10-8. German scrap balance 1997 (BAW 1998, BAW 1999).

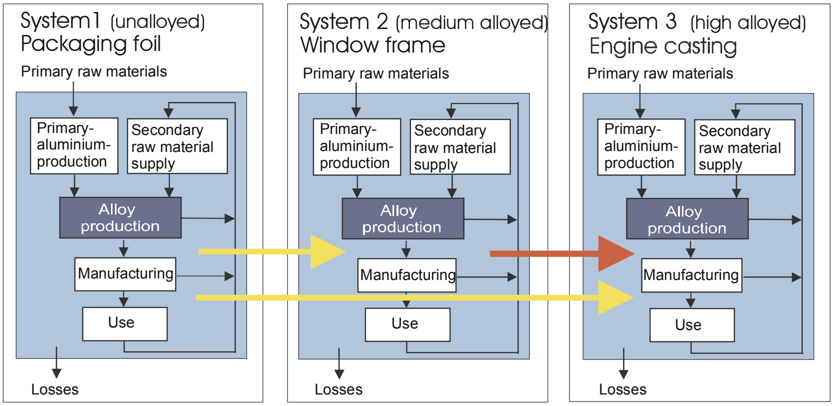


Figure 10-9. Interaction among aluminium recycling systems.

Copper:

For the metal supply of the copper-processing industry in Germany, of 1.14 million t in 1998, a similar import dependency results as for aluminium, however the secondary production with 370,000 t was already situated above the primary production (320,000 t), which also uses large quantities of secondary raw materials (WBMS, 1999). The recycled metal content of the German total production amounts to 51%.

The recycling of copper can take place in purely secondary smelters as well as in primary smelters, where the process steps and intermediate products are similar or the same. The scrap is differentiated into metallic copper and copper alloys and raw materials with non-metallic copper contents. Metallic raw materials of secondary copper smelting are pure and high copper-bearing scrap as well as copper/iron combined materials. Slag, ash and copper-bearing sludge from galvanising (with copper contents under 30%) are non-metallic secondary raw materials. Depending on its copper content, mechanical characteristics and chemical composition, secondary raw material is inserted into different process levels (fig. 10-10). Only about 28% of the feed materials are non-metallic or oxidic and must be reduced in the blast furnace with a high coke consumption.

After the final electrolytic refining, the quality of secondary copper is identical to the primary metal, so that a direct substitution of primary raw materials is achieved. This is important because the energy demand for primary and secondary smelting (for a representative mixture of raw materials) with 21.8 respective 20.5 GJ/t copper cathode is almost equal, but additionally, copper mining requires 35 GJ/t copper content in the concentrate, due to the low ore content (Bruch, 1995).

Copper fulfils the preconditions to reach high recycling quotas much more easily than aluminium or zinc, since it is used mainly in pure metallic form, e.g., in wires and pipes. Likewise, the most important alloys brass and bronze can be remelted in pure form. Beyond that, the electro-chemically noble character of copper and the associated excellent refining conditions enable a recovery from very low copper bearing raw materials with a high metal yield.

Zinc usually returns in the recycling cycle indirectly, since it is used mainly as an alloying element (brass) or as a coating on structural steel. Only about 22% of zinc production is converted to semi-finished material or castings (tab.10-3) (ILZSG, 2000). Beyond that, zinc is consumed as active corrosion protection or chemicals and cannot be recovered from these applications.

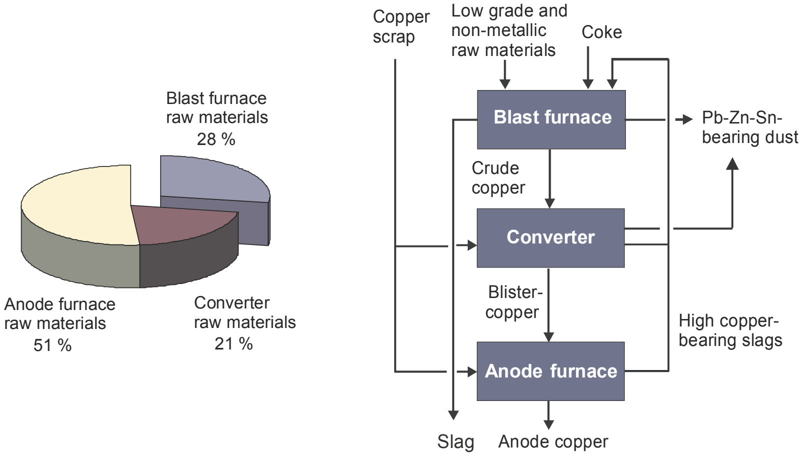


Figure 10-10. Raw material distribution on the process levels of the secondary copper production.

Table 10-3. End use of zinc (ILZSG, 2000)

Application	Share
Galvanising	47 %
Brass alloying	19 %
Zinc alloys	14 %
Semi-finished products	8 %
Chemicals	9 %

Altogether, the recycled metal content of the world-wide production amounts to 18% due to the discussed applications. In Germany the share of recycled material of 49% is clearly higher, 21% of the primary zinc production alone originates from secondary raw materials. This is achieved to a large extent by the use of the so-called Waelz oxide from the processing of steel plant filter dust in the hydrometallurgical zinc production (fig. 10-11). On the other hand, the different ways of zinc recycling are difficult to compare because of the different products. Only New Jersey Refining and electrolysis can produce Super High Grade quality (SHG >99.995% Zn). Besides that, lower metal qualities like cadmium free zinc (98.5% Zn), zinc dust or zinc oxide are produced.

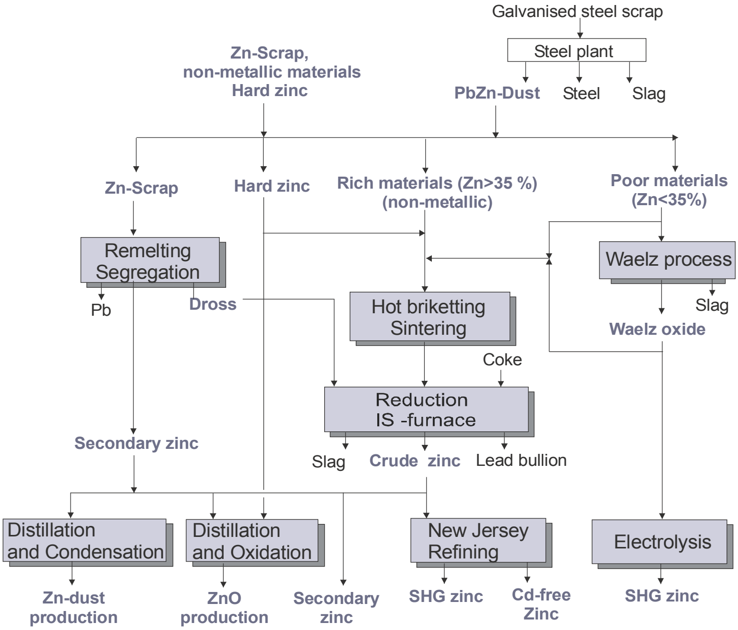


Figure 10-11. Process scheme of the secondary zinc production.

4. TECHNOLOGICAL DEVELOPMENT

By the example of aluminium packaging, the potential for technological development, particularly resulting from interactions of processing and smelting, can be clarified. Figure 10-12 shows the existing system of light packaging recycling. The aluminium fraction from the sorting plants, with 40% aluminium content and predominantly organic remainder, cannot be remelted. Combining mechanical and thermal processing routes, it is possible to obtain a high-quality fraction with about 99% aluminium, which can be remelted with a metal yield of over 90%. However, the overall processing quota of 73.4% is relatively low. By the application of fully automated sorting plants, the metal yield of material processing could increase from 80.6 to 94.0%. Then the process-specific energy consumption increases, but related to the larger product quantity, this turns into an advantage.

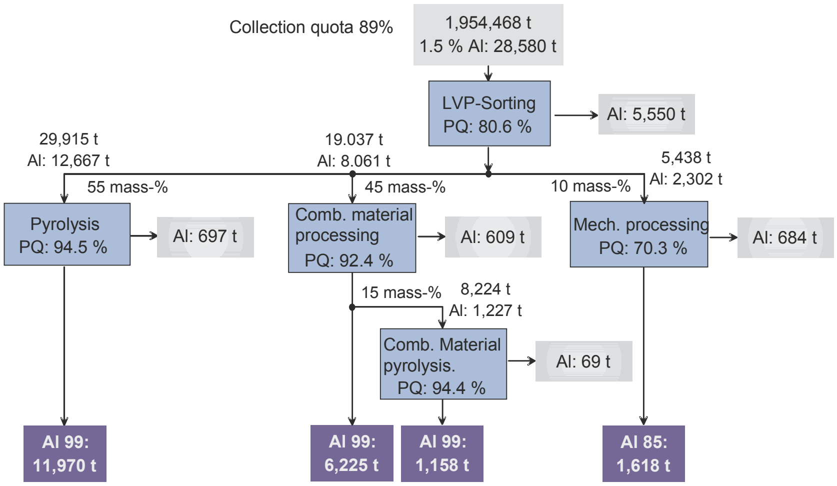


Figure 10-12. Processing of the Al-fraction of light packaging material (SFB, 2000).

Scenario calculations show that in the case of appropriate smelting techniques for the future recycling concept NT (exclusively newest technology) and its possible implementation in the year 2010, saving potentials of 2,000 respective 1,370 MJ/t of produced alloy results, with an increase of the aluminium quantity around 20, respectively 4% (fig. 10-13) (SFB 2000, Rombach 2001).

The energy requirement limits a further increase of the processing quota above 90% (fig. 10-14), due to additional processing steps necessary for sorting remainders and wastes.

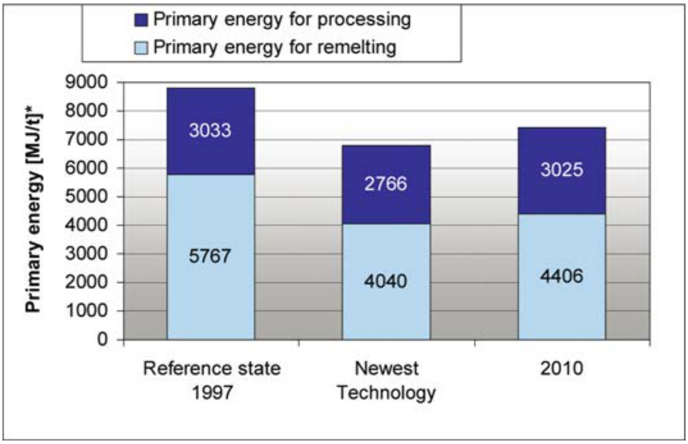


Figure 10-13. Comparison of the primary energy demand of today's and of possible future concepts of light packaging recycling (*without Al-recovery from salt slag and dross)(SFB 2000, Rombach 2001).

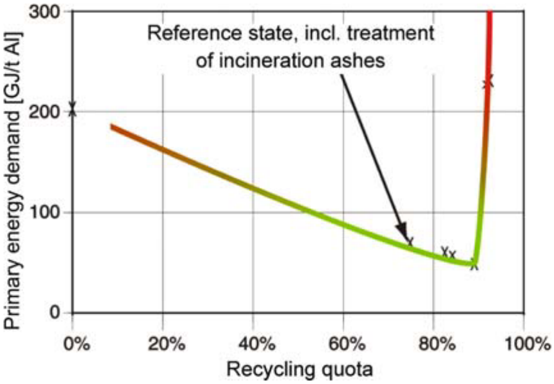


Figure 10-14. Primary energy requirement as a function of the recycling quota for the example of aluminium in light packaging (SFB, 2000).

However, further questions about the limits of recycling arise, also for the other metals. Is the high expenditure for the handling of certain materials also in correct relation to the obtained result concerning emissions and wastes? Is it meaningful to close material cycles at any price? Such questions cannot be answered generally but clarify the demonstrated necessity for a differentiated view of the respective production lines.

5. LIMITS OF ECONOMIC UTILISATION

The economy of metal recycling is determined by the difference between the scrap price and the attainable selling price of the different secondary alloys. The price for secondary alloys is subjected to many influences, e.g. the availability of certain kinds of scrap on the production level and in particular the competitive situation on the consumer level. The price calculation for scrap is at the moment still based on standardised cast alloys, i.e., on the product properties. Here certain deductions depending upon metal content, alloy and impurity degree are made. Due to the large number of cast alloys concerned and company-specific requirements, the indicated price for the cast alloys can be regarded at best as reference value (Krone, 2000).

Table 10-4. Prices for aluminium alloys and scraps, March 2001 (VDM, 2001)

Kind of metal or scrap	Price [€/100kg]		
Aluminium-alloy 231 G AlSi12(Cu)	190	to	195
Aluminium-alloy 226 G AlSi9Cu3	175	to	180
Primary metal 99.7 standard-ingots (EU declared)	170	to	175
Pure aluminium wire scrap	140	to	145
Aluminium extrusion scrap	140	to	145
New alloy scrap (low copper)	95	to	100
Aluminium casting scrap	70	to	75
Aluminium turnings	75	to	80

The price development in the period of 1993–1996 for pure aluminium scrap and casting scrap as well as primary aluminium, silicon and copper-bearing cast alloys (fig. 10-15) shows the common trend, i.e., the relatively constant difference of the prices for scraps and alloys (OEA, 1998).

Even if the prices for pure aluminium (Al 99.8) and pure aluminium scrap behave similarly, they are nevertheless subjected to stronger fluctuations.

Since the costs of the recycling are mainly independent of the metal price, they control the yield. Additionally, the yield depends on the quality of the secondary raw materials (fig. 10-16). If the quality is high, the scrap purchase price is also high, but compared to low-grade raw materials returns can be increased due to the small processing and remelting costs. A scrap depot is thus exploited, in order to maximise the present difference between entire production costs and the anticipated selling price.

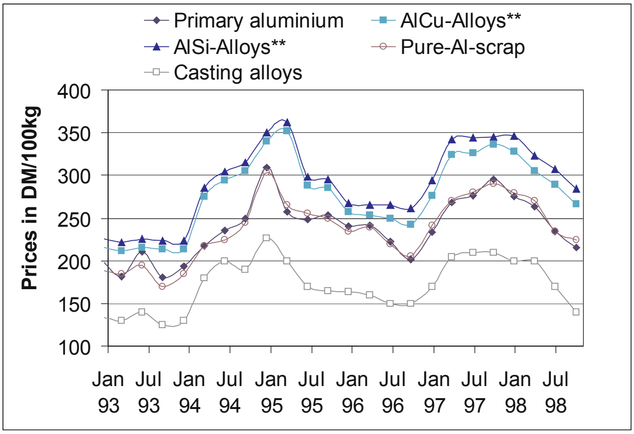


Figure 10-15. Price comparison among pure aluminium, silicon and copper bearing alloys as well as scrap from pure aluminium and casting from 1993 to 1998 (*LME-Cash quotation for duty-free commodity **Small quantities to 3 t) (OEA, 1998).

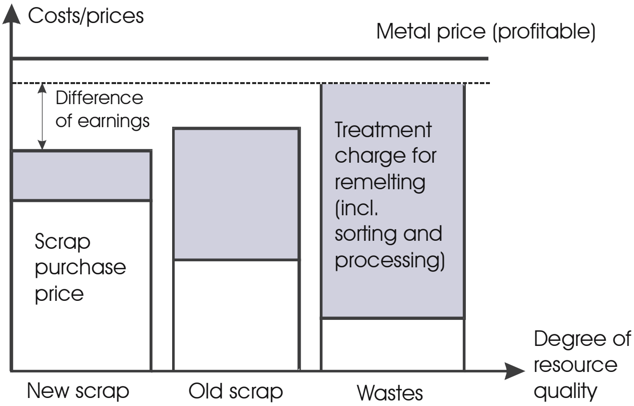


Figure 10-16. Connection between scrap price, remelting costs and difference yield for different scraps (Bomsel, 1992).

For the secondary smelters the price limit of the metal scrap is governed by its utility value during the metallurgical process (fig. 10-17). This again depends linearly on the metal price and beyond that on the condition of the raw material, the plant utilisation and the technical parameters of the process. Falling metal prices finally, when achieving the price limit, lead again to larger inventories.

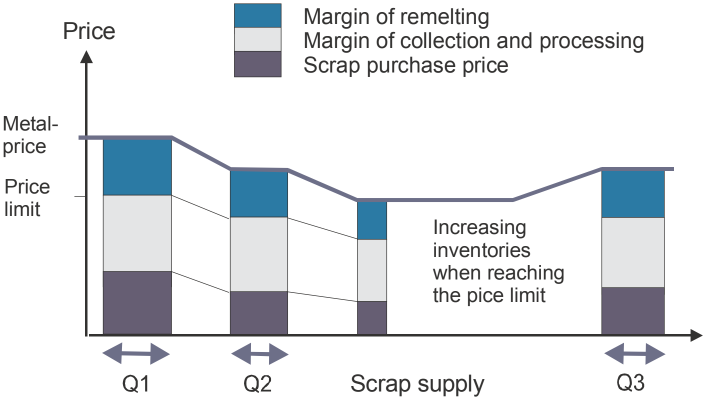


Figure 10-17. Metal price and stock behaviour (Bomsel, 1992).

The remelter is interested in getting as precise information as possible about the composition of the scrap in order to limit the risks of the price calculation. On the other hand, the scrap metal dealer sells his product to that secondary smelter, for which it has the highest utilisation value. He must consequently guarantee the quality of the raw materials, which results in the necessity for a stronger differentiation during scrap collection or the investment in processing and sorting equipment.

Not considering the obtained and possible productivity increases of collection and material processing, at a certain point the utilisation value of secondary raw materials becomes too low to cover these costs. For some residues and low-grade wastes, e.g., steel plant dust, this point has already been achieved. Here the question arises of how the costs of such a subsidised recycling concept are to be carried (Bomsel, 1992).

From this point of view, limits of metal content in the secondary raw materials can be derived for the discussed metals (table 10-5). Following the price calculation for ore concentrates, the calculations are based on the value of the receivable metal content. Beyond that, additional payments for the treatment of low-grade metal-bearing wastes, which enable the recycling of such raw materials are considered.

Table 10-5: Limiting metal contents of economic utilisation for aluminium, copper and zinc-bearing secondary raw materials. (Metal price basis, 5/2000)

Al
50 % Al (without processing)
Metal content (gainable after deduction of melt loss): 40 %
Metal value: 450 €/t material

Treatment charge: 350-700 €/t material

Cu
1. 2 % Cu, Metal value: 40 €/t material + 100 €/t disposal charge
2. 3 % Cu, (10 ppm Au, 50 ppm Ag) Metal value (loss-free): 55+80+10 = 145 €/t material
3. 7,5% Cu, Metal value: 145 €/t material

Treatment charge: 130 €/t material
Refining charge : (130 €/t copper)
5 - 10 €/t material
total 135 - 140 €/t material

Zn
Oxidic raw materials: 23% Zn (+ Pb), Metal value after deduction of melt loss : 260 DM/t material + 100 DM/t additional payment (prorated) = 155 €/t material

Waelz Charge : 130 €/t Material
Refining charge: (255 €/t Metall)
30 €/t Material
total 160 €/t Material

6. SUMMARY

This work points out different limits for the metal recycling of aluminium, copper and zinc. Being the most important parameter of the recycling activities of every metal, the scrap availability is focused on by the discussion. Knowing the availability of secondary raw materials in an existing system, the respective recycled metal content of production can be determined. However, this varies regionally, temporally and product and metal-specificity. On the other hand, the recycling quota is a predominantly technique-specific measure for the success of recycling activities, which also has to consider the collection of secondary raw materials. The recycling technique itself can be described by metal yield and energy consumption. For both the recycled metal content and the recycling quota, the quality of the raw material, i.e., the conditions at production and use, the alloying elements and the metal content have to be considered. Finally, the treatment costs of secondary raw materials limit the recycling, which are again influenced by metal price, metal contents and quality.

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Chapter 11

SECONDARY MATERIALS IN STEEL PRODUCTION AND RECYCLING

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1. RECYCLING OF SCRAP

With regard to the utilisation of the by-products of the steelmaking process (slag, dust, sludge, mill scale) the German steel industry has been in a leading position for many years. Slags, especially those from the blast furnace process, are utilised as materials for the construction industry (road building, cement production, fertilisers). Dusts, sludges and mill scale are either re-used directly in the steelmaking process or treated in special equipment to recover valuable metals (iron, zinc).

Steel is undoubtedly one indispensable material of our modern technology-driven society. At present, steel encompasses a class of over 2500 different steel grades, hence there is a wide variety of properties leading to an even wider range of uses. There are countless possibilities of combinations with regard to micro and macro structures, alloying elements, heat and mechanical treatment procedures. Steels represent materials with a high potential for innovation, although they have been known to mankind for several thousand years. Another peculiarity of steels is their high rate of recycling, some aspects of which will be discussed in this paper.

There exist two different technological routes for steel production. One is based primarily on the reduction and smelting of iron ore, this is the so called blast furnace – oxygen converter route (BF-BOF). The other one is based on steel scrap smelting and employs electric arc furnaces (EAF). Steel scrap is used as a source of iron in both processes but the scrap proportions in the charge are quite different. While in electric steelmaking the iron-bearing charge consists only of scrap, the oxygen converter uses up to 25% scrap, the rest being hot metal from the blast furnace.

It is evident that electric steelmaking plays a more important role in the recycling of steel than the BF-BOF process. That is why this paper concentrates on the material cycle steel-scrap-steel and discusses the complex relationships between

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quantity and quality of scrap, production and use of new steel and the life cycle of consumer goods made of steel.

Figure 11-1 shows that the percentage of steel produced by electric steelmaking processes is steadily increasing (Janke, Savov, Weddige and Schulz, 2000). This tendency is observed not only on a worldwide and European basis but is also typical for Germany.

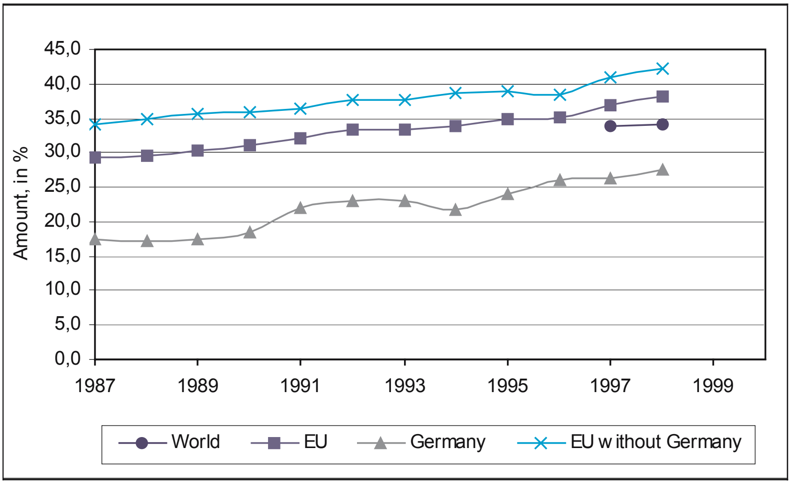


Figure 11-1. Development of percentage of electric steelmaking.

Figure 11-2 illustrates the location of steel plants in Germany. It can be seen that both BF-BOF and electric steelmaking plants are distributed rather evenly, which gives evidence of the excellent capacity of the steel industry to recycle scrap nationwide. Steel continues to be the world's most recycled material, with an overall worldwide recycling rate of more than 55% (Savov, Janke, 1998). This means that 55% of the steel produced comes from scrap and not from iron ore. Theoretically, the recycling rate can reach 100%, since new steel can be produced using exclusively scrap. But at present, the annual steel consumption considerably exceeds the annual scrap generation, meaning that steel has to be produced from iron ore to a large extent.

The recycling of steel significantly reduces the solid waste stream. Besides saving landfill space, recycling also saves valuable energy and natural resources. Steel scrap is not a waste material but a valuable raw material with a high energy content. Every ton of recycled steel scrap saves 1134 kg of iron ore, 635 kg of coal and 54 kg of limestone (American Iron and Steel Institute, 2000). The energy consumed to produce a ton of steel in EAF plants amounts to 5,7 GJ/t, while it is 14,9 GJ/t in integrated plants based on the BF-BOF technological route. This means that the production of new steel from scrap in electric arc furnaces (EAF) consumes less than half of the energy necessary for producing steel from iron ore. Looking at the sources of electric power in the EU (figure 11-3) it strikes one that renewable energies and nuclear power account for half the power produced. This suggests that

EAF plants, which are important consumers of electrical energy, are ecologically very beneficial since in most cases they use energy that is produced without CO_2 emissions. It is evident from figure 11-4, which shows the overall cost split for EAF plants in Germany, that scrap and energy are the predominant sources of costs. This underlines once more the importance of scrap recycling for saving natural resources.

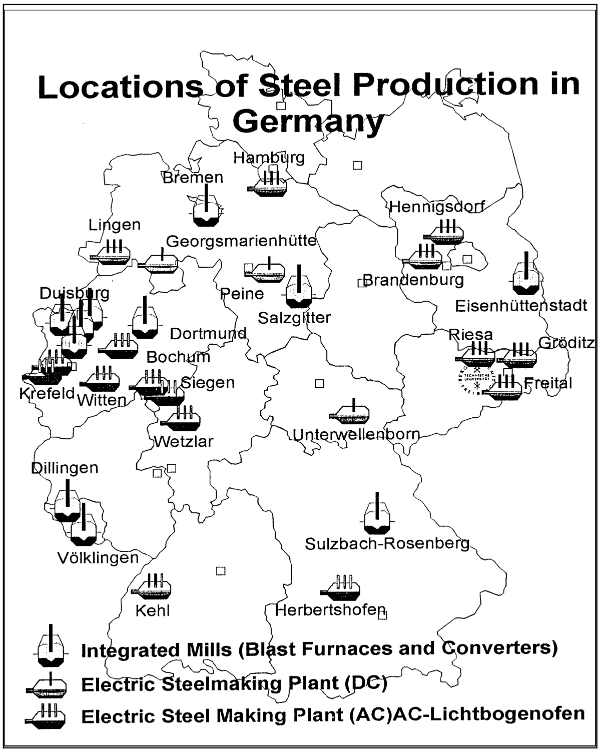


Figure 11-2. Type and location of steelmaking plants in Germany.

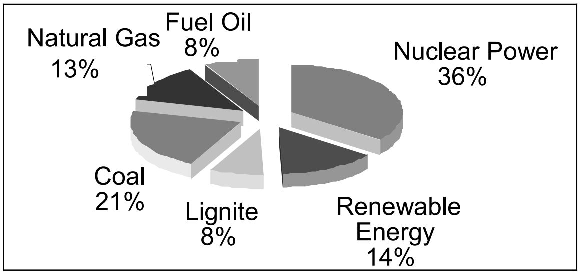


Figure 11-3. Split of power production in the EU.

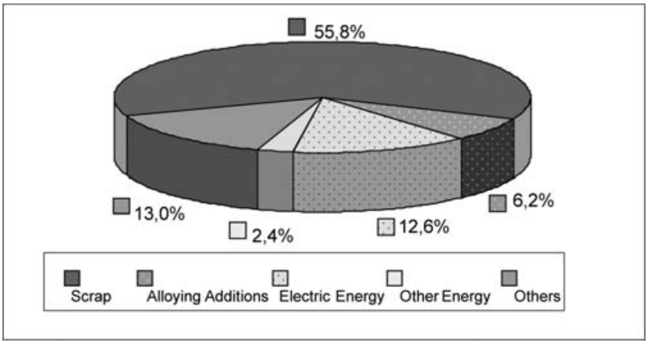


Figure 11-4. Distribution of production costs in electric steelmaking in Germany.

Generally, steel scrap can be divided into three categories (Savov, Janke, 1998):

a) home scrap (plant scrap)
b) process scrap (prompt scrap)
c) obsolete scrap (capital scrap)

A diagram illustrating the flow of iron and steel scrap is given in figure 11-5.

a) Home scrap is generated in steel mills during the production of steel. It is relatively pure and its chemical composition is known, so it can easily be recycled.
b) Process scrap is generated in the manufacturing of products made from steel. This scrap occurs during production of both industrial and consumer end products. Process scrap is available for recycling within a relatively short time after its generation. However, scrap preparation and classification are essential before smelting. The rate of process scrap generation will be decreasing due to better steel utilisation in steel processing.
c) Obsolete scrap consists of iron or steel products that have been discarded after the end of their service life. Post-consumer steel products include old passenger cars, steel cans, electric appliances and other items. Obsolete scrap is often mixed or coated with other materials such as copper, zinc, tin, glass and plastics. That is why usually the content of tramp elements in obsolete scrap is high. Moreover, the chemical composition of obsolete scrap fluctuates widely depending on its origin and degree of processing. Obsolete scrap, especially originating from old passenger cars, is usually processed by shredding. The steel industry has always aimed at a higher steel yield through rationalisation of equipment and technology. Consequently, the rate of home scrap generation has been gradually decreasing. The sharpest decrease ever was achieved with the introduction of continuous casting. This technological innovation reduced the amount of home scrap.

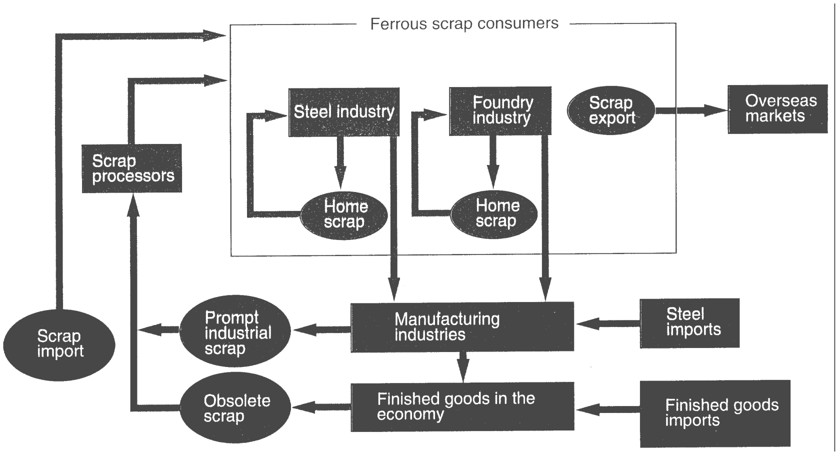


Figure 11-5. Generalised flow of iron and steel scrap.

Figure 11-6 shows that during the period 1966–1989 the home scrap generation rate in Germany fell from 250 to 100 kg scrap/t produced steel, while the share of continuously cast steel reached 90% of the total steel production (Ender, 1997). No great changes in home scrap generation will occur because the steel yield in state-of-the-art steel mills has already been maximised. However, local differences have to be taken into account. While western industrialised countries have successfully implemented continuous casting technology, other steelmakers are lagging behind. The share of continuously cast steel in the total output of some major steel producers such as China, Russia and India is still below 50% (Savov, Janke, 1998). In order to be competitive in an increasingly globalising economy, these countries will have to implement the continuous casting technology. Consequently, the generation rate of home scrap is expected to decrease sharply in some regions of the world. It is assumed that the occurrence of home scrap and process scrap are simple functions of crude steel production and semi-products manufacturing, respectively. However, the occurrence of obsolete scrap depends on previous manufacturing numbers for steel end products. It was found that on average 70% of the tonnage of steel end products is returned into the materials cycle 20 years after the manufacturing took place (figure 11-7). The remaining 30% is lost mainly by rusting of the steel. For example, the world occurrence of obsolete scrap in 1994 was 272 million tons, which represents 70% of the amount of manufactured steel end products in 1974 (Willeke, Ewers, Kreuzer, 1994).

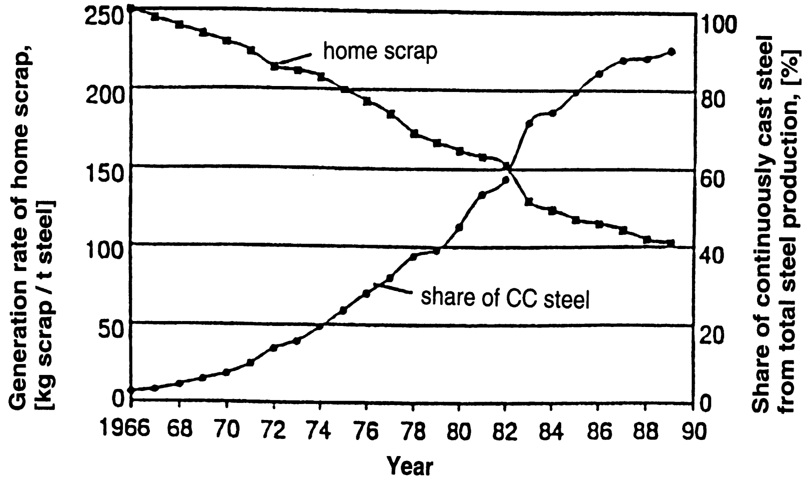


Figure 11-6. Development of the home scrap generation rate as a function of the implementation of continuous casting technology (Germany, 1966-1989).

However, there are consumer goods which are recycled very shortly after being manufactured, e.g., the life cycle of steel cans is 6–12 months, compared to 12 years for automobiles and electrical household appliances and 25 years for steel used in construction (Ender, 1997). Certainly there exists an interdependence between the rate of obsolete scrap generation, scrap quality and the life cycle of the common consumer goods made of steel. The complex nature of these interrelations has not yet been investigated sufficiently.

Another problem, which is in the beginning stage of investigation, is the evaluation of the average chemical composition of scrap coming from a given group of consumer goods (e.g., small cars, washing machines, electric stoves) or the analysis of the chemistry of given components of consumer goods. The aim of such investigations is to gain information that is necessary for the prediction of the chemical composition of obsolete scrap and to determine proper measures to reduce the impurity content of scrap by dismantling single components of post-consumer goods, which are particularly harmful for scrap purity. For example, it was found that by selective dismantling of auto-parts the Cu content of shredder scrap can be reduced from 0.27 to 0.12% (Marique, 1997).

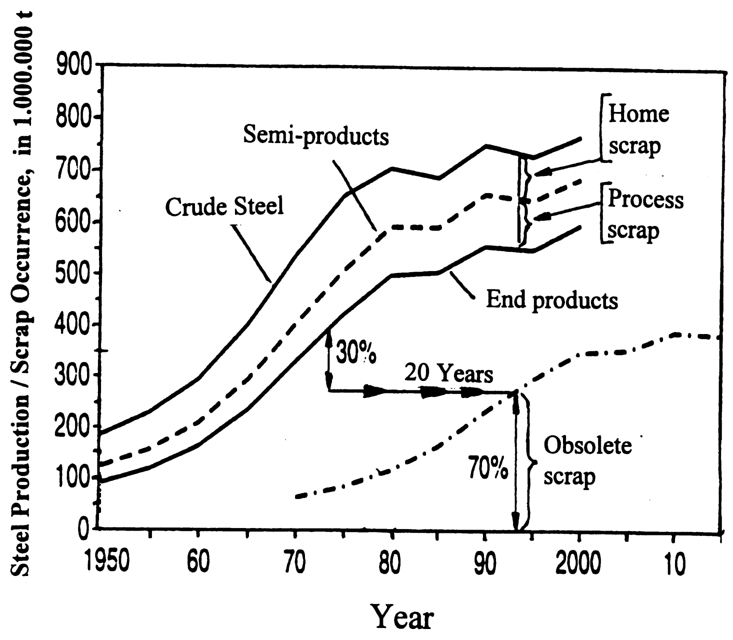


Figure 11-7. Interrelations between world steel production, steel consumption and scrap generation.

Table 11-1 shows the desired limits for tramp element contents in most contaminated scrap qualities as defined in the European Scrap Quality List, which went into effect in July 1995. The processing of scrap using currently available methods of scrap preparation ensures that the tramp element contents are kept below these limits.

Basically, there are three different modes of existence of harmful tramp elements in scrap:

1. Tramp elements in pure state coexisting with pieces of steel scrap. The impurities are mixed with the ferrous portion of the scrap and are mechanically separable. Example: discarded electric motors where iron and copper coexist in pure states.
2. Tramp elements used as coating material for steel products. The iron and the non-ferrous coating metal comprises a series of layers consisting in different phases. Example: galvanised steel consisting of zinc-rich layers on the steel sheet.
3. Tramp elements used as alloying additives in certain steel grades. The impurity elements are dissolved in the bulk steel scrap and are separable only after scrap melt down. Example: Ni, Cr, Mo as alloying elements in steel.

Table 11-1. An Excerpt of the European Scrap Quality List Showing the Limits for Tramp Element Contents in Different Scrap Qualities

Type of scrap	Specification code	Impurity content in %		
		Cu	Sn	Cr, Ni, Mo
Obsolete scrap	E 3	≤ 0.250	≤ 0.010	Σ ≤ 0.250
	E 1	≤ 0.400	≤ 0.020	Σ ≤ 0.300
Home scrap with low content of tramp elements, free from coated steel	E 2	Σ ≤ 0.300		
	E 8	Σ ≤ 0.300		
	E 6	Σ ≤ 0.300		
Shredded scrap	E 40	≤ 0.250	≤ 0.020	
Steel turnings	E 5 H	subject of additional specification		
	E 5 M	≤ 0.400	≤ 0.030	Σ ≤ 1,0
Scrap with high content of tramp elements	EHRB	≤ 0.450	≤ 0.030	Σ ≤ 0.350
	EHRM	≤ 0.400	≤ 0.030	Σ ≤ 1.0
Shredded scrap from municipal waste incinerators	E 46	≤ 0,500	≤ 0,070	

1.1 Copper

Following this basic classification, the occurrence of the most important impurities in steel scrap (Cu and Sn) will be discussed. The main source of Cu in steel is the obsolete scrap obtained from discarded passenger cars. Cu in old cars is present mainly in the form of wires, electric motors and cooling elements. At present, 40–50 electric motors are installed in a passenger car. The tendency is to supply vehicles featuring even more parts containing copper. If these parts are not dismantled prior to scrap shredding, they are shredded with the bulk auto-body and copper is mixed with steel scrap. The subsequent magnetic separation is not able to completely divide the non-ferrous fraction of the scrap from the ferrous one. Moreover, industrialised countries are characterised by high labour costs, which hinder to a great extent the dismantling of old cars and the manual sorting of shredded scrap. Furthermore, many auto-parts containing copper are reduced in size in contemporary designs, which makes the liberation of the copper fraction from the bulk iron fraction difficult using the existing shredding technology. Cu is also introduced into steel melts by the smelting of scrap which originates from steel grades containing an increased amount of copper. For example, structural steels can contain up to 0.5% Cu. In some cases copper is also used as an alloying element, which gives some steels mild resistance to corrosion (e.g., up to 0.25% Cu). The recycling of scrap originating from such steel grades is an additional source of contamination with Cu.

1.2 Tin

About a third of all tin produced today goes to make tinplate for food and beverage steel cans and other packaging. The amount of tinplate produced in the EU was almost unchanged in the last few years and fluctuated around 4.1 million tons per year (Tomellini, 1996). Tinplate production in Germany remained constant at a level of 0.9 million t. The main source of tin in steel is the recycling of post-consumer tinplate packaging. The discarded tin cans are retrieved from the municipal solid waste by magnetic separation, which is carried out either before or after incineration. At present one of the world's highest recycling rates of tinplate cans is achieved in Germany (81% in 1998) and German law requires that a minimum of 70% are recycled (Informations-Zentrum Weissblech e. V.). Tinplate scrap is pressed in bales and transported to the steel mills, where it is recycled. Over the last ten years, the thickness of the walls of a typical steel can has been reduced by 20%. The thickness of the average tin coating has also been progressively reduced by 20% over the same period and currently amounts to 5 g Sn/m^2 sheet (Informations-Zentrum Weissblech e. V.). Thus, the supplied packing volume per unit of tin has increased considerably. However, the present level of tin used for steel coating is not satisfactory in view of the recycling of tinplate scrap. If tinplate is smelted without previous detinning, the scrap melt contains approximately 0.3% Sn. This is an unacceptably high level of tin for every steel grade.

1.3 Other tramp elements

Tramp elements influence steel quality in two different ways. First, they can influence the processing conditions of steel from ladle treatment through casting to final annealing, thus indirectly affecting the quality of steel. Second, as constituents of steel they can directly influence the mechanical properties of steel products.

Basically, all tramp elements contribute to an increase in strength associated with a ductility loss and a decrease in the drawing properties. These effects are more pronounced for low carbon clean steels (low carbon, (ELC) extra low carbon and ULC-IF (ultra low carbid-interstitial free) steel grades) than for medium and high carbon steel grades.

Copper is the key element related to surface defects in steel caused by a loss of ductility in the temperature range 1050–1200 °C (hot shortness). Surface defects can appear along the whole hot processing line, during casting or during hot rolling. Hot shortness is due to surface scaling and the low solubility of Cu in austenite, resulting in the formation of a liquid copper-rich phase under the scale. This phase penetrates along grain boundaries and leads to loss of ductility in the critical temperature range due to intergranular fracture. Alloying and tramp elements in steel modify the negative effect of Cu. Some of them amplify while others neutralise the negative effect of copper. For example Sb, Sn and As when present in steel increase, each of them to a different extent, the negative effect of copper, while the presence of Ni reduces it (ECSC, 1995).

The tramp elements Sn, Sb, As and Bi tend to segregate at surfaces, grain boundaries or other interfaces. Segregation occurs during cooling and coiling in the hot strip mill or during final annealing after cold rolling. The segregation reduces grain cohesion and makes fracture more likely, thus causing embrittlement. An example of the negative effect of Sn on the toughness of low carbon steels is shown in figure 11-8 (Herman, Leroy, 1996). It can be seen that steels containing tin become brittle in the temperature range –30°C – 0°C, while tin-free steels preserve their toughness at much lower temperatures.

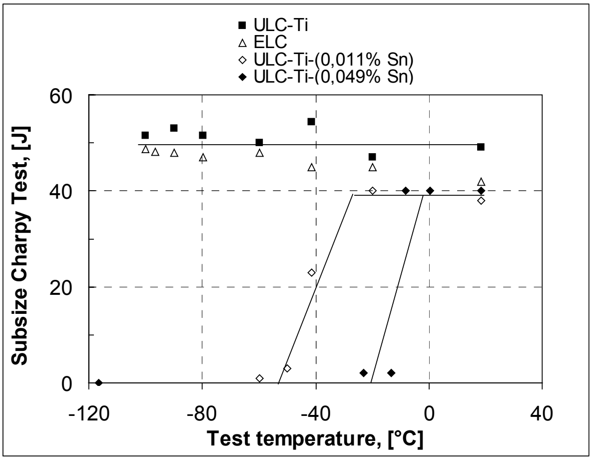


Figure 11-8. Effect of Sn content on the toughness of IF-Ti hot strips.

Tramp elements are more likely to cause embrittlement in alloyed steels than in plain carbon steels. Furthermore, the lower the carbon content of the steel, the greater the segregation of tramp elements on grain boundaries. Ni, Mn and Cr enhance the segregation of tramp elements, while Mo, Ti and rare earths can combat it. Some formulae have been proposed which link embrittlement to the alloying and tramp element level in steel.

In the field of cold rolled and annealed sheet, the major part of the product mix is low carbon or ULC steels. The properties of these steels are trimmed for very demanding applications. Consequently, these steel grades are very sensitive to tramp elements. It has been shown that Sn, Cu, Ni and Cr increase the tensile strength of ULC-Ti steel grades and decrease their ductility expressed in terms of elongation. Drawing properties are also dependent on the tramp element content in steel. Sn, As, Cu, Ni, Cr and Mo have adverse effects on the drawability and, to some extent, the ductility of ULC-IF and ELC grades.

Many tramp elements dissolved in steel melts, e.g., Cu, Sn, Sb and Pb, are not oxidised in the presence of iron due to their low affinity toward oxygen. This means that these elements cannot be removed from a steel scrap melt by a common pyrometallurgical process, as is the case with Si, Mn and Al, which are oxidised and dissolved in slag. In order to remove tramp elements, scrap can be pre-treated at lower temperatures while it remains in the solid state. Pre-treatment of scrap in the solid state often has the advantage that the tramp elements are present in pure state, either mingled with the ferrous portion of the scrap or existing at scrap surfaces, a fact which should facilitate their removal.

1.4 Detinning

The electrolytic detinning of tinplate scrap has been a commercialised process for a long time. Tinplate scrap is pressed into bundles with a density of about 1.5 t/m^3. The bundles, which serve as anodes in the electrolytic process, are immersed in a caustic soda bath at a temperature of 85 °C. Tin is deposited on a steel cathode as a sponge material, which is then scraped off, pressed into large pills and sold to the tin industry. After detinning, a residual tin content of scrap as low as 0.02% can be achieved. Electrolytic detinning is economically efficient only for installations with an annual capacity higher than 30 000 t scrap (Marique, 1997). Furthermore, the electrolytic detinning is suitable for prompt scrap but is problematic for obsolete scrap. Thus 47% of the prompt tinplate scrap which was recycled in the steel industry had been electrolytically detinned but only about 10% of the obsolete tinplate scrap was detinned (Marique, 1997). The tin coating on tinplate cannot be removed by mechanical treatment (e.g., by shredding). A laboratory study at the Institute of Iron and Steel Technology (TU Freiberg) showed that in the temperature range 400–550°C the sulphidation of the coating with reactive gases featuring a sulphur potential and its subsequent removal as a brittle sulphide phase, can be applied successfully for detinning of tinplate scrap (Savov, Tu and Janke, 2001). At present it is impossible to remove tin from steel scrap melts under industrial conditions. However, on the laboratory scale, tin was successfully removed by vacuum treatment from steel melts at a pressure of 0.1 mbar (Savov, Janke, 2000; Savov, Tu, Janke, 2000). This study of the vacuum distillation process for detinning was also carried out at the Institute of Iron and Steel Technology in Freiberg.

1.5 Decopperisation

Copper cannot be removed from scrap-based iron melts by conventional refining methods. Several approaches to reduce the Cu content of steel have been proposed, namely, improvement of scrap sorting, dilution of contaminated charges by directly reduced iron as well as mechanical or chemical scrap pre-treatment aimed at impurity removal. Significant research efforts have been made to develop pyrometallurgical decopperisation techniques. It was confirmed on a laboratory scale that copper can be removed by treatment with sulphide fluxes but a more promising method is the treatment of iron melts at a reduced pressure of the gas phase. This method, which consists in the selective vaporisation of copper, has been successfully tested at the laboratory scale (Savov, Janke, 2000). At present, investigations are being carried out to optimise the shredder operation with respect to the Cu content of the shredder scrap. Preliminary results show that the Cu content can be controlled by varying the degree of the shredder's grid opening (ECSC, 1999). With respect to sorting of scrap, it was found that copper is most effectively removed my hand sorting (Marique, 1997).

1.6 Slag, dust and sludge in the steel cycle

The discussion of better uses of natural resources and the compliance to high environmental standards can not be conducted without consideration of the various by-products. With regard to the use of by-products (slag, dust, sludge, mill scale[1]) of the steel making process, the German steel industry has been in a leading position for many years.

Apart from a nearly complete re-use of slags, the emission of dust has been reduced by over 90% in the last two decades. Over 95% of filter dust and sludge is recycled today. To maintain and improve these results in the future, great efforts will be made by steel producing companies and also by the relevant research institutes. To give an example, Thyssen-Krupp-Steel AG is spending over 300 million euros or nearly 30 euros per ton of steel, to reach these aims (Internet Site of Thyssen-Krupp-Stahl AG).

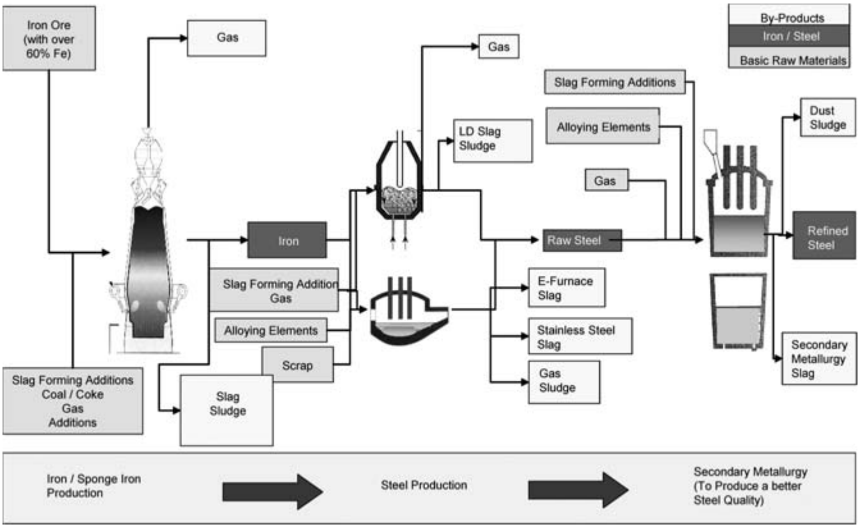


Figure 11-9. Formation of by-products during steel production (main processes in Germany).

The origins of by-products and their recycling will be illustrated along the production line of iron and steel in this chapter.

Currently, there exist two routes to producing steel in Germany. The predominant route is based on ore utilisation, which is processed in the blast furnace to obtain hot metal, which is then used to produce crude steel in the basic oxygen converter process, followed by refining stages in the secondary metallurgy processes, aimed at higher steel qualities and finally, the continuous casting of steel. About three quarters of the total crude steel production come from this route.

The second route is based on steel scrap, which is fed into an electric arc furnace to be smelted and subsequently refined in secondary metallurgical processes before being continuously cast. Using other feeds than scrap, such as direct reduced iron, a quality comparable to converter steel is obtainable. This route will most likely be of increasing importance in the future.

Further information concerning steel production can be found in the relevant literature (Burghardt, Neuhof, 1981; Stahlfibel, 1999). Figure 11-9 gives an overview of all by-products occurring during steel production (yellow boxes).

1.6.1 Slags

Slags occurring in ferrous extraction metallurgy can be divided into blast furnace slags and steel slags. The steel mill slag is divided according to the kind of production route in basic oxygen (LD-converter) steel slags and the electric arc furnace slags (Geiseler, 1998).

Nearly all of the ferrous metallurgical slags are lime-silica slags, but there are substantial differences of basicity, that means of the ratio between CaO and SiO_2, which has a great influence on their properties.

In general the amount of slags produced has continuously decreased over the last 50 years owing to better ore preparation and better metallurgical processes. As a consequence of their role in producing good iron and steel qualities, further substantial reductions in the amount of slags seem unlikely.

Blast Furnace Slags

In 1998 over 30 million tons of iron were produced in blast furnaces in Germany resulting in 7.8 million tons of slag. From the produced blast furnace slag, 41% is air cooled blast furnace lump slag and 59% is granulated blast furnace slag (Geiseler, 2000) (see figure 11-10). Blast furnace slags can be completely used. Granulated blast furnace slag is used to produce cement. Air cooled slag is employed in road construction and similar fields of application. A small amount of the blast furnace slag serves as fertiliser in agriculture.

The development over the last 20 years exhibits a tendency to high-class products, such as granulated blast furnace slag. Thus the share of production of granulated slag in 1984 was about 20% (Blunk, 1985) while in the year 2000 it will be more than 70%.

It is possible to produce deliberately different forms and different qualities of blast furnace slag. The procedures used are shown in figure 11-11.

Today the most used technology is to granulate the slag to obtain grainy granulated blast furnace slag. The liquid slag is quenched with water in special granulation plants. The resulting material is latently hydraulic, hence if added to an "activator" it can hydraulically harden on its own (Geiseler, 1988-91). Using portland-cement material and a sulphate, it is possible to produce portland blast furnace cement or blast furnace cement.

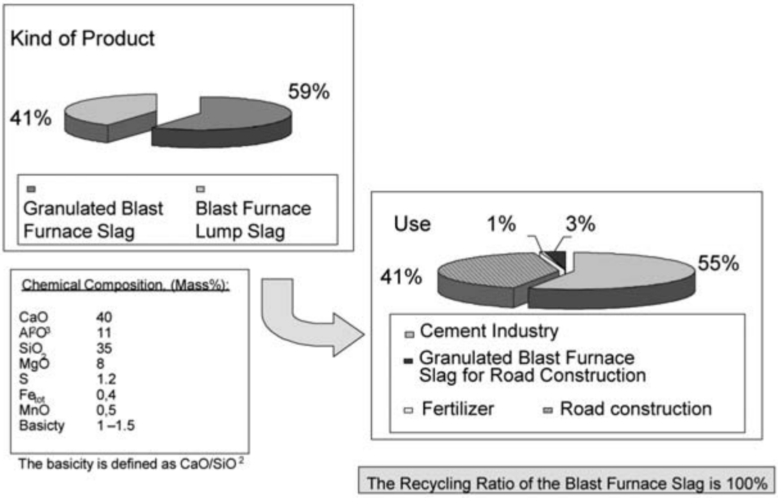


Figure 11-10. Blast furnace slag

The production of 30.1 million tons of hot metal in the blast furnace in 1998 in Germany is accompanied by a production of 7.8 million tons of slag as a by product.

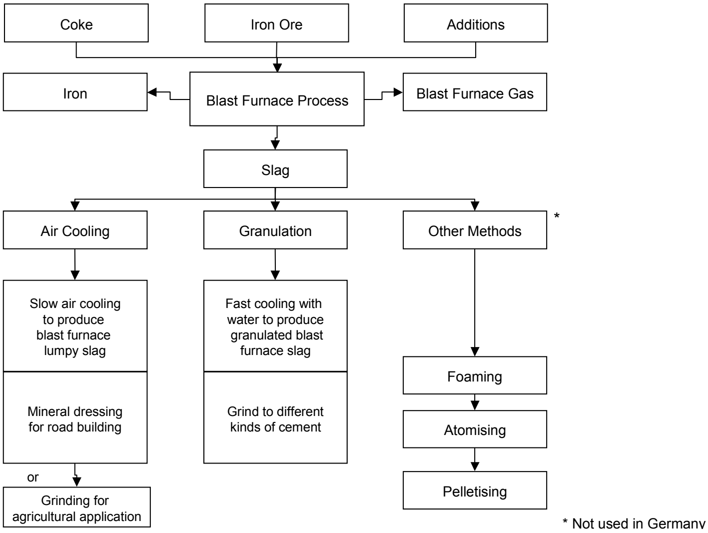


Figure 11-11. Routes of blast furnace slag processing.

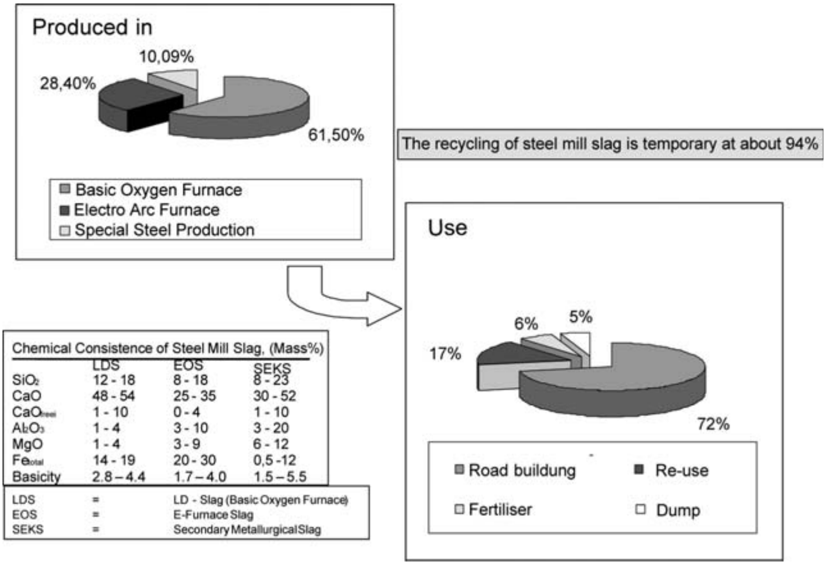
The furnace slag is produced in special kinds of beds, where it slowly cools in air. Such aggregates are used for road construction.

The blast furnace lump slag can be ground to serve as fertiliser in agriculture, which has been practiced for more than 100 years.

Steel Making Slags

Steel slag includes those slags which are produced in the oxygen steel converter process and the electric arc furnace steel production (including stainless steels) and the slag which is produced in secondary metallurgy (see figure 11-12).

Most of those slags are lime-silica slags, but their basicity is always higher than that of blast furnace slags, which increases the risk of hydration. In 1998 the German crude steel production was about 44 million tons resulting in nearly 5.5 million tons of slag. The largest proportion of slags was produced in the basic oxygen steel converter with a percentage of over 60%. Next were the electric arc furnace steel production with about 30%. The others (secondary metallurgy, ESR) accounted for 10%. The steel mill slags are mainly used as a construction material. About 17% can directly be recycled in the steel production, for example in the sinter or the blast furnace process and in some cases also in the converter steel making process. Of those slags, 6%were used as fertilisers and nearly 6% cannot be used again (Geiseler). The main reason is that this remaining 6% is fine grained or does not fulfil the requirements of technical standards.



Chemical Consistence of Steel Mill Slag, (Mass%)

	LDS	EOS	SEKS
SiO_2	12 - 18	8 - 18	8 - 23
CaO	48 - 54	25 - 35	30 - 52
CaO_{free}	1 - 10	0 - 4	1 - 10
Al_2O_3	1 - 4	3 - 10	3 - 20
MgO	1 - 4	3 - 9	6 - 12
Fe_{total}	14 - 19	20 - 30	0,5 -12
Basicity	2.8 – 4.4	1.7 – 4.0	1.5 – 5.5

LDS = LD - Slag (Basic Oxygen Furnace)
EOS = E-Furnace Slag
SEKS = Secondary Metallurgical Slag

Figure 11-12. Steel mill slag.

In 1998 44 million tons of steel and 5.5 million tons of slag, as a by-product were produced in Germany

Future development proceeds towards steel slags with a high volume stability. But especially LD slags do not fulfil this requirement. Thus it is necessary to develop technologies to produce better quality slags. Some of these technologies will be introduced next.

Similar to blast furnace slag, the LD and arc furnace slags are also standardised (Versteyl, 1998). Owing to metallurgical demands it is necessary to build up finishing slag with a high lime content.

LD slags can be treated similarly to blast furnace slags, hence it is possible to produce several different slag qualities (figure 11-13). The easiest way is to pour the slag in special beds where it is cooled with air and water over a longer period. This aims to decrease the amount of CaO_{free} to obtain a material suitable for building and construction applications. The disadvantage of this procedure is partial disintegration into small particles as a result of hydration, so that the slag cannot easily be sold to road construction companies.

Other kinds of slags which where used for special steel qualities, require a higher portion of lime resulting in a high amount of CaO_{free}. These slags cannot be used in other industries due to their tendency of hydration.

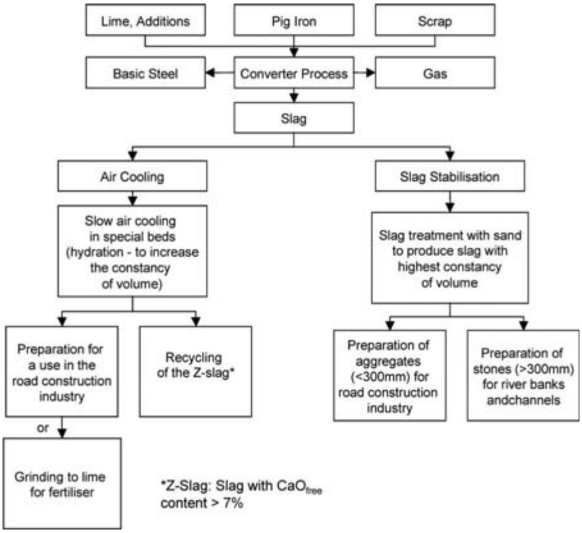


Figure 11-13. Routes of Steel Mill Slag Processing.

A possibility is to re-use the so called Z-slag (with high amount of $CaO_{free} > 7\%$) in the converter process and in such a way to substitute lime by converter slag. It is possible to apply this treatment on all slags with high amounts of CaO_{free} and low sulphur and phosphor contents (Vogel, 1997).

Another technique to lower the CaO_{free} is shown in figure 11-14. The liquid slag is treated with cheap sand and oxygen. The aim of this procedure is to produce a composition in the area of the dicalciumsilicate (grey area in the ternary system $CaO\text{-}FeO\text{-}SiO_2$), as shown in figure 11-14. According to this treatment basicity is close to one, which results in steel slags with a low risk of hydration. This "conditioned" slag is cooled slowly resulting in slag stones of more than 300 mm in diameter to be used for the reinforcement of shipping channels and similar tasks. Even though this procedure is more expensive than the others, it results in a high-quality product which can be easily sold to other industries (Herwig, Schicks, Ulrich und Pluschkell, 1995).

The electric arc furnace slag is mainly air-cooled as shown on the left-hand side of figure 11-13. The slag is cooled down for longer periods in special beds before being sold to different industries. The advantage of electric arc furnace slag results from its lower basicity compared to converter slag.

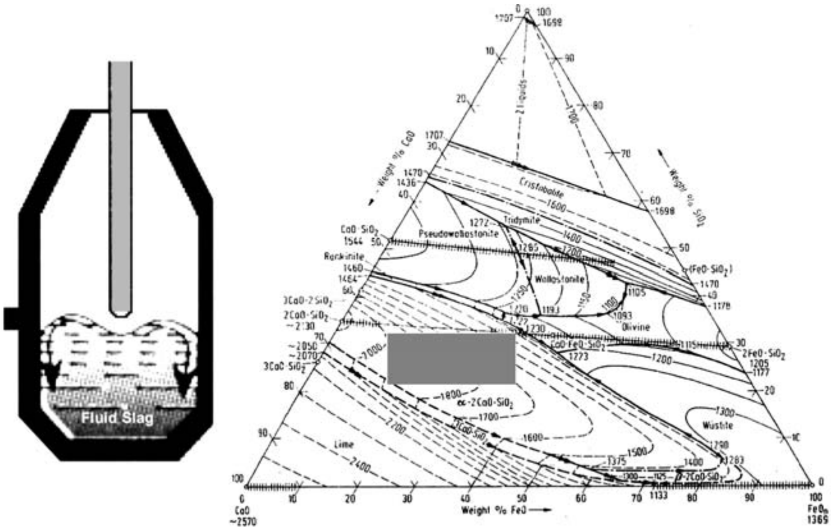


Figure 11-14. Treatment to reduce the amount of CaO_{free} in slag, explanation see text.

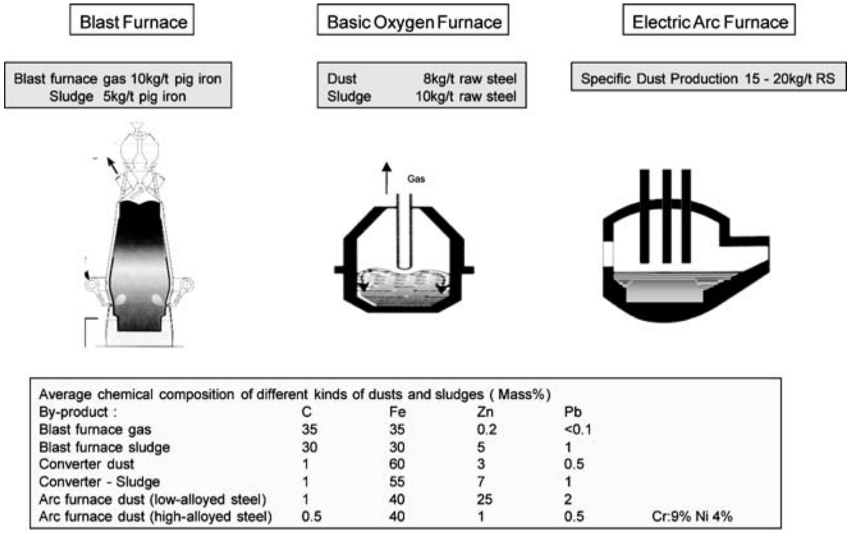
Dust and Sludge

Because of the extensive precautions to reduce environmental pollution, steel companies produce a large amount of filter dust and filter sludge.

In 1998 about 970000 tons were produced in Germany. The major part (51.1%) was produced in the oxygen steel plants, followed by blast furnace plants (18.9%) and sinter plants (13.9%). Electric arc furnace dust and sludges amount to 70000 tons, which represent about 7% (Ameling, 2000). The average chemical composition of the different kinds of dust and sludge are summarised in figure 11-15. Nearly all of those materials can also be used in the building industry, but owing to the high amount of metallic components in the dust and sludge it is more useful to treat them for re-use in the steel making process.

Blast Furnace

Blast furnace gas contains about 10kg of dust / t of pig iron. Sludge amounts to about 5kg/t pig iron. The coarse grained blast furnace dust is fed to the sinter process, the recycling rate of which is 100%. The fine grained fraction cannot be completely recycled. Its recycling rate is about 50%. This is due to the ZnO content of about 5% which is too high to be used in the steel production again and too low to concentrate in special units under current economic conditions.



Average chemical composition of different kinds of dusts and sludges (Mass%)

By-product :	C	Fe	Zn	Pb	
Blast furnace gas	35	35	0.2	<0.1	
Blast furnace sludge	30	30	5	1	
Converter dust	1	60	3	0.5	
Converter - Sludge	1	55	7	1	
Arc furnace dust (low-alloyed steel)	1	40	25	2	
Arc furnace dust (high-alloyed steel)	0.5	40	1	0.5	Cr:9% Ni 4%

Figure 11-15. Dust and sludge.

Converter Steel Making

The dust from the oxygen steel converter (about 15kg/t of crude steel) can by use of sensors be split into a fraction which is low in non-ferrous metals and a fraction which contains a high amount of ZnO and PbO. The former fraction is recycled for cooling steel heats in the oxygen converter or can be fed to the sinter process. The other fraction is used in the non-ferrous metal production.

Electric Steel Making

The specific dust and sludge resulting from the electric arc furnace is about 15 – 20kg/t of crude steel. The dust can be divided in three fractions:

- Dust with a low content of ZnO and PbO. This can be used in the sinter process again.
- Dust with a high amount of non-ferrous metals. This can be sold to producers of non-ferrous metals.

– Dust with a medium content of non-ferrous metals. In recent years it was not possible to use this dust. But presently there exist several developments to recycle it in a concentrated form and to sell it to non-ferrous metal producers.

	1985	1990	1992	1994
Production of Zn-coated steels in the EU (1000t)	6286	11104	12880	13030
Production of Zn-coated steels in Germany (1000t)	1894	2731	3887	4978

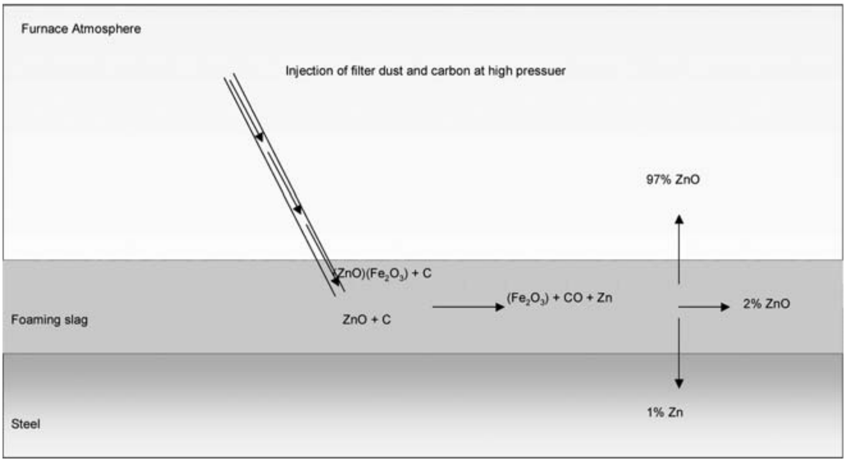


Figure 11-16. Example to enrich Zn-dust for a later economic use [31].

Electric arc furnace dust has a metal oxide content of more than 50% Me_xO_y which makes its use economically viable. For example the price per ton of Zn is at present about 1060 US$[2].

In the case of unalloyed steel production there exists a high amount of ZnO and PbO. In the case of high-alloyed (stainless) steel the alloying elements can be found in the dust, too.

In the near future zinc containing dust will be more and more important, because recycling of Zn-coated steel sheet scrap (Kohl, Antlinger, Peterek, Kösters, 1998; Daniels, 1998; Heinen, 1996) from automobile bodies will result in a much higher Zn input to the process.

The technique shown in figure 11-16 represents a possibility to enrich the Zn content in the dust. There exist several other developments to recycle the zinc containing dust.

The filter dust is blended with carbon and then blown under high pressure into the slag zone during the electric arc furnace steel making process. ZnO is reduced by carbon to Zn. About 97% of the Zn content is returned to the dust filter where it is collected. A residue of less than one per cent of the Zn content will remain in the steel, so that the steel quality will not be affected (Geiseler, Drissen).

SUMMARY

Steel continues to be the world's most recycled material, with an overall worldwide recycling rate of more than 55%. Steel scrap is not a waste but a valuable raw material with a high energy content. Every ton of recycled steel scrap saves 1134 kg of iron ore, 635 kg of coal and 54 kg of limestone. However, the occurrence and accumulation of harmful tramp elements in the materials cycle of steel should be prevented. The control and removal of problematic substances in the process of scrap-based steelmaking therefore represents a responsible task to complete and maintain the desired cycle in the production of steel.

In 1998 over 8 million tons of blast furnace slag were produced as a by-product during the blast furnace process. The recycling rate was 100%. These products were sold as granulated blast furnace slag to the cement industry or as air cooled blast furnace slag for road construction. The tendency is to produce more high-quality products such as granulated slag.

In 1998 5.5 million tons of steel mill slag were produced in Germany. Its recycling rate was about 94%. 74% were used in civil engineering, 17% re-used in the steel production, 5.5% went to agriculture as fertiliser and about 6% could not be used due to minor industrial properties. In the near future it will be necessary to raise the recycling rate and to develop products with higher quality (for example stones for hydraulic structures).

The recycling rate of dust and sludge is momentarily at about 95%. But it will increase in the near future, too. There has been a lot of development to build up systems to enrich the Zn amount in the dust for increased sale to the non-ferrous metal industry.

The existing recycling rates demonstrate the huge efforts the iron and steel industry has undertaken in the last years and will continue to do so in the future. They represent an active contribution for more efficient use of natural resources and a better protection of the environment.

NOTES

[1] The mill scale will not be a matter of this article, the recycling-quota is 100%, it can be used as high-quality material for the sinter process again.

[2] London Metal Exchange, 10.11.2000

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Chapter 12

OPTIMISATION POSSIBILITIES OF COPPER SMELTING AND -PROCESSING

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1. INTRODUCTION

The main quantity of primary copper is still won from sulphide ores after processing them into corresponding concentrates; only their smelting is considered here. The copper extraction clearly differs from other metals. Among others the reasons are as follows:

- Copper ores are always poor, on average they contain 0.8% of Cu.
- However, normally they can be enriched to concentrates with 20-30 % of Cu as well.
- The cause for the enrichment to be only 20-30 % of Cu is to be seen in the fact that the main mineral usually is $CuFeS_2$. The Cu content in the concentrate can thus reach 34 % at most.
- The sulphides don't allow any metal extraction through direct reduction, since the bound sulphur is already in its reduced form.
- Today a metal extraction is possible through a controlled oxidation of the sulphur and through controlled reduction of the copper. The iron should remain as untouched as possible and be slagged.
- The latent energy existing in the sulphidic sulphur is used for smelting the concentrates and converting.

Varying procedures for processing of sulphide copper concentrates are given. However, all of them follow the same process scheme (see figure 12-1). Concentrates with approximately 30% Cu are smelted autogenously to matte and slag. The matte is blown to blister copper under addition of sand to facilitate iron slagging, the copper-rich slag is sent back to the smelting process. The blister copper is refined and casted to anodes. These anodes are submitted to a refining electrolysis in order to separate precious metals and further tramp elements (Ni, As, Sb) which are difficult to remove. The cathodes can be processed in many different ways.

A. von Gleich et al.(eds.), Sustainable Metals Management, 335-346.

	Products	Quantities
Mining ↓	Ore 0.8 % Cu	4,500 kg
Processing ↓	Concentrate 30 % Cu	100 kg
Reaction smelting ↓	Matte 65 % Cu	45.5 kg
Converter process ↓	Blister copper 99 % Cu	29.8 kg
Pyro-Metalurgical refining ↓	Anode copper > 99 % Cu	29.7 kg
Refining ↓	Cathode copper > 99,99 % Cu	29.5 kg
Recasting		

Figure 12-1. General process scheme of copper extraction (Biswas & Davenport, 1994)

2. THE REACTION SMELTING PROCEDURE

Environmental protection is not always the reason for a better process engineering, as the following example shows: on June 9, 1944 the Red Army attacks the Finnish troops with strong forces on the Karelian Isthmus. These must give way to the superior strength, Wiborg / Viipuri gets lost for the Finns. On July 5, 1944 the management of the Outokumpu Oy receives a secret command from the Finnish army, to have the Imatra copper smelter (then close to the front) transferred westward to Pori / Harjavalta, that it should not fall into Russian hands. Preparations had already been made previously. The production was started at the new location at the end of 1944. But now a new problem appeared: energy had become scarce because Germany did not deliver coal for the power station any more. The electric furnace used so much energy as was necessary for 50% of the Helsinki supply. This gave the impulse for developing the flash smelting procedure. The energy being stored in the sulphides was meant to be used during the oxidation in order to smelt the charge. The principle of the procedure had already been proposed before World War II in Canada, with oxygen as the reacting gas. However, using oxygen was not possible in Finland, since the electric energy needed for decomposing the air was not available. Therefore the oxidation air was only pre-heated in order to save further energy. Today, all furnaces are run with oxygen-enriched air. Figure 12-2 shows such a reactor.

With the Outokumpu procedure, dry concentrates are dispersed in an oxygen airflow when they enter a reaction shaft. This gas-solids mixture freely falls downwards, is heated, the sulphides ignite, with an exothermic reaction SO_2 is set free, the particles melt. In a horizontal settler, the particles are separated and form a layer of matte and slag, which are tapped at opposite ends of the reactor. Figure 12-3 shows a comparison of the proportions of two Outokumpu furnaces of the same performance, which run with pre-heated air, and highly oxygen-enriched air, respectively.

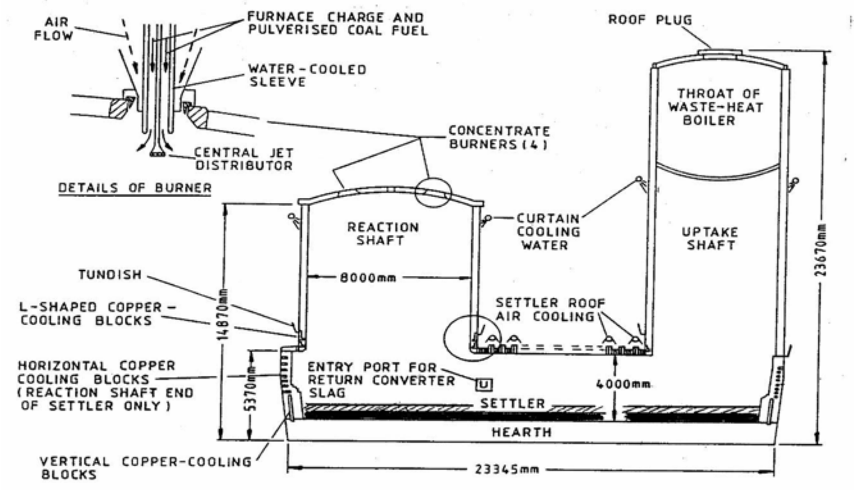

Figure 12-2. Scheme of an Outokumpu furnace (McCain & Floyd, 1993)

Nowadays, it is possible to process large concentrate quantities with only one burner as table 12-1 shows. A high oxygen enrichment is then necessary: the gas speed is around 2m/sec., the time in the reaction shaft around 2-3 sec. After ignition at 400-550°C, 1,300°C is reached in fractions of a second. Compared with air pre-heating, oxygen enrichment is obviously superior. After one second the necessary oxidation is finished. Thus the shaft cooling gained a crucial importance.

Table 12-1. The Outokumpu furnace (McCain & Floyd, 1993)

Reaction shaft	Height: 7.5 m, 1 concentrate burner, Diameter: 7 m
Furnace	25 x 9.5 m
Bath volume	up to 240 m^3 *
Feed (t/h)	125 t concentrate °°(+ 9 t surcharge + 9 t converter slag + dust)
Products (t/h)	57 t matte (70 % of Cu), 90 t slag **
Process air (Nm^3/h)	50,000*Nm^3 (70 % O_2), (up to 80 % O_2)

* Estimated value, ** slag flotation ⇒ secondary concentrate (35% Cu), °° up to 200 t/h feed

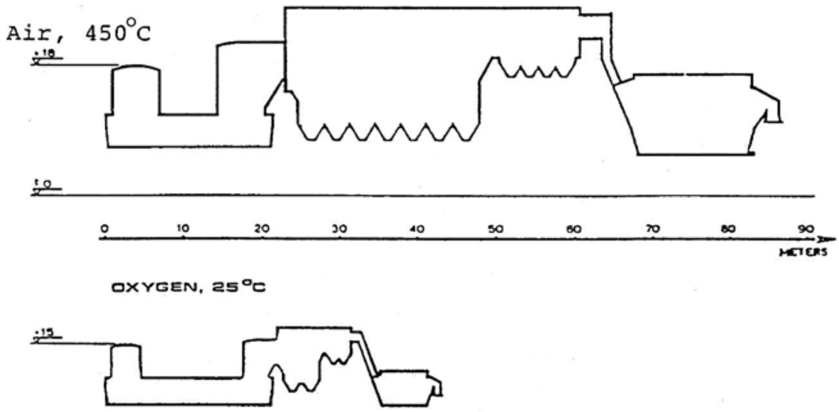

Figure 12-3. Comparison of an Outokumpu furnace, operated with pre-heated air, with one of same capacity, but operated with highly oxygen enriched air. (Kudryk & Rao, 1985)

3. THE CONVERTER PROCESS

While all concentrate smelting procedures are operated continuously, this is not true for the usual converter, it is operated in batch mode: matte is added pan by pan, blister copper and slag discharged into pans. Filling and discharging of the converter takes place over the front. Figure 12-4 shows such a converter.

Doubtless, the liquid transport, the filling and discharging procedures lead to diffuse emissions. However, if there are at present only two serious considerations aimed at a continuous improvement of the converter process, this is mainly because of them working at the most unfavourable operating point. The concentration of the elements to be discharged has to be very low and thus a large amount of copper is slagged.

Only two continuously working procedures are able to maintain their market position: the Mitsubishi converter and the Kennecott Outokumpu flash-converting furnace. Both procedures allow to avoid diffuse emissions to a large extent.

In the Mitsubishi converter (see figure 12-5) matte flows continuously into the copper bath of the converter and is dissolved. By means of lances, slightly O_2 enriched-air with lime powder is blown onto the bath. Scrap metal can be added, too.

Iron is slagged, sulphur is removed as SO_2. Continuously copper and slag are tapped and slag is back to the reaction smelting procedure. Table 12-2 shows some data of the converter operation.

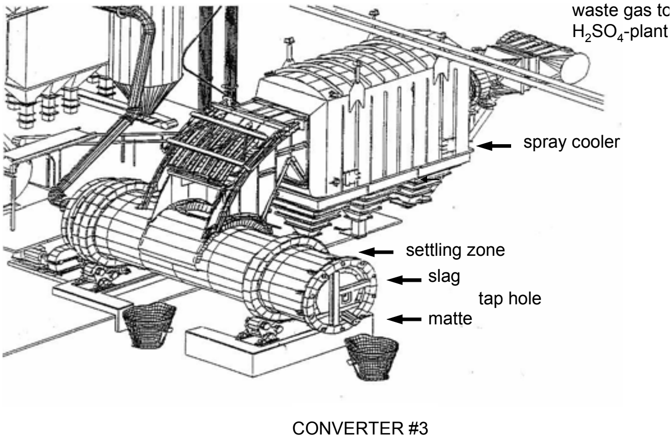

Figure 12-4. A large Peirce-Smith converter (Leroux, 1999)

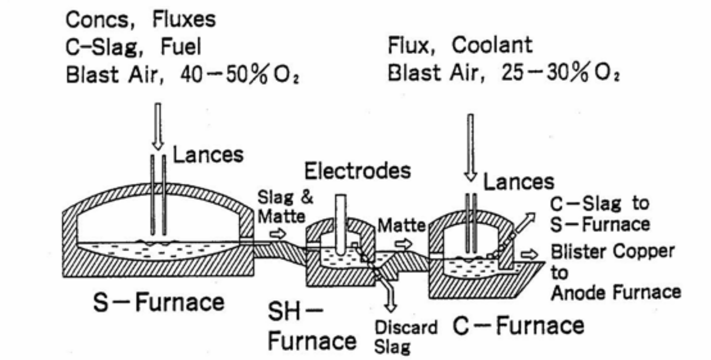

Figure 12-5. Scheme of the Mitsubishi-Procedure, S = smelting furnace, SH = slag matte separation furnace, C = converter, Concs = Cu concentrates (Brimacombe & Mackey, 1994)

The Kennecott - Outokumpu flash converter follows the ideas of the flash smelting. By means of highly O_2 enriched air ground and dried matte of the furnace (80 % minus 0.14 mm) is sent to the reaction shaft via a matte furnace. The matte is heated, ignites and oxidises to blister copper. Since the matte is high in copper, only a low amount of slag is produced, which is sent back to the flash smelting furnace. Table 12-3 shows first data of the converter in Garfield / Utah. Disadvantageous in both procedures is the high sulphur content of the blister copper, separated in the refining furnace and leading to an additional emission of 6 and / or 14 kg of SO_2/t Cu, if the exhaust fume of the refining furnace cannot be sent to the reaction furnace. Usually these gases are only de-dusted.

Table 12-2. Data about the C-Furnace (Mitsubishi-Procedure) (Brimacombe & Mackey, 1992)

Diameter	8.05 m
Bath volume	46 m^3 (55 m^3)
Number of lances	10
Feed	45.7 t matte (67% of Cu) 2.8 t lime, 3.0 t scrap iron (99 % of Cu)
Products	31.8 t copper (0.6 % of S) 18 t slag (14 % of Cu)
Process air Nm^3/h	30.000 Nm³ (30 % O_2)

Table 12-3. The Kennecott - Outokumpu converter (Biswas & Davenport, 1994; Chen & Diaz, 1995)

Reaction shaft	Height: 6.5 m, 1 matte furnace, diameter: 4.5 m
Hearth	18.75 x 6.5 m
Bath volume	up to 120 m^3 *
Feed (t/h)	57 t matte°°, (70% of Cu) (+ 1.6 t surcharges)
Products (t/h)	36 t Cu (0.3% S, 9 t slag (18% of Cu)
Blast air Nm^3/h	25,000 Nm³, (70% O_2) (up to 80% O_2)

°° up to 82 t/h feed, * estimated value

4. ANODE PRODUCTION

The conventional anode production works batch-wise on a casting wheel, where one or two casting moulds are filled with liquid copper before being weighed and cast into the anode form. With anode weights of 400 kg, the precision is better than 1%, leading to an anode weight between 396 and 404 kg. Through weighing and sorting, anodes of the same weight can be used in the electrolysis. The constant weight plays a crucial role in the dissolution of the anodes and the balanced current distribution, thus also influencing the cathode quality and the amount of reverts. The casting wheel moves step-by-step. On accelerating the wheel, liquid metal can remain in the mould and can build up on stopping the wheel. Swing edges can occur at the anode. Casting performances up to 80 t/h with one wheel, and about 100 t/h with two smaller twin wheels can be achieved. Figure 12-6 shows such a twin installation. Nowadays, belt-cast anodes offer an alternative worth being considered. Anode copper is cast between two water-cooled and simultaneously operated steel belts. The sides are sealed with so-called dam blocks. The ears of the anodes are inserted in the dam blocks. By means of pinch rolls the cast band is sent towards a hydraulic shear or plasma separation blades where the anodes are separated and insolated. These anodes show a highly constant weight, no swing edges and have an even surface. According to the individual demand, the casting speed varies from 60-100 t/h. Such anodes actually belong into a Mount Isa-Electrolysis. Figure 12-7 shows such a contil-anode plant. Band-cast anodes lead to an elevated current distribution, less reverts and thus to a better energy utilisation.

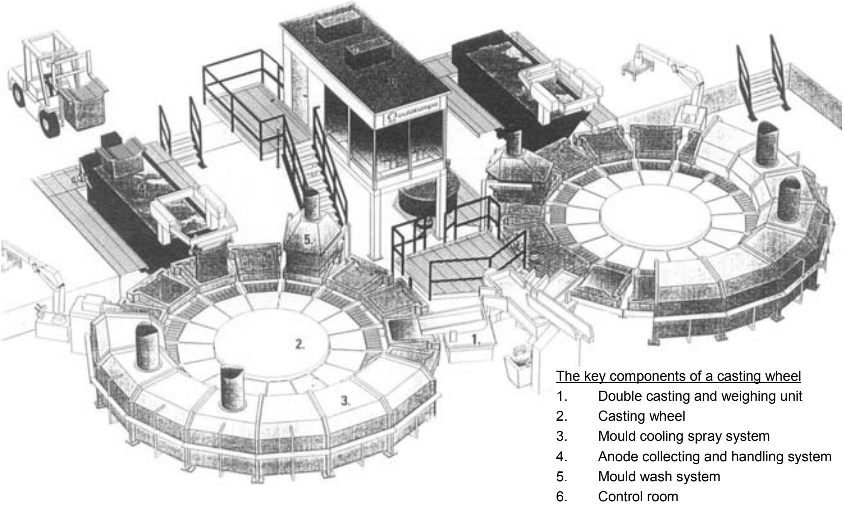

Figure 12-6. Twin casting wheel (Outokumpu, 1997)

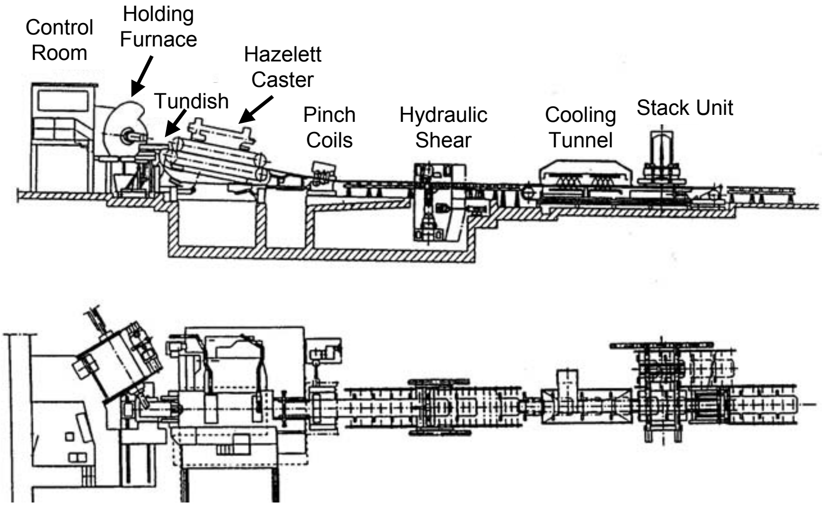

Figure 12-7. Scheme of a Contil anode casting plant (SMS Sea, 2000)

5. REFINING ELECTROLYSIS

For 90 years, the refining electrolysis was performed without any alteration until the Australian zinc electrolyses was being investigated and that know how was used for the copper electrolysis. For 10 years and all over the world, the electrolyses have been converted into Mount-Isa-Systems. Nowadays, approximately 50 plants with a capacity of 4 x 10^6 t/a Cu use this procedure. Above all, the productivity is increased by the higher current density, and the automation leads to a lower manpower requirement.

Table 12-4. Comparison of the copper electrolysis systems (Landau & Traulsen, 1990)

	Conventional	**Mount Isa**
Starting sheet metal	Copper	Steel
Current efficiency	94% with 200 A/m^2	98% with 260 A/m^2
Steam demand	1 t/t Cu	0.15 t/t Cu
Energy demand	250 kWh/t Cu	260 kWh/t Cu
Personnel expenditure	2.4 h/t Cu	0.5 h/t Cu

The differences to the conventional electrolysis clearly turn from table 12-4.

- higher current density ⇒ higher productivity
- higher current efficiency ⇒ less energy needed because of a more precise positioning of the electrodes at comparable current density
- less manpower needed ⇒ lower costs
- high degree of automation ⇒ lower costs at better supervision

6. RECASTING

In the past, the cathodes were recast in a hearth furnace. Nowadays such furnaces have been replaced world-wide by the gas-heated Asarco shaft furnace, which was introduced approximately in 1965.

This furnace is marked by:

- an outstanding heat exchange
- thus a low energy expenditure
- a high melting speed

It serves as casting aggregate for the following continuously working casting and casting-rolling procedures. The melting and casting speed is varying between 6 and 80 t/h. The energetic efficiency of this furnace reaches approximately 60%.

This furnace is a slim shaft furnace and covered with SiC refractories. As far as to the platform height the furnace is filled with cathodes. The heating is achieved by means of max. four burner rows. There are natural gas operated tunnel burners, adjusted to weakly reducing conditions. The burned gas streams upwards in the shaft, is then warming up the cathodes, which melt. Liquid Cu is drained directly into a holding furnace (see figure 12-8).

This furnace can be shutdown at the push of a button. Liquid copper is drained off, the melting process stops. After the interruption (e.g. during the night), the furnace produces liquid metal again within 10 minutes.

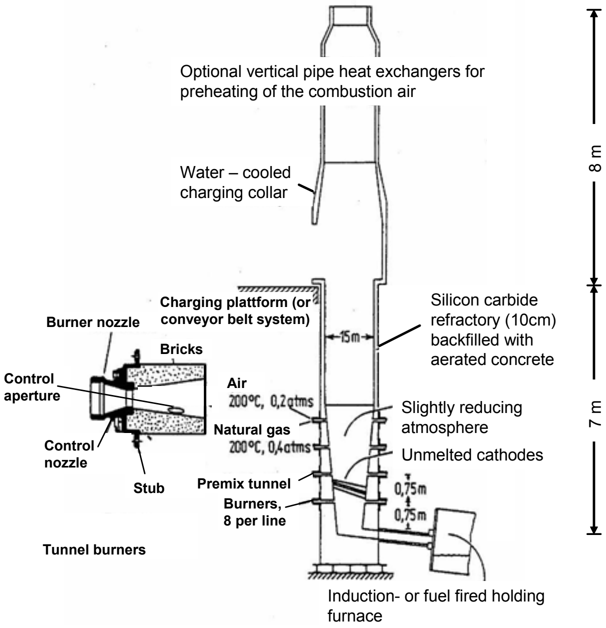

Figure 12-8. Scheme of an Asarco-Shaft furnace (Biswas & Davenport, 1994)

7. CASTING-ROLLING PROCEDURE

For more than 30 years, copper and aluminium works have efficient, continuously working casting-rolling plants. Table 12-5 gives an overview of today existing plants. Figure 12-9 shows a Southwire plant for the production of casting wire where the cable is generated on a casting wheel. Figure 12-10 shows a Contirod plant for the manufacturing of casting wire, and alternatively, for the production of plane strips (150 mm). Next step is the production of broad strips, with prototypes still being tested. With these casting procedures for strips and wire, considerable energy saving is possible, since they work on the same heat level. Furthermore their productivity is very high, leading to lower overheads.

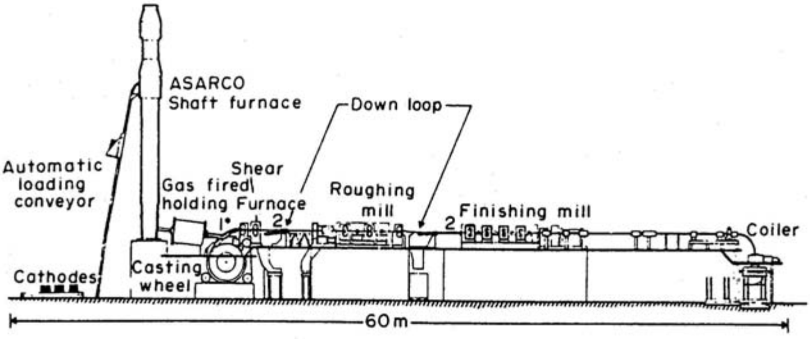

Figure 12-9. Southwire plant for the manufacturing of casting wire (Biswas & Davenport, 1994)

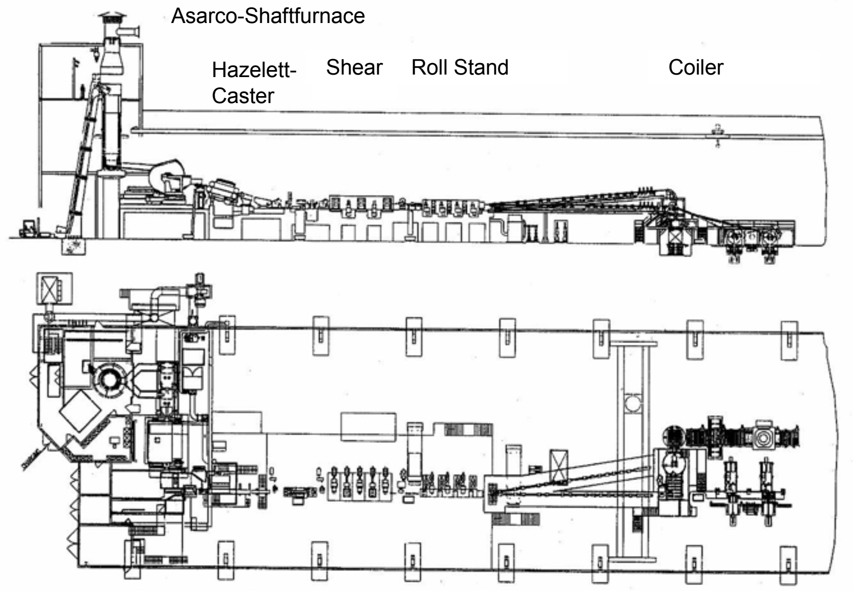

Figure 12-10. Contirod plant for the alternate manufacturing of casting wire as well as copper strip (SMS Sea, 2000)

Table 12-5. Overview Casting-rolling plants (Habashi, 1997)

Procedures	Principle	Number of plants	Performance
Properzi	Casting wheel	10**	Up to 30 t/h
Southwire	Casting wheel	30**	Up to 50 t/h
Contirod	Double belt	33°°	Up to 60 t/h
General Electric *	Passage of a core wire	20**	Up to 10 t/h
Outokumpu *	Suction mould	20**	Up to 16 t/h

* oxygen-free / ** 1985 / °° 2000

8. CONCLUDING COMMENTS

This report presents the milestones in the development of copper manufacturing procedures and processing. Crucial steps in reducing energy consumption, the emissions and the costs took place between 1950 and 1980 (see table 12-6). Recent years were marked by optimisation of process supervision and process control. They led to remarkable production increases and an increase of the product quality. While, without a doubt, less energy expenditure or a low emissions level can be assigned to the sustainability in the copper metallurgy, this is applicable also to better process supervision and process control. However, all these procedures led to reduced personnel expenditures.

Table 12-6. Technological advances in the copper metallurgy

Flash smelting of copper concentrates Outokumpu Inco	[A, B, C]	 1950 1955
Bath smelting of concentrates (Noranda, El Teniente), suitable for primary and secondary materials (Sirosmelt, Mitsubishi)	[A, B, C]	 1975 1990
Special cooling at reactors (PW)	[C]	1995
Continuous Cu-conversion Mitsubishi SMOC	[B]	 1970 1995
Injection and granulation at reactors (PW)	[A, C]	1995
Shaft furnace smelting of secondary copper (MKM-Küttner) Crude copper (Contimelt) Cathodes (Asarco)	[A, C]	 1995 1980 1965
Intensive refining of copper HTM (Junker)	[C]	2000
Belt casting of anodes (Contilanod)	[C]	1980
Modern electrolysis technology permanent cathodes, current density > 300 A/m², process control	[D, C]	1980
SX-EW (Oxide ore processing)	[E]	1970
Continuous casting-rolling procedures Contirod GE-dipforming, Outokumpu, Properzi, Southwire,	[A, C, D]	1960-1970

(Continued)

Flash smelting of copper concentrates	[A, B, C]	
Outokumpu		1950
Inco		1955

A: lower energy expenditure
B: better emission control
C: higher productivity
D: better quality
E: utilization of previously not suitable raw materials

SMOC: solid matte oxygen converting / HTM: High turbulence mixers / SX-EW: solvent extraction-electrowinning / PW: Paul Wurth / GE: General Electric

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Chapter 13

THE HAMBURGER ALUMINIUM-WERK GMBH'S CONTRIBUTION TO A SUSTAINABLE CLOSED LOOP ALUMINIUM SYSTEM

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1. INTRODUCTION

The Hamburger Aluminium-Werk GmbH (HAW) is built next to the Hamburg harbour (figure 13-1). Since 1974 aluminium has been produced by electrolysis of the raw material alumina. This alumina is extracted from bauxite at the plant in Stade (4 t bauxite → 2 t alumina → 1 t aluminium). Alumina and calcined petcoke, the raw material for the carbon anodes, are shipped to and unloaded in HAW's own harbour. 110kV power lines supply HAW with the electricity needed for the electrolysis process. The liquid aluminium that is produced in the electrolysis is cast into sheet ingots in the casthouse.

During the last few years, in addition to liquid (primary) aluminium from the electrolysis, large amounts of return metal from the market (secondary aluminium) has been melted in the casthouse. This recycling material is melted in the casthouse furnaces that are fired with natural gas and, together with primary metal from the potrooms, cast into new products. At the moment HAW produces about 130,000 t/y in the potrooms (approx. 20% of the total primary production in Germany), which is processed together with 80,000 t/y of clean recycling material to approx. 200,000 t/y of sheet ingots. Most of these sheet ingots are further processed in the aluminium rolling mill, located next to HAW.

A. von Gleich et al.(eds.), Sustainable Metals Management, 347-354.

Figure 13-1. HAW aerial view.

2. ALUMINIUM / APPLICATION / RECYCLING

In 2001 in Germany 2.9 million tonnes of aluminium were used (figure 13-2), 0.65 million tonnes of primary aluminium were produced and 0.62 million tonnes of recycling (secondary) aluminium were remelted (figure 13-3).

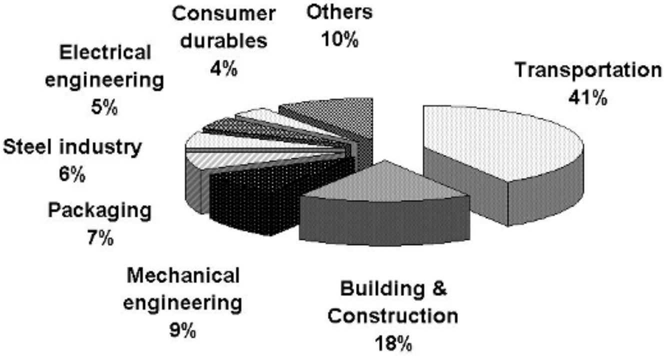

Figure 13-2. Aluminium market in Germany 2001. Source: Gesamtverband der Aluminiumindustrie.

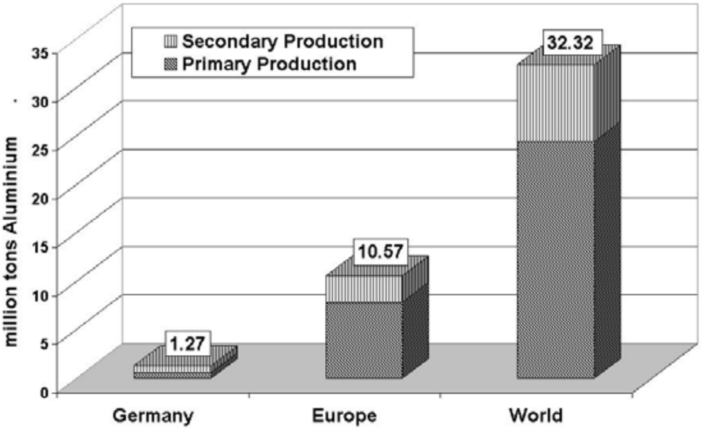

Figure 13-3. Aluminium Production 2001(million tonnes). Source : Aluminiumzentrale.

Applications for aluminium are increasing from year to year (in Germany 3.8% per year from 1991 to 2001) due to its extraordinary characteristics, such as low specific weight for all methods of transportation, low level of maintenance for corrosion resistance, good electrical conductivity and packaging for food.

Aluminium has much potential as a sustainable material and this can be illustrated with the following examples:

Due to it's excellent recycling properties, aluminium can be processed again and again to constantly high quality products. Secondary aluminium production uses up to 95% less energy than primary aluminium production. Metal loss during the complete recycling and melting process is approx. 1%. The recycling level in Germany is quite high, with an average of about 80 – 90%.

In the transportation sector, aluminium has become an important material for car, aeroplane and train production. If a car is produced using aluminium for the engine block, body work and chassis, a weight saving of 100 kilograms can be achieved, which reduces fuel consumption by up to 0.7 litre per 100 km. The energy needed to produce the aluminium can easily be recovered over the period of use.

The Volkswagen Lupo only weighs 826 kg (of which 135 kg is light metal). The Lupo shows an average fuel consumption of 2.38 litres per 100 kilometres (figure 13-4). Predictions for the future use of aluminium in the automobile industry are illustrated in Figure 13-5. Aluminium used in automobile production can be recycled and this continues to increase the use of secondary aluminium for car production. The quality of the recycled material, for example an engine block, is, after remelting, of the same quality and can be used for a new engine block.

Figure 13-4. VW Lupo.

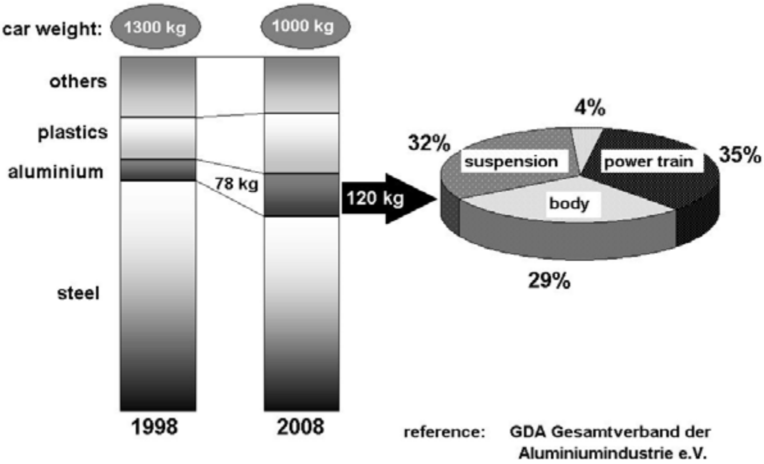

Figure 13-5. Aluminium in the automotive industry.

3. HAMBURGER ALUMINIUM-WERK GMBH'S CONTRIBUTION

The plant's contribution to a sustainable system can be illustrated with savings in energy and raw material consumption, as well as the avoidance of, or reduction in waste material and emissions.

3.1 Energy

Due to the chemical qualities of aluminium (base metal) production by fused salt electrolysis is energy-intensive. All around the world low cost sources of energy are being used, mainly hydro power (figure 13-6). During the last 10 years HAW has developed and improved the control provided by computer and magnetic compensation of high amperage cells. This has resulted in a 10% reduction in energy consumption (figure 13-7).

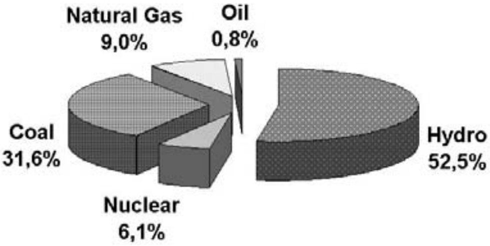

Figure 13-6. Sources of energy for aluminium production in 2001. Source: International Aluminium Institute.

The electric power makes up about 30% of the total production costs of aluminium produced in the potrooms.

Overall energy consumption for aluminium products at HAW is continuously decreasing due to the increased production of aluminium from recycling material:

The values are now:

- 130,000 t/y at 13.5 kWh/kg (electric power)
- 80,000 t/y at 0.7 kWh/kg (natural gas)

In the casthouse the flue gas from the furnaces is used in recuperators to heat up the combustion air (15% of melting energy can be saved in this way).

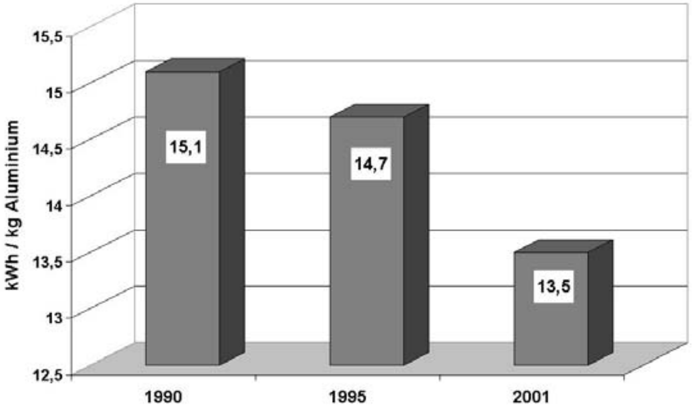

Figure 13-7. Development of specific energy consumption in the HAW electrolysis.

3.2 Raw materials

The amount of raw material alumina needed for the production of aluminium is defined in the electro-chemical process and cannot be reduced, even with optimised processes. This corresponds to the simplified equation:

$$2\ Al_2O_3 + 3\ C \rightarrow 4\ Al + 3\ CO_2$$

However, the carbon "C" in form of anode material that is needed in the electrolysis offers potential for savings. Over the past 10 years the specific consumption has been significantly reduced. This means that over the last 10 years HAW has been able to reduce specific carbon consumption (from 450 kg C per t aluminium to 403 kg C per t aluminium) and at the same time reduce the amount of CO_2 produced.

For more than 50 years aluminium producers have been working on the development of an inert anode made of ceramic materials or special metal alloys. Such an anode would not be burned off by the oxygen, which is what happens to the carbon anodes that we are using now.

The use of inert anodes could mean that in 10 years no carbon material would be needed for the production of aluminium. The shareholders of HAW are working with expert groups in this field. Up to now there are only a few small pilot cells in operation.

3.3 Emissions/Waste

Fluorine gas is a waste gas from the electrolytic cell. Since the start up of the plant these gases have been cleaned using the first dry scrubber ever used in Europe.

This scrubber does not use additional cleaning agents, because alumina (Al_2O_3), the raw material for the electrolysis process, serves as an absorber. The alumina is enriched with fluorine that passes through the dry scrubber and is then fed back into the electrolysis, which forms a closed-loop system. This dry scrubbing system runs with an efficiency of 99.7%. There is no waste at all (figure 13-8).

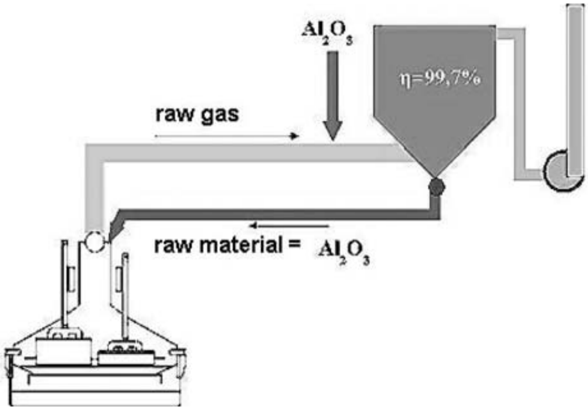

Figure 13-8. Cleaning of electrolysis gas principle of the dry scrubber system.

The same dry scrubbing principle is used in the Carbon Plant. The raw material coke is used as a cleaning agent for pitch vapours. In this scrubbing system no waste water is created.

Water at HAW only comes from the cooling towers for the furnaces, metal cooling during direct chill casting and domestic waste water after biological treatment.

Equipment such as the electrolytic cells, the melting and casting furnaces and the anode baking furnace that operate at high temperatures only have a limited service life. Used equipment is relined with new firebricks and put back into operation.

There are two methods that can be used to reduce the amount of waste bricks:

– Increased service life
– Material and energy reuse of waste products

HAW makes use of both of these methods. The base heat insulation of the HAW electrolysis cells is made of alumina, instead of firebricks that are commonly used world-wide. HAW's insulation does not cause waste and can be reused in the electrolytic process.

Further technical progress due to the introduction of powerful computers and simulation software have considerably increased the service life of equipment parts and generally reduced repair costs and the amount of waste products. The service life of the HAW electrolytic cells has increased during the last 10 years from 4 to 7 years.

4. FURTHER DEVELOPMENTS

The Hamburger Aluminium-Werk GmbH, beside it's own projects, has carried out a number of projects in co-operation with the Federal Environmental Agency and the Universities in Hamburg and other neighbouring projects or companies.

We are discussing the possibility of feeding recovered heat/warmth (potroom cells, casthouse furnaces) into a long-distance heating network for local residential areas.

However, all these above-listed improvements from the last 10 years could only have been achieved with motivated employees, these milestones are:

- a well-developed environmental management system
- the certification of all divisions in the plant according to DIN ISO 9002
- an active employee suggestion system (4 suggestions per employee in 2001)
- a benchmarking system with the global leaders in the field of aluminium production

This helps us to search for potential for improvements, to achieve high quality products in all divisions and to reduce emissions and waste.

This just goes to show that sustainable production not only conserves the environment and resources, but also minimises production costs.

The reduction of electric power consumption, about 30% of the production costs of primary aluminium, is the main area that needs to be addressed if HAW is to survive on the global market.

In comparison to the other world primary aluminium smelters we are a frontrunner with our energy and carbon consumption level, service life of the electrolytic cells and the amount of emissions and waste material for 180 kA cell technology.

Chapter 14

SUSTAINABLE USE OF COPPER

Impediments and goal conflicts of consistency, sufficiency and efficiency strategies

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1. SUSTAINABLE DEVELOPMENT AND THE USE OF COPPER

With the publication of the report “Our Common Future”, in 1987 the World Commission on Environment and Development (Brundtland Commission) established the concept of “sustainable development” in international policies. It defined sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” (WCED, 1987). A more precise definition of the ecological dimension of the use of raw materials was given by the Enquete Commission “Protection of people and the environment” of the 12th German Bundestag in its report “Designing the Industrial Society[1]. “ It established four rules (Enquete Commission, 1994, p. 45ff):

- The extraction rate of renewable resources should not exceed their regeneration rate. This complies with the demand to uphold the ecological capability, or (at least) to conserve the ecological real capital as defined by the functions.
- Non-renewable resources should be used only to the extend to which a physically and functionally equivalent replacement in the form of renewable resources or higher productivity of the renewable as well as the non-renewable resources, is created.
- Releases of materials into the environment should be oriented at the resilience of the environmental elements, while all functions are to be taken into account, not in the least the “silent” and more sensitive regulatory function.
- The tempo of anthropogenic releases or intrusions into the environment must be balanced with the reaction time for the natural processes relevant to the environment.

A. von Gleich et al.(eds.), Sustainable Metals Management, 355-373.

The current handling of copper and the other metallic resources must be able to be measured, above all, by the second and third management rule.

The second demand refers to the exhaustion of primary resources. However, its origin is the discussion about finite fossil energy carriers. It aims at the expansion of the renewable energies as a perspective for the solution. Even if by now the discussion of the seventies and eighties about the range of the resources no longer is the center of interest, it is, however, undisputed that the metallic resources on earth are finite and it is anticipated that in the not so distant future some of the mineral resources probably will not be available to future generations. This is applicable particularly to some special important metallic resources like copper, lead, zinc and magnesium. The consumption of virtually all metallic resources rises continuously and is subdued only temporarily by continental or global economic crises. The essential cause for this rising consumption is the world economic growth as well as the development of demands of many threshold and developing countries. Consequently, the supplies of metals like copper are continuously increased and expanded in the technosphere.

The third demand is oriented at the release of materials into the environment, which is connected with the use of metallic resources over the entire life cycle. It is undisputed that copper mining as well as mining of other resources is associated with considerable burdens on the environment. In this context high energy consumption, the improper disposal of mining waste and overburden, special waste through the insertion of toxic chemicals, contamination of ground and surface water with chemicals and heavy metals, destruction of habitats and dust emissions are to be named. The magnitude of the use of the environment through the primary copper production (mining and production) can be approximately clarified based on some figures if a yearly worldwide production of circa 13.2 million tons of copper ore is assumed for the year 2000 (Edelstein, 2000, p.8). However the range of the emissions and the consumption of auxiliary resources are very large due to the different storage facilities and processing technologies (UBA and BGR, 1999):

Table 14-1. Demands on the environment through copper

Category	quantities / t Cu	totals for 13,2 million t Cu
Overburden	ca. 100 - 350 t	ca. 1.3 to 4.6 bil. t
Spoils (contaminated)	ca. 50 - 250 t	ca. 0.7 to 3.3 bil. t
Consumption of primary energy	ca. 30 - 100 GJ	ca. 400 to 1300 Mio. GJ
Water consumption	ca. 200 - 900 m^3	ca. 2.9 to 11.9 bil. m^3
SO_2-Emissionens	ca. 300 kg	ca. 4 Mio. t
Flotation chemicals	ca. 5 - 25 kg	ca. 66,000 to 330,000 t

For comparison: the Federal Office for Statistics states that Germany's annual consumption of abiotic resources, including sand, gravel, rocks and soils, etc. is a little over one billion tons (without overburden) . However, it shall be noted here that the environmental burdens through copper mining are evident mostly in the producer countries and, therefore, can be influenced only to a small extend by national politics of the industrial countries like for example Germany. Emissions by the copper industry are further directly dependent on the respective national legislative framework, so that for example the Norddeutsche Affinerie, which runs a production facility in the city area of Hamburg, essentially has to comply with considerably more strict emission restrictions than a producer in the remote copper mining regions.

The management rules call on us to reconsider our procedures for the use of resources and to change them in the cases, in which they don't comply with the four rules. Even if the chances are low on one hand that national politics in Germany can take influence on the production conditions of copper in other states, on the other hand, as the increase of the supplies due to the world economic growth strides forward, there is leverage to decrease the environmental burdens in the producer countries: Sustainable handling of copper in Germany.

However, the difficulty lies in the interpretation of what constitutes "sustainable handling". Since sustainability is an open term, the way to sustainability has to be understood to be a search process only. And this process will yield different answers depending on the patterns of use for copper. For example, usually it is differentiated between the input side with the creation of supplies and the output side with the waste and recycling flows (s.a. Erdmann, 2002). On the input side, "sustainable use" means to achieve defined effects with minimal copper use, whereas both, the use as well as the effect are dependent respectively on the highest standard of technology. On the output side "sustainable use" means that we should achieve a maximum recycling quota of used up copper products, to be able to work with the existing supply of copper products and use as few primary resources as possible. In search of an interpretation for the sustainable use three basic strategic directions have developed in the German-language scientific discussion, each of which gives specific answers to the search process. These three directions are consistency, sufficiency and efficiency. Bellow some aspects of these three strategic options will be described.

2. CONSISTENCY AND USE OF COPPER

Consistency means the compatibility of material flows mobilized anthropogenically and the natural cycles. The basic idea here is that the world as a global system is regulated by natural cycles and human activities should influence these cycles as little as possible. The classic examples for an adaptation of the human activities to these cycles are, for example, the use of hydrogen (provided it is produced with regenerative energy) as a gasoline substitute, or wood instead of stone for house construction. The demand for consistency in the anthropogenic copper flows may be interpreted from two principal directions: For one, the copper emissions cannot lead to the exceedance of the critical loads of the ecosystems. For the other, the copper emissions are to be minimized throughout the entire life cycle.

As is obvious from estimates of the UBA and the BGR regarding the emission side, such a strategy of consistency must aim above all at the decrease of the energy usage and the heavy metal emissions during production through modern technology.

Another principal option for a consistency strategy is the use of regenerative substitutes, which fit into the natural cycles. Since copper is used in very different areas due to its many different specific qualities, it must be decided for every individual application purpose whether regenerative substitutes should be considered. In the following table 14-2, some essential application purposes of copper are listed.

Table 14-2. Substitute for copper in the framework of the consistency strategy

Application purpose	regenerative substitute	not-regenerative substitute
Power line	not known	conductive aluminum
Information transportation	not known	fiberglases, richtfunk
Heat management, refrigeration	not known	steel aluminum
Material transport (pipes)	biopolymers?	plastic, steel tubes, plastic tubes (for example polypropylene)
Casings construction industry	partial wood	plastic, bricks, steel, zinc,
Sterile production and storage	not known	steel, glass,
Machine parts	not known	steel, possibly ceramics
Metal figures	wood	tin

Does one consider the application purposes listed in the table, the column "regenerative substitutes" shows many gaps. Only for some quantitatively insignificant applications in construction, (copper as decorative panels, for example, roofs), or for brass figures, a substitution through wood is possible. Currently an important substitute for water and heating pipes from copper are pipes from propylene, which is produced from non-regenerative resources, though. Biopolymers are a possible regenerative substitute for copper pipes. However, neither technical nor economic concepts are in view at present.

For the majority of the copper applications only non-regenerative substitutes are available, whose ranges, however, are presumably considerably greater than that of copper. The use of these substitutes opens at least the option to fulfill the principle of intergenerative equity because the copper resources are conserved and remain usable in the same form for future generations as they are for us. However, the use of these substitutes is frequently problematic, not only because they lack the ability to regenerate. For example, conductive aluminum can be used for power lines, but it has inferior conductivity. This causes a less efficient use of energy. From an ecological view it has to be considered that efficient provision and distribution of energy is of great importance due to the greenhouse effect. More exact information whether substitutes are suitable from the ecological view can be documented only through life cycle assessment.

3. SUFFICIENCY AND USE OF COPPER

The second possible strategy is sufficiency. This is understood as modesty and it means in general, that one abstains from material things consciously although one could afford them. Sufficiency is an element of sustainable consumption or lifestyle and has certain similarities with the philosophy of Epicurus. Its goal is a life without a lack of well-being, which satisfies the principles of the inter- and intra-generative equality. These principles are derived from the realization that we as citizens of the first world afford ourselves too much consumption of resources and nature and, therefore, diminish the chances of development for both, a large part of the now living generation as well as the future generations. According to Bleischwitz and Schütz the rich fifth of the world population in the industrial countries uses approximately 4/5 of the global resources (Quoted by Bund and Misereor 1996, p. 15). To avoid disproportional limitation of development options for poorer countries, the highly developed countries would have to reduce their resource consumption and their emissions drastically. Therefore, Weterings and Opschoor demand in their study "Sustainable Netherlands" that the availability of non-renewable materials needs to be guaranteed for at least another 50 years to fulfill the intergenerative equality (Weterings and Opschoor, 1992). From this they draw the conclusion that the Netherlands must lower its copper consumption by at least 80 percent.

The fulfillment of this demand through sufficiency strategies can, without a doubt, create big ecological advantages like the decrease of recovery and overburden materials, decreased energy consumption or reduced heavy metal emissions. A noticeable influence on the global material flows through national policies in Germany is possible, in principle, since Germany had a world market share of approximately 4,7 percent of the production of refined copper in 2000 (Edelstein, 2002, p.23) and is consequently the fifth-largest producer of refined copper in the world. On the consumption side, Germany also has a considerable share. Due to the economic structure with a high export share of products of the highest manufacturing level (for example motor vehicles EE-appliances, machines) it is the fourth-largest consumer worldwide in 1999 with approximately 8 percent (BGR 2000).

However, sufficiency as an actually lived strategy can lead to considerable problems in developing countries as well as in the industrial countries. For one, reduced copper consumption would lead to income losses for the producer countries. Approximately 1.7 million tons, or 13 percent, of the ore production in the year 2000 comes from countries with a gross domestic product of less than $745.00 per capita (low income[1]). Further 2.7 million tons or 20 percent of the ore are produced in countries with a GDP between $746 and $2.975 per capita (lower middle income). In addition, these two groups of countries produce 1.76 million tons or approximately 43 percent of the commercially pure copper. This means that approximately 33 percent of the copper ore and approximately 43 percent of the commercially pure copper originates from developing countries. A conscious decrease of imports admittedly reduces the ecological effects connected to mining; however, it leads with a high degree of certainty to a decrease in the ability to developing for those countries that produce considerable amounts of ore and commercially pure copper, such as Indonesia, Kazakhstan Peru, Philippines South Africa, Uzbekistan, Zambia and Zimbabwe. Hereby, a considerable conflict emerges between the goals of the Rio convention: environment and development. The following table 14-3 summarizes the most important producer countries of commercially pure copper and copper ore according to their per capita gross domestic product:

Table 14-3. The most important producers of copper ore and their production of commercially pure copper (2000) according to their GDP per capita (2001)

	Ore production (t)				Commercially pure copper production (t) (primary production)	
Country	low income	lower middle income	upper middle income	high income	low income	lower middle income
	<745 $	746 to 2975 $	2,976 to 9,205 $	> 9206 $	<745 $	746 to 2975 $
Argentina			145,200			
Australia				829,000		
Botswana			38,400			
Brasil			31,800			
Bulgaria		75,000				160,600
Burma	26,800					
Chile			4,602,400			
China		590,000				990,000
Finland				11,600		
India	35,500				225,600	
Indonesia	1,012,100				173,700	
Iran		145,000				150,000
Canada				634,200		
Kazakhstan		430,000				400,000
Congo	21,000				21,000	
Mazedonia		10,000				
Mexico			364,600			
Mongolia	124,800					
Namibia		5,100				13,500
North Korea	14,000				20,000	
Papua New Guinea	200,900					
Peru		553,900				340,400
Philippines		32,000				140,000
Poland			456,200			
Portugal				76,200		
Rumania		16,100				16,500
Russia		570,000				580,000
Zambia	241,200				194,500	
Sweden				75,600		
Serbia / Montenegro		41,000				86,000
Spain				23,300		
South Africa		137,100				126,100
Turkey		76,300				37,000
USA				1,440,000		
Uzbekistan	65,000				75,000	
Zimbabwe	2,100				10,000	
Cyprus				11,300		

In the developed countries of the world, the status of "consumption" and "property" are another impediment. The rate of households equipped with electrical appliances has reached or surpassed the 100 percent mark in most areas. An equipment rate of over 100 percent has been reached in Germany also for passenger cars due to the increase in second cars. Second homes and vacation apartments are another considerable "prosperity supply" for copper. The sufficiency strategy offers a multitude of well justified more sustainable answers to these specific prosperity uses. So, sufficiency is enabled by the use of a rental car instead of a second car, a vacation in a rented room or house instead of a second home, or the acquisition and renovation of an old condominium in the city versus a new construction in the suburbs. It is to be noted, however, that all strategies, which aim toward "sustainable consumption", are presently still confronted with serious impediments especially regarding the acceptance of such consumption patterns.

But also the economic significance of copper presents a grave impediment provided the strategy of the sufficiency is supposed to lead to a "life of well being without lack." This can be shown exemplarily based on the production values of goods with copper as functional share for the year 2000 (Statistical Federal Office, 2001 p. 214ff).):

Table 14-4. Production values of some merchandise groups relating to copper for 2000 (Germany)

Merchandise group	production value
Refined copper and alloys	1.2 bil. €
Mechanical engineering (only combustion motors pumps, compressors, armatures, electro carts, packaging, tool, spin, woodwork, plastic machines, machines for metal production and processing, for paper and printed trades)	39.4 bil. €
Household appliances (refrigerators wash and dishwashers, herd, vacuum cleaners)	5.7 bil. €
Appliances for electricity production and -distribution (electric motors, transformers, accumulators, sockets, switch, and steering installations, modules, cables, lamps, alarm and fire alarm)	26.8 bil. €
Radio, television and news technology (modules, transmitters TVs, video recorders, appliances for the conductor bound communication, motor vehicle receivers)	23.8 bil. €
Office machines, digital data processing appliances	10.6 bil. €
Private car, truck, busses, tractors	113.6 bil. €
Medicine, measuring-, steering instruments, and regulation technology	4.2 bil. €
Total	225.3 bil. €

The production value for refined copper in Germany is approximately 1.2 bil. € in the year 2000. The actual values for the import of copper ores are approximately 0.35 bil. €. In addition, copper is imported in its raw state, as alloy, and as scrap metal. Here, the value of the merchandise was approximately 2.2 bil. € (Federal Office of Statistics 2001 p. 285,ff). Beginning with these copper products, the manufacturing of semi-fabricated products follows (wires, pipes, sheet metal and form pieces, see illustration below). These and their successive products in turn make up an essential part of products from the sectors of mechanical engineering, electronic technology, motor vehicle construction, among others. For only the above mentioned examples a production value of approximately € 225 bil. is the result. Even if the bulk of the above listed goods can contribute to export and consequently also to the development of other countries, a large part remains in Germany and is supplemented by imports. A strategy of the sufficiency that aims at a conscious reduction of consumption would be connected to considerable economic effects on the labor market, tax revenues and social security systems. This shows another serious goal conflict on the way to sustainability. Ecologically, it makes sense to limit resource use through sufficiency. But the effects of a truly sufficient lifestyle have immediate consequences which contradict other goals of sustainability, for example the protection of jobs and occupations. Sufficiency strategies are, without question, one element on the route to a sustainable and future-capable economy in the ecological sense. The economic dependency on copper for the merchandise production of the industrial and the developing countries and the lacking willingness of the populations to reduce consumption are impediments too substantial for sufficiency strategies to contribute significantly to the reduction of material use in the near future.

4. EFFICIENCY AND THE USE OF COPPER

The third possible strategy for sustainable copper use is the efficiency. Simplified, this means minimal copper use to acquire a maximum benefit. In the widest sense, efficiency has diverse facets regarding the use of copper, for example, avoidance of dissipative applications, longer life of products, minimization of the material use or improved recycling. While the first three approaches aim at the input side, the focus of recycling is on the output side. Following, the four aspects are presented briefly.

4.1 Avoidance of Dissipative Applications

Under dissipative applications one understands the use of copper in a form, in which it cannot be recovered anymore technically or economically. The meaning for the efficiency lies hereby in the fact that due to the usage patterns of the copper material flow in the sense of the cycle economy it cannot be closed and, therefore, a continuous input of primary resources must take place. Three cases are to be distinguished.

In the first case, copper is used in very low, compact quantities, which are mixed with large quantities of other substances. This applies to copper foil as Christmas tree ornaments or brass screws that are disposed of through household garbage, for example. However, these applications are quantitatively of subordinated importance. Small electrical appliances, that are also disposed of through household garbage pose a relevant exception. Disposal leads to the discharge of the copper from the economic cycle. Through household garbage incineration the copper is also withdrawn from the economic cycle because it would be recoverable from the heterogeneous inerted slag only with very big expenditure.

The second case is the use of copper connections or copper solutions for specialty applications. Copper sulphate is used in medicine as an emetic or as a pesticide in wine-growing. In addition, copper sulphate is used to copper plate household appliances. This type of copper application also causes an elimination of the copper from the material flow since a recovery is possible only in theory due to the low copper quantities for the respective use. Quantitatively, such copper applications are insignificant in relationship to the main application types of copper. In 1999 approximately, 10.000 tons of copper sulphate were produced altogether but from this only a part was used openly and was released into the ground.

The third case is quantitatively the most important. With the third type of the dissipative application compact quantities of copper or its alloys are used in such a form that their retrieval on a large scale is currently economically not profitable. This applies, above all, to the laying of power lines and water pipes in the ground and walls. For example, approximately 180.000 tons of copper cables were laid in the year 1999 in buildings in Germany (New building and modernisation, European Copper Institute, 2000, p. 29). The share of copper pipes for sanitary and heater installations should be of the same magnitude. That is contrasted by the demolition of buildings and the recovery of cable and pipes. Affected by the demolition, however, are older buildings (therefore built mostly before 1950) buildings, where the copper share is clearly lower due to fewer cross-sections and less electrical provisioning as well as the use of aluminum pipes. Easily accessible cables, water and heater pipes, as well as armatures still are mostly removed before demolition because easy accessibility makes this selection economical. The cables and pipes that are encased in the stonework are mixed in with the rubble during the demolition. The amount of construction rubble in Germany is estimated to lie between 26 (1990) and 46 (1995) million tons per year, according to different sources (see the compilation of different studies in Scharp et al. 2002). Considering the different studies about the use of copper in buildings, it can be estimated that the copper share in the construction rubble is clearly less than 0,5 percent (see Behrendt, Klinski, Scharp and Zwiesele 1999 p. 68 ff). If applications with a high amount of copper like pipes or fittings are separated first, the copper share declines to roughly under 0,1 percent. In principle, it would be possible, to recover the copper from building rubble if the share was larger than 0,1 percent[3]. However this process is faced by various impediments. For one, the metallic-pure form of copper prevents the usual ore concentration techniques. Manual separation is made more difficult through tearing of the pipes when breaking open the rubble, but is suitable for more stable pipes. Further impediments are the discontinuous accumulation of rubble, the presently regional disposal of rubble, the very low disposal prices as well as the high transportation charges of the large central reclamation sites.

The dissipative uses currently expand to partially include products like motor vehicles or large EE-appliances. The cause for this is not the lack of recycling, as this often is the case with trashcan-suitable EE-small appliances, but recycling technology itself. The usual shredder procedures crush the products and sort unselectively, and different separation procedures sort mostly by mass. Especially small copper applications are carried off into other fractions this way and are, therefore, ejected from the so from the material flow. The copper content alone in lightly shredded fraction is 2% so that annually more than 9000 tons of copper are lost. The share of copper from motor vehicles that is carried off into the steel fragments can easily have the magnitude of 5.000 t per year (Erdmann, 2002).

4.2 Lifespan Extension

A further strategy of efficiency is the lifespan extension or rather the construction of long-lived appliances. This strategy affects above all the input side of the copper material flow, because the desired function of use remains in tact longer with the same use of materials. The fundamental hindrance of such a strategy, however, lies in the difference between life span and useful life. While nowadays the lifespan can be steered to a high degree through the selection of long-lived construction modules as well as through the coordination of components, the useful life is subject to the user's subjective attitude. In the framework of a study by the IZT and the DIW about innovations in sustainability, useful life as well as the trends in the use of ICT-appliances were discussed (Behrendt et al. 1998, p.. 190). Especially for appliances with high innovation dynamics (for example computers) the useful life lies far below the technical lifespan. The following table 14-5 shows this for some products:

Table 14-5. Lifespan and useful life for selected IuK-Appliances

Appliance class	lifespan r (a)	Useful life (a)	Trend
TV	7-20	7-15	→
PC	10	3-5	↘
Workstation	10	5	→
Laser printer	10	3	→
Large copier	>10	5	→
Telephone	12	5	↘

The example of the telephones is especially interesting. Viewed retroactively, in the times of the postal monopoly, there was only a limited selection of expensive models. With the liberalization of the telecommunication market, the postal service lost the monopoly for the distribution of end-user equipment and beside Siemens and DeTeWe, other manufacturers also established themselves. The number of the models increased very strongly. However, the high competition pressure also led to a price decline. This was partially compensated for through the functional improvement of the equipment. However, simultaneously to the increase in offers and the price decline, the usage life of the end-user equipment sank. Since the innovation cycles with many IuK-appliances still accelerate, the usage life will sink even further as the example of computers shows. Besides the consumption habits with their trend toward the use of the "most innovative model", high repair costs for EE-appliances are also an essential impediment to the exhaustion of the maximum lifespan.

4.3 Minimization of Material Use

The third efficiency strategy aims directly at the material use. Sustainable handling of copper should be guaranteed by minimal input. However, for the decrease of material use the incentives are missing due to the low material prices. The IZT executed an ecological balance sheet for television sets with the goal of environmentally sound product construction in a project with LOEWE (Behrendt, et. al. 1997). The share of copper mass in the examined television sets amounted to on average 1.040 g or 2.7 percent, with the largest quantities located in some few wrapped parts like transformers, relays and spools. A study about computers shows that considerable quantities of copper are used in this important area also. In the examined computers approximately 500 g copper was used. The weight share is, therefore, between 4 and 5 percent (Soldera, 1995).

If one puts the medium copper content in television sets in relation to the current prices of electrolyte copper of 170 € per 100 kg (Handelsblatt 06.07.2002, Elektrolyt Kupfer für Leitzwecke) the result is a material value of not even 2 €. This corresponds to approximately three thousandth of the retail price for end user equipment. This low material value cannot affect any steering function for the material use or recycling. According to the second economic rule by the Enquet commission for the operationalization of sustainability it is stated: “Prices must durably take up the fundamental steering function in the markets. They shall reflect largely the shortage of the resources, lowering, production factors and services” (Enqete-Commission “Schutz des Menschen und der Umwelt” 1998, p. 48). The material would have to become substantially more expensive, for example, by means of raw material taxes, in order for the material prices to assume a steering function. Beside problems with the international realization of such a tax due to the GATT and its succession agreements, the problem of comparativeness would be added in the national area (see Behrendt, Klinski, Scharp, Zwiesele 1999).

However, it can be determined that there are further factors that promote the decrease of material use. However, they are not derived from “ecological” motivations. While the product use behavior tends to shorten useful life spans and has a negative effect on the copper material flow. It promotes the minimization of material use through the demand for miniaturized products. This can be observed through the example of mobile phones. Another control factor with influence on material use is the cost of wages per unit, for example, with the installation of copper-containing prefabricated parts. Since mostly electrical sub-distributors are used today for multistory homes in the building industry instead of the central connection for which the cables have to be laid from each room to the transfer point in the cellar. The driving force for an economical cable installation here is not the cost for the cable but rather the wages for the installation.

4.4 Recycling

The fourth efficiency strategy involves the output side directly through optimized recycling. Since metals like copper can be recycled technically easily secondary materials are traded as valuable resources. Even though considerable energy quantities must be used for the recording, separation and refurbishing and an "ideal cycle economy" is not attainable, the recycling of materials clearly contributes to the decrease of environmental burdens on many levels. The following table 14-6 presents some important aspects of the environmental demands, (needs of materials and emissions) through the example of the production of 1t pure copper. Krüger and Rombach looked at four different mines (two open-cast mines and subterranean mines each) with poor and rich ore (Krüger and Rombach, 1998). In the framework of the ecological balance sheet it was established, that both the primary energy needs as well as the CO_2-emissions are decisively dependent on the selection of the energy carrier. For example, the primary energy consumption of a mine with poor ore and the preparation of the energy from hydro power can be much less than the energy consumption of a mine with rich ore and the use of crude oil products for the energy production. For the comparison between the production of pure copper from concentrate or from secondary materials the same process steps (scrap metal preparation, reduction of converter work, fire refining with anode casting and conventional refining electrolysis) were put in place.

Table 14-6. Primary energy consumption, emissions and by-products for the manufacturing of copper from primary and secondary material (Bruch, et al. 1995)

	from	to	Unit
Copper mining and concentrate manufacturing *			
Primary energy use - Mining	4.2	24.2	GJ
Preparation	14.4	37.9	GJ
Overburden (lower value due to selective mining)	6	292	t
Mountains (Mining)	29	140	t
CO_2-Emissions (lower value due to use of hydro power)	0.5	5.3	t
Water consumption	0.003	0.118	t
Sulphuric acid	0	0.27	t
Transportation, production of commercially pure metals, refining of primary materials **			
Primary energy use production	6.3		GJ
Primary energy use, provision of electrical energy, a.o.	15.5		GJ
CO_2-emission production (per t cathode consumption, 0,46 t,)	0.46		t
CO_2-emission energy preparation (per t cathode consumption)	0.92		t
Sewage (approximation value)	1.0		t
Co-products (slag, H_2SO_4 anode slag, $NiSO_4$)	3.0		t
Transportation, production of commercially pure metals, refining of secondary materials ***			
Primary energy use production	9.2		GJ
Primary energy use, provision of electrical energy, a.o.	11.3		GJ
CO_2-emissions production (per t cathode consumption)	1.23		t
CO_2-emissions energy provisioning (per t cathode consumption)	0.73		t
Dome products (slag, H_2SO_4 anode slag, $NiSO_4$)	0.7		t

* Quantities per t copper concentrate dry,

** per t pure metal, use 2.13 t concentrates and 0.57 t scrap metals,

*** per t pure metal, use 1.04 t scrap metals and 0.58 t secondary resources

The decrease of the environmental demands through the use of secondary materials emerges, above all, through the avoidance of ore production and concentrate manufacturing. Krüger and Rombach assume approximately 20 GJ per ton copper for these trials. Further saving are possible, however, if the different scrap metal types don't need to be prepared over shaft ovens (drosses, slags and shredder wastes with approximately 30 percent of copper) and converters (shaft furnace products and red bronze with approximately 75 percent of copper) but are refurbished directly in the anode furnace (blister copper and refinery copper materials with approximately 95 percent of copper) (DKI 1995, p. 8).

Recycling currently contributes most to the sustainable use of copper. However, it is difficult to determine the position of recycling in form of a recycling quota due to the multiplicity of perspectives and calculation procedures.

The determination of the recycling quota, for example, by the German copper institute reaches the result, that the "real recycling quota" is nearly 80 percent (DKI e.G. p. 5). This value emerges as quotient of the secondary material use during the year 1998 and the copper production of the year 1965. The reference point 1965 results from the average lifespan of products containing copper. Thus, copper reemerges from motor vehicles after 8 to 10 years, from electric motors after 10 to 12 years and copper from buildings after 60 to 80 years again as possible resource. This results in an average lifespan for all copper products of 33 years, according to the material use in the different fields of application. The secondary material accruing in the year 1998, therefore, has its origin on average in the year 1965.

However, the problem with this type of the calculation is the origin of the secondary material. This can be production waste from primary copper manufacturing, new scrap from semi-fabrication treatments or old scrap from used products. Especially new scrap metals can be recast again easily for the semi-fabrication production. Admittedly no statistics are compiled of the composition of the secondary material, however a survey of experts by the IZT showed that new scrap and production wastes amount to the largest part of the secondary copper (Behrendt, Klinski, Scharp, Zwiesele 1999). In particular, this large amount of the new scrap metals is created by the presently high production volume of copper. Therefore, they can't be put in relation to copper production from 33 years ago.

In order to be able to present the problem of the recycling rates better, it is helpful to look closer at the material flow of copper. In the following illustration the data of own and different statistical inquiries (BAW, 2001 and BGR, 2000) were collected and supplemented with estimates (p.a. Erdmann et al., 2002):

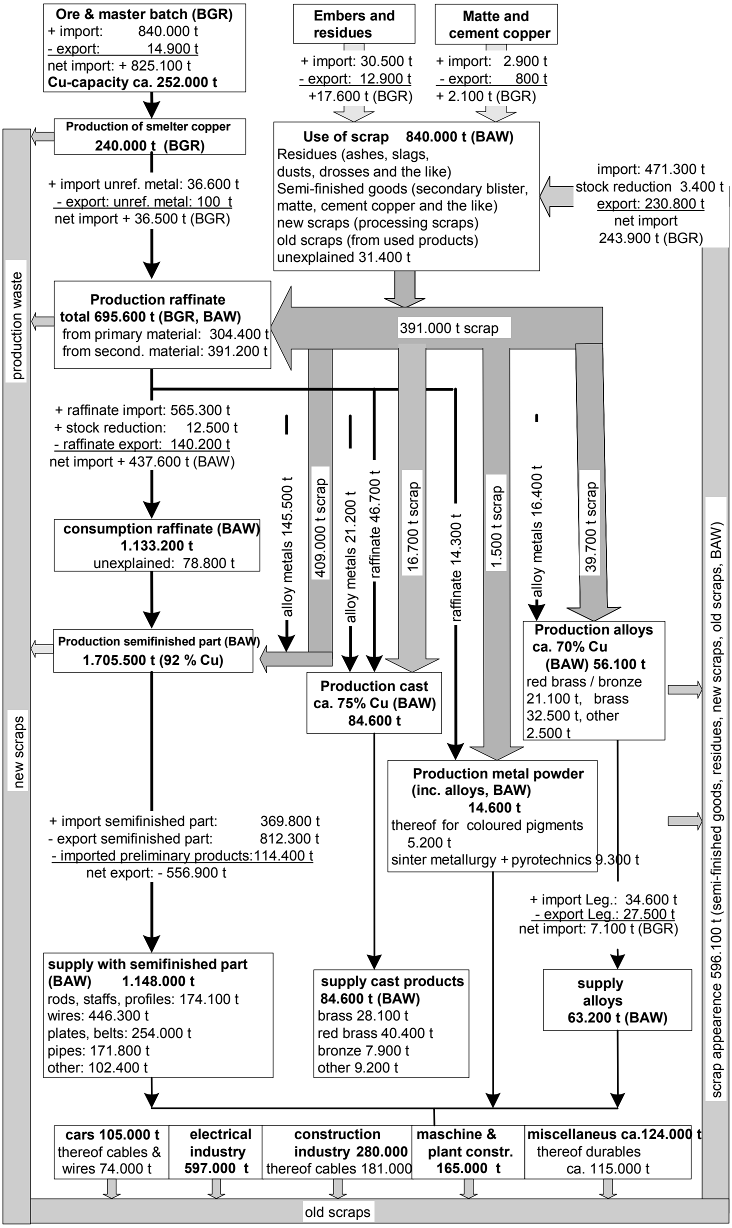

Figure 14-1. The copper material flow 1999 (BAW 2001, BGR 2000 and own estimations)

In the year 1999, the production of commercially available pure copper from ores and concentrates amounted to approximately 240.000 tons. In 1999 more than 695.000 tons of copper were produced through electrolysis or fire refining from the commercially pure copper and the copper scrap metal in Germany. Approximately 391.000 tons of copper scrap metals were fed into these two steps. To determine the use of the refined product the im- and exports as well as the alterations of the stockpiles of the producers have to be taken into account. Use of refined copper in the amount of 1,13 million tons is the result. On the next level semi-fabrications were produced based on the refined copper with a weight of 1,7 million tons. The direct scrap metal usage amounted to 409.000 t, the use of alloy metals to approximately 145.000 t.

Beside the semi fabricating track, there is still the manufacturing of alloys, founded parts and the production of metal powder, which add up to approximately 155.000 tons of copper. The scrap metal use amounts to approximately 57.000 tons for these three lines. On the application level (market supply 2. processing level in accordance with the BAFA, formerly federal office of economy BAW) the electrical industry with a copper consumption of almost 600.000 t and the construction industry with approximately 280.000 tons dominate. The following table 14-7 shows a rough estimate of the copper applications in which the market supply of the second level was divided by US measures[4]:

Table 14-7. Estimated application quantities of copper in selected areas for Germany 1999

Application	t
Power supply	60,000
Telecommunication	20,000
Building cabling	190,000
Roofs and facades	40,000
Mechanical engineering	120,000
Pipes	180,000
EE-Appliances	50,000
Motor vehicles	125,000
Climate and Cooling facilities, production facilities, inc. armatures,	200,000
Remaining goods	260,000
Chemicals	10,000
Total	1,250,000

Up to the application level (product), mostly well secured, primary statistical data is available, even if there are, as the above illustration shows, gaps in the quantity regulations. Some primary statistical data is published also to the total emergence of secondary materials. However, none or only very little data, is available for the copper backflow from the supply and about the relationship between old and new scrap metal. These uncertainties impede the determination of recycling quotas considerably.

The conventional calculation of the recycling quota doesn't distinguish by the origin of the secondary material either. However, it takes into account the im- and export of secondary materials. In the year 1999, the total use of secondary materials amounted to approximately 840.000 tons on all processing levels. This amount of 840.000 tons was spread out relatively evenly over the production of refined copper and semi-fabrications. Based on the im- and export the national scrap metal emergence can be determined to be 596.000 tons (BAW, 2001). The DKI estimates on this occasion that the emergence of new scrap metals and foundry wastes was 2/3 and the quantities of the old scrap metals was 1/3 in 1999.

For the calculation of the production-specific recycling quotas, the respective used quantities of secondary materials can be related to the production volume. Hereby one gets a recycling quota for the manufacturing of refined copper of 56 percent (this is the so-called secondary material usage quota). This means that in Germany every second ton of refined copper is produced from scrap metal. However, the refined copper produced this way is insufficient to cover the market and another 437.600 tons of refined copper have to be imported (net import).The amount of secondary material included in this quantity is unknown. In the extreme case, the imported copper originates exclusively from primary materials. In this case, the recycling quota for the national use of refined copper would be approximately 34 percent. Further quotas are possible besides these two determinations like, for example, the relation of the national scrap metal emergence to the copper demand on the first or second handling level. This can be substantiated by setting the goal to cover all necessary national needs in the respective countries from secondary material in the sense of the sustainability of the cycle economy. Within the frame of a global and labor dividing world such reflections partially lose their sensibility.

Even if it is difficult to determine the condition of recycling more exactly, it is obvious that the supply accumulation dominates at present. Zeltner determined, therefore, that the mobile and immobile supplies in the USA have a weight of 70 million tons and represent, approximately 20 percent of the copper reserves worldwide (Zeltner, 1998). If one projects this on the population of the industrialized world with approximately one billion people, this results in a copper stock with the magnitude of 60 to 80 percent of the estimated profitable world reserves. However the uncertainties of this calculation are relatively large since they depend on a multiplicity of factors. Real estate use in buildings is significant for the supplies since more than 50 percent of the copper in the western world is used for the cables in buildings, for sanitary facilities and heating and for telecommunication facilities. According to Obernosterer et al. (1998) single family homes require approximately 65 kg of copper for the exterior and interior electric development,(of that 35 kg for the interior development), Multiple family buildings, in contrast, only need approximately 24 kg of copper, (of that 20 kg for the interior development per residential unit). If one uses these estimates as basis for the supply in Germany in the year 1999, of approximately 17 million residences in one-family homes and duplexes as well as approximately 20 million apartments in apartment houses (Federal Office for Statistics 2001, p. 244,) they add up to a supply of at least 1,6 million tons of copper .

Beside the supply build up and the foreign trade the lacking recording and reappraisal of the waste flows explains, why the recycling quota is not at 100 percent. Zeltner estimates here that the disposal sites in the United States alone contain 40million tons copper. This corresponds to three times the yearly mining production of the entire world or 45 percent of the estimated profitable ore deposits of the USA. Regarding the disposal of copper-containing products, only rough estimates can be given for Germany about intermixing with household waste and subsequent disposal or incineration. Altogether, approximately 17.000 tons of copper-containing products like small EE-appliances and other small applications (for example ballpoint pen cartridges) could be deposited annually, (Erdmann et al. 2002). In view of these problematic situations, it is not astonishing, that the International Copper Study Group assumes that the world-wide use of secondary materials for the production of refined copper lays only at 13 percent (ICSG quoted Ayres, 2001p. 71).

5. CONCLUSIONS

Sustainable economic management should satisfy the needs of the living people, but not endanger the needs of the future generations. One can approach this regulative central idea in different ways concerning the copper use. The long-term objective for the highly developed countries has to be to work with the existing supply, without diminishing the copper deposits worthy of mining considerably, in order for the developing countries and future generations to fall back on these deposits. It is obvious though that even Germany with its comparatively high recycling quota still is far away from this goal. However, the German production of goods contributes to the global development with the export of copper-containing goods.

On a global level, mankind is far removed from the goal of supply economics. Another reason for this, beside the supply build-up, is that we do not think about the use of resources and budget, as if they were indefinite and in principle substitutable on the one hand, and on the other hand as if we had sufficient energy at our disposal to be able to exploit even the deposits with low concentration.

To achieve a sustainable economic management the above strategies must be pursued intensively and the respective applications of copper have to be optimized. Substitution with regenerative materials for pipes or construction modules, avoidance of dissipative applications, useful life extension through timeless design, miniaturization of EE-appliances, upgrading strategies for short innovation cycles, a more in-depth discussion about the prosperity provisioning of the industrial countries, recycling-friendly construction of motor vehicles or electric cables in the building industry as well as the avoidance of the discharging copper-containing products through disposal are only some of many possible approaches to decrease the copper consumption. Each of the strategies can make its contribution to the decrease of copper consumption. However, the potentials and chances for realization of the efficiency strategy are to be valued as more effective than those of the consistency and sufficiency strategies.

NOTES

[1] According to statistics from the World Bank for 2001, different countries are classed by their GNI (Gross national income), the former GNP (Gross national production)

(www.worldbank.org/data/coutryclass/countryclass.htm from 07/30/2002. The production values of copper ore and commercially pure copper refer to the Year 2000 (Edelstein tables, 20 ff.)).

[2] Achieved or achievable sales prices (rounded) from the production facility (Federal Office for Statistics 2001, p. 192).

[3] For comparison: the copper content of natural ores can be below 0.3 %/weight.

[4] For the German market only one division is available as shown in illustration 1. Through different patterns of use different applications like in the field of automobiles and air-conditioners, might be valued to high.

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4

ECOLOGICAL, SOCIAL, TOXICOLOGICAL, AND CULTURAL EFFECTS

Chapter 15

HEAVY METALS IN THE NETHERLANDS

Problems, causes and possible solutions

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1. INTRODUCTION

Environmental problems related to heavy metals have a long history. Heavy metals have toxic properties, leading to adverse effects on human and ecosystem health even in small doses. Another problem-causing property is their non-degradability: once they enter the environment, there is no getting rid of them. Metals tend to accumulate in soils and sediments. Immobilisation only occurs through geological and therefore extremely slow, processes. Accumulation in the food chain may lead to an increased stock in biota, thereby magnifying the human dose.

Well known examples of metals poisoning in past centuries include the lead poisoning from water pipes in ancient Rome and the mercury poisoning of the "mad hatters" in Europe. In the 20th century we have encountered among others the disaster of mercury poisoning in the Minamata Bay in Japan through coastal fish, and of cadmium poisoning through rice. Lead in petrol has led to health problems in cities, especially related to children. These and comparable incidents have stirred up governments to formulate environmental policies and industries to reduce emissions considerably. If we compare the current emissions from industrial and point sources to those of several decades ago, at least in the industrialised countries, we can see that they are very much reduced (Ayres & Rod, 1986; Stigliani & Anderberg, 1992). Present policies regarding heavy metals include not only end-of- pipe emission reduction, but also recycling and even more source-oriented measures limiting or banning certain applications altogether (VROM, 1991; Council of the EC, 1991). In the Netherlands, a comprehensive heavy metals policy is currently being formulated. In general there is the feeling that the main problems have actually been solved and that now it is a question of tying up some loose ends and then maintaining legislation. One of these loose ends is the existence of polluted sites, a leftover from the past, described by Stigliani & Salomons (1993) as chemical time bombs. Such

A. von Gleich et al.(eds.), Sustainable Metals Management, 377-392.

sites are not suitable for agriculture and not feasible for residential building and if they remain unattended, metals may become available and leak to the groundwater through increasing acidity. Other loose ends refer to still existing open applications considered risky, such as metal-based pesticides and paints.

Although the emissions in the Netherlands have undoubtedly been reduced – at present, the major source for surface water pollution is what enters our country via the Rhine – there are some aspects still causing concern. One is the fact that the environmental concentrations in the Netherlands are not decreasing. This might be due to a time lag – once the emissions are lowered, the metals already in the environment disappear only at geological speed – but it may also have more serious causes. We observe that the inflow into the economic system, on a global level equivalent to the amount of metals being mined, has not decreased but has remained at a high level. This leads to the question that if emissions are indeed reduced, then where does this inflow end up? Possibilities are, in theory:

- Although point source emissions have decreased, we have no insight in the more diffuse emissions. An example of such diffuse emissions is phosphate fertiliser, which is polluted with small amounts of metals and which is emitted directly into agricultural soils. Of such emissions there is no record, they may even have increased.
- Emissions may have been replaced by landfill, there has been a shift from emissions to the atmosphere and surface waters to dumping on landfill sites.
- The metals entering the economy may accumulate in materials in products, thus increasing the societal stock and in due course, upon entering the waste stage, causing emissions to rise once again.
- The Netherlands might have exported the more polluting stages of the metals' life cycle to other countries, thus enjoying the benefits of consumption while putting the burden of mining, production and waste management elsewhere.
- A safe storage may have been established for waste metals, reducing the emissions from waste materials to zero.

Beforehand, one possibility seems more credible than another. We do know, for example, that no storage at present qualifies as “safe” in the sense of reducing emissions to zero. Pollution export may indeed take place on the level of a small country but does not allow for a global emissions decrease. The other three possible explanations all appear reasonable. All of them, in varying grades and shapes, place question marks on the image of the metals problem as a problem of the past.

The problem of heavy metals in the Netherlands has been investigated within the framework of the NWO research programme *Sustainability and Environmental Quality*. Five environmental research groups from four universities – Leiden University, University of Amsterdam, the Free University of Amsterdam, and Wageningen Agricultural University – have tackled this problem in a combined effort in the Metals Programme (Guinée et al., 1999; van der Voet et al. (eds), 2000). An inventory was made for the flows in 1990. Input data for 1990, such as data on flows in the economy, accumulations, emissions and transboundary pollution were taken mainly from Annema et al. (1995). Methods, models and indicators have been developed to analyse this problem and generate solutions. Models in the realm of Substance Flow Analysis (SFA) were designed and applied to calculate the societal and environmental flows of heavy metals. Indicators regarding the various research questions were defined based on the overview of flows. This modeling-and-evaluation combination is applied to the metabolism of cadmium, copper, lead and zinc for the total Dutch economy.

The 1990 situation is compared with the steady-state situation: the situation that ultimately emerges when the present metals' management is continued indefinitely. The reason for this was to obtain an insight in the long-term consequences of the current metals management regime. It is at present unclear whether the emission reduction realized over the past decades does not have unforeseen adverse consequences in the future. The procedure for calculating the steady-state situation boils down to establishing the equilibrium belonging to the present structure of supply and demand of the metals. Note that the steady state must not be interpreted as a prediction of any future situation: it contains no trends, no socio-economic developments and no policies. It is a tool to evaluate the present management on its potential long-term consequences from a sustainability point of view. For two of the metals, copper and zinc, packages of measures were formulated to combat remaining problems. These measure packages were also modelled on a steady-state basis and were compared to the current management.

2. DUTCH METALS MANAGEMENT IN 1990

2.1 The flows of the four heavy metals

In Appendix 1, an overview of the flows of the four metals is presented. From this overview, a number of conclusions can be drawn:

- The flows of copper, zinc and lead are several magnitudes larger than the flows of cadmium.
- For all metals, we can view the Dutch economy as an open economy: the imports and exports are large compared to the domestic flows, especially in production and refining. This makes it difficult to connect the use and waste flows to the production and refining activities within the Netherlands in an analysis. Especially for cadmium this is striking: the rather large amount extracted from the zinc ore is exported in its entirety, while virtually all cadmium-containing products entering the use phase are imported.
- For all metals we observe that the emissions are indeed small compared to the flows through the economy.
- For all metals we can detect a relatively large accumulation in the economic system.
- Although there are no mines in the Netherlands, major flows can be found in the 'extraction' phase for zinc and cadmium. These are the flows connected with the large zinc refinery located in the Netherlands, where cadmium is extracted from zinc ore as well as zinc.
- For copper, zinc and lead, a significant 'back-flow' can be observed. This indicates that a large fraction of the waste materials is recycled. For cadmium,

this is not the case: waste materials either end up in landfill (accumulation in the waste treatment phase) or are re-used as building and road construction materials containing cadmium as a trace contaminant.

If we take a closer look at the underlying figures, it can be concluded that functional 'bulk' applications are dominant for copper, zinc and lead, while for cadmium the 'trace' applications are dominant. Copper, zinc and lead have major applications in the building environment: gutters, roofs, fences, wiring, pipes, etc. Specific applications include lead in batteries, copper in public transport overhead wiring and zinc in brass products. 'Trace' applications can also be found: lead in petrol, copper in ships' anti-fouling paints, zinc in textiles and tyres, copper and zinc as fodder additives. Comparatively minor flows can be found in the non-functional realm: all three metals are trace contaminants in phosphate rock and iron ore and the subsequent products.

The main applications of cadmium, on the other hand, belong to the 'trace' category: use as a pigment or stabiliser, or in surface coating, for example. Quite a significant part of Cd flows are in fact non-functional, i.e., they represent Cd contamination in all sorts of raw materials and concurrent products: phosphate rock, fertiliser and fodder additive; fossil fuels and plastics; iron ore and iron & steel products; especially zinc ore and zinc products. The only important product group in which metallic cadmium is applied in concentrated form is nickel-cadmium batteries, which in 1990 was a rapidly growing application in the Netherlands and which is one of the few applications still allowed by the Dutch Cadmium Decree.

The results of the model calculations are evaluated with the help of the indicators concerning environmental risks and societal metabolism. The indicators are divided in three groups, related to the research questions of the Metals programme:

- indicators for the fate of the mined metals
- indicators for the evaluation of the present management in terms of sustainability
- indicators for the design of a sustainable management.

2.2 The fate of the metals

Below in Figures 15-1 and 15-2 the indicators for the fate of the metals that have flown into the Dutch economy in 1990 and the steady state are presented.

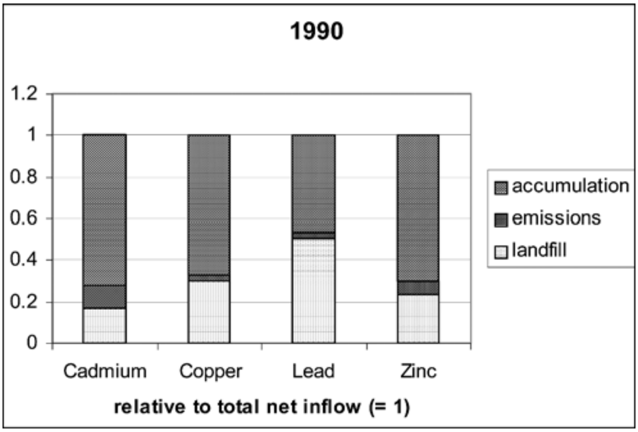

Figure 15-1. The fate of the inflow of the 4 heavy metals into the Dutch economy, 1990.

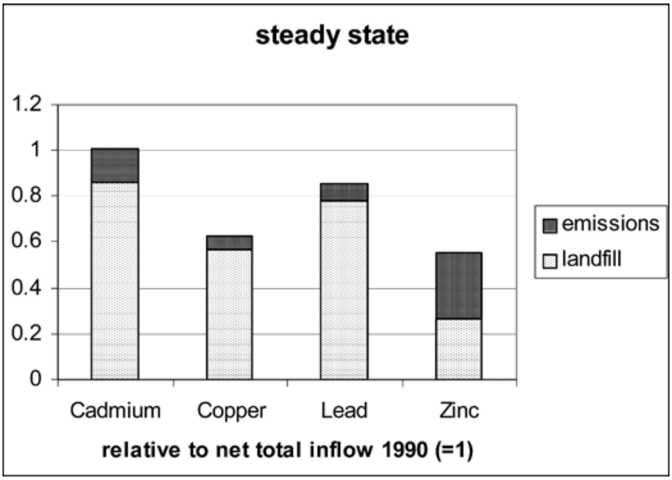

Figure 15-2. The fate of the inflow of the 4 heavy metals into the Dutch economy, steady state.

At present, only a small amount of the metals ends up as emissions. A larger part is being transferred to landfilled waste. Most of it, however, stays within the economy and accumulates in stocks of all kinds of materials and products. In the steady state there is by definition no accumulation. Stocks are at a constant size and the inflows match the outflows. Both emissions and landfill have increased. The answer to the first research question thus is disturbing: metals accumulate in the economic system at a rapid rate and in the end will cause emissions to rise again.

2.3 The risk associated with the present metals management system

The second question regarding the sustainability of the metals is also answered by using indicators. The sustainability is measured by the risk for human and ecosystem health:

- human intake (PDI/TDI, predicted daily intake divided by tolerable daily intake; the TDI is defined in the same manner as the ADI, acceptable daily intake, only it does not have a WHO status)
- environmental concentrations (PEC/PNEC, predicted environmental concentrations divided by predicted no-effect concentration)

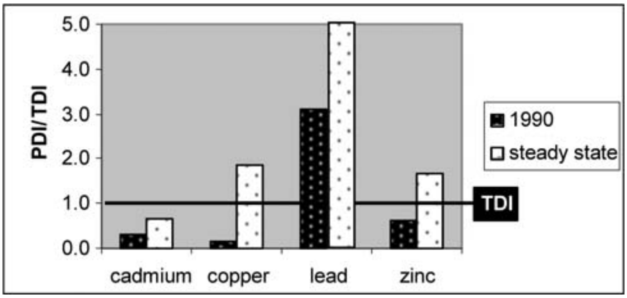

Figure 15-3. Human health risk associated with the societal metabolism of four heavy metals in the Netherlands: human intake.

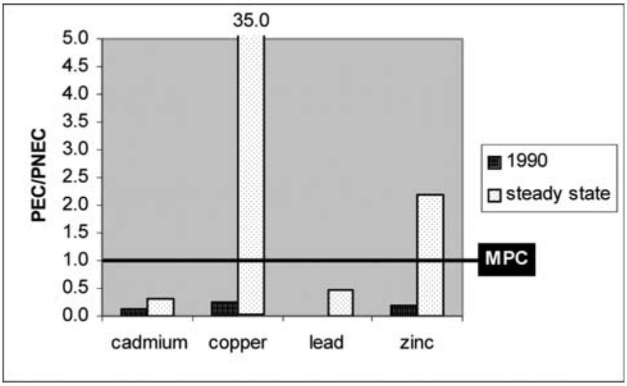

Figure 15-4. Ecosystem health risk associated with the societal metabolism of four heavy metals in the Netherlands: concentration in surface waters.

In Figures 15-3, 15-4 and 15-5 the horizontal line at the value of 1 represents the acceptable risk level. For human health, this is the aforementioned TDI value, for ecosystem health the MPC, maximum permissible concentration, a Dutch environmental quality standard. Regarding human health, it can be seen that in 1990 only the TDI for lead is exceeded. This risk may be expected to decline or disappear entirely, since it is due principally to lead in petrol, which is being phased out altogether. However, in the steady state the TDI is exceeded for three of the four metals, which indicates that the present metals management regime might lead to health risks in the long run. For ecosystem health, it can be concluded that in 1990 the MPC values are not exceeded for any of the metals.

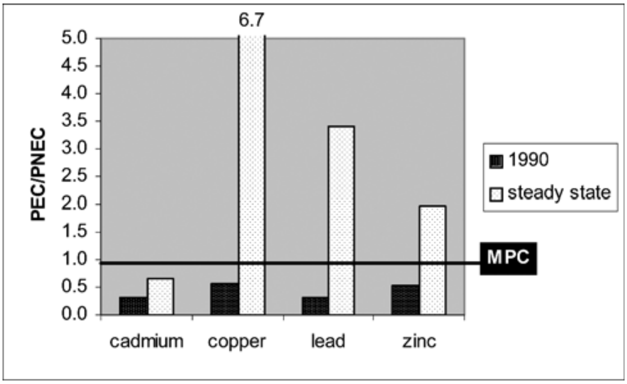

Figure 15-5. Ecosystem health risk associated with four heavy metals in the Netherlands. Concentration in agricultural soils.

However, in the steady state ecotoxicological risk ratios are expected to be over 1 for all metals except cadmium. This implies that the present management regime, although there are no problems at present, is not sustainable in the long run. Steady-state modelling provides no insight into the speed of the process of accumulation of concentrations. To obtain an idea of the time periods involved, table 15-1 contains a very rough estimate:

Table 15-1. Indicative time period until transgression of risk ratios for four heavy metals in the Netherlands

	cadmium	copper	lead	zinc
MPC aquatic	∞	years	millennia	a decade
MPC terrestrial	∞	decades	centuries	a century
TDI	∞	centuries	(now)	a century

Apart from the lead TDI, copper and zinc in aquatic ecosystems appear to be the first to cross the threshold. Copper in soils is expected to become a problem within a number of decades. The other indicators are not likely to surpass the value of 1 in one or more centuries.

2.4 The management of the metals

Especially for copper and zinc, it appears to be necessary to make changes in the present metals management. Two indicators have been used to obtain an insight into where these changes may best be realized: the technical efficiency of the society's metabolism, and the recycling rate. The technical efficiency is indicated by the percentage of the metal going into the life-cycle stage that comes out again in an economically useful flow, be it raw material, product or recycled material. The recycling rate is defined as the percentage of the metal going into the waste management stage that is recovered (as a metal or in secondary materials from waste incineration processes) The indicators are presented in Figures 15-6 and 15-7.

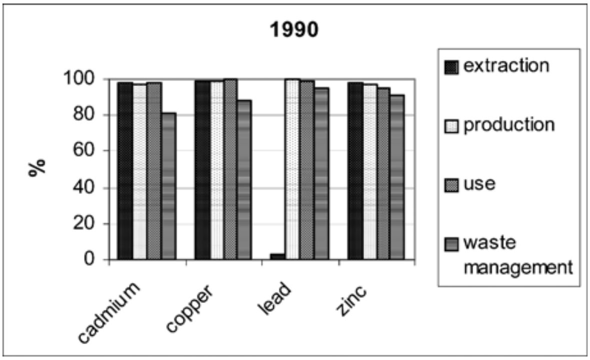

Figure 15-6. Technical efficiency of the life-cycles stages of the four heavy metals in the Netherlands.

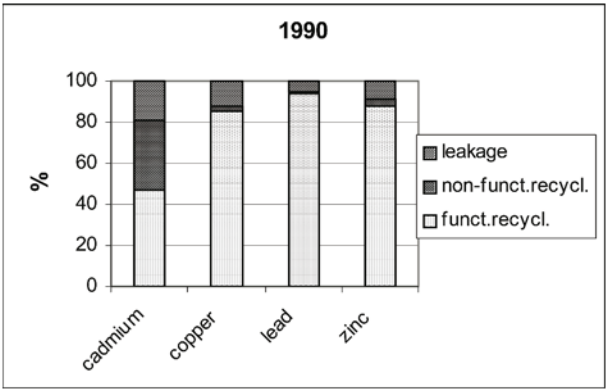

Figure 15-7. Recycling rate of the four heavy metals in the Netherlands.

Both the efficiency and the recycling rate are already quite high. This indicates that in order to prevent emissions, not much can be gained by a further increase in industrial efficiency. The recycling rate is determined largely by the recycling of building materials. A boost in recycling seems difficult, since only the dissipative applications are not recycled at present. For cadmium, recycling refers mainly to various types of NiCad batteries. Because of the present rapid growth of stocks, this recycling is expected to increase. Non-functional recycling, meaning recycling of metals that have ended up in waste materials such as fly-ash, slag and compost, is quite high for cadmium. This might lead to problems in the future.

In order to design a sustainable management strategy, it is important therefore to focus on the trace applications rather than the bulk applications, which appear to be managed quite well already. This is discussed further in Section 3.

3. SCENARIOS FOR COPPER AND ZINC

Because copper and zinc are expected to be most problematical in future, the design of management strategies is narrowed down to those two metals. Two scenarios, or rather measures packages, were defined and their effectiveness was assessed using the steady state once again:

1. a moderate scenario, containing such measures as are considered to be relatively easy to implement
2. a stringent scenario, containing such measures as are required to keep the steady-state risk below acceptable levels, regardless of costs or societal acceptance.

These were compared to the steady state of the 1990 management as a reference.

3.1 Origins of pollution

Before defining any measures, the origins of the pollution of surface waters and soils were assessed.

For surface water, transboundary inflow from foreign countries is at present the largest source of pollution. However this cannot be regulated by any Dutch policy. The main sources to address are therefore inland sources. The most important ones are:

- copper water pipes
- anti-fouling treatment of ships with copper-containing materials
- zinc building materials or building materials coated with zinc

and especially in the long term:

- emissions from landfill sites
- agricultural flows of both copper and zinc.

For agricultural soils, animal manure is the largest source. Animal manure is not a direct source but derives its input from other sources. Concentrations in manure build up due to the process of closed-loop recycling. It is therefore important to reduce the input to the closed cycles:

- copper and zinc additive to fodder
  and to a lesser extent:
- copper and zinc pesticides
- phosphate fertiliser containing trace concentrations of metals.

3.2 The moderate scenario

This has led to the following package of technically specified measures for the moderate scenario:

Table 15-2. Measures of the moderate scenario

measures, 'moderate' scenario	copper	zinc
technical emission reduction from open applications in present and new buildings	water decalcification: 2000–2010, 10% reduction of corrosion	coating of gutters, roofs, fences, etc.: 2000–2025, 75% reduction of corrosion
substitution of applications in the built environment – new buildings only	no substitution; more efficient building leads to 1% reduction of new water pipes per year, starting in 2000	gutters, roofs, etc.: 70% substitution by stainless steel or plastics
terminating the use of metal-based pesticides	complete substitution by non-copper pesticides	complete substitution by non-zinc pesticides
reduction of additions to fodder	reduction by 30% of P and Cu additions, leaving production unaffected	reduction by 30% of P and Zn additions, leaving production unaffected
reduction of fertiliser use	reduction by 10%	reduction by 10%
reduction of livestock	reduction by 10%	reduction by 10%

In Figures 15-8 and 15-9 the resulting risk ratios for surface water and soils is shown. It appears that the 'moderate' scenario leads to lower concentrations in the steady state. However, the PNEC values are still transgressed, which implies that by our definition the 'moderate' management regime still is not sustainable.

3.3 The stringent scenario

More stringent measures are therefore required to solve the problems. In the case of aquatic ecosystems, foreign as well as domestic emissions must be tackled, since it is not possible to meet quality standards by national emission reduction alone. In order to reach the standards, foreign countries have to co-operate and an international agreement on emissions reduction is required. To simulate this, it is simply assumed that the transboundary inflow will be reduced by 75% as a result of some sort of policy in other countries. In addition, domestic sources must also be reduced, especially for copper. For zinc, the major remaining source is leaching from sites and soils. This is also true of copper, but in addition corrosion from water pipes is still an important source. The input into agricultural soils must be reduced further to meet the standards for human intake and soil concentration. For soils, domestic sources are still dominant even in the 'moderate' scenario. The main polluting sector is still agriculture itself. Stringent measures must therefore be defined for agricultural applications of copper and zinc. This should also have a beneficial impact on leaching from soils to surface water. It should be kept in mind that the stringent scenario is defined strictly from a metals point of view. Any side-effects due to substitution or changes in society are ignored, as are economic and cost aspects.

The measures of the stringent scenario, additionally to the moderate scenario, are presented in Table 15-3.

Table 15-3. Measures of the stringent scenario

Additional measures in 'stringent' scenario compared to 'moderate'	copper	zinc
Measures in foreign countries	'stringent' measures lead to 75% reduction of transboundary inflow by air and water	'stringent' measures lead to 75% reduction of transboundary inflow by air and water
Technical emission reduction from open applications in present and new buildings	no additional measures	no additional measures
Substitution of applications in the built environment; new buildings only	pipes and water-heating equipment: 100% of Cu substituted by stainless steel or plastic	additional substitution of Zn in road fencing: 80% substitution of Zn total
Terminating use of metal-based pesticides	terminate Cu-based anti-fouling	no additional measures
Reduction of additions to fodder to physiological minimum	reduction by 80% of Cu additions	reduction by 65% of Zn additions
Reduction of fertiliser use	reduction by 50%	reduction by 50%
Reduction of copper addition to soils	reduction by 75%	-
Reduction of livestock	reduction by 50%	reduction by 30%
Reduction of industrial emissions	reduced by 90%	-
Immobilisation of metals in landfill	100% reduction of emissions from landfill	100% reduction of emissions from landfill

Figures 15-8 and 15-9 represent the risk ratios for the different scenarios. The reference is the steady state of the 1990 management regime.

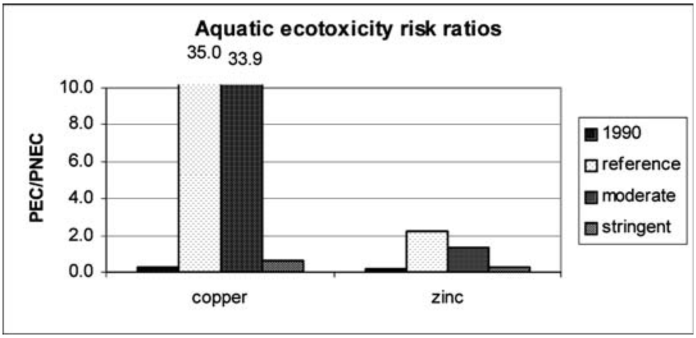

Figure 15-8. Aquatic ecotoxicity risk ratios for the different scenarios.

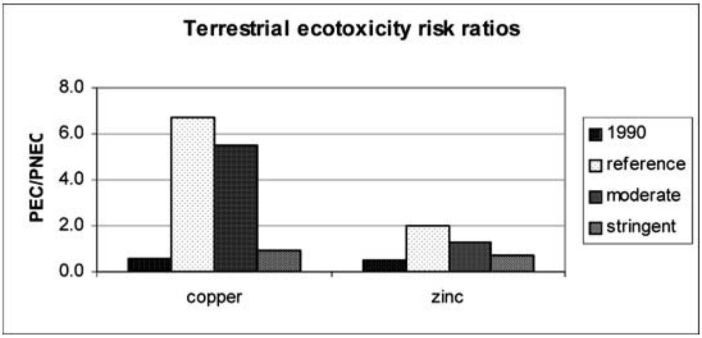

Figure 15-9. Terrestrial ecotoxicity risk ratios.

The overall conclusion from these calculations is that it appears to be very difficult to reduce the environmental flows and stocks of the metals to acceptable levels. The measures in the 'stringent' scenario, required to meet the standards also in the long run, are quite unrealistic or even impossible at present. The side-effects and societal costs of such measures may be considerable.

4. DISCUSSION AND CONCLUSIONS

The present accumulation of metals in stocks of products is expected to cause an increase in landfill and emissions in the future. By the subsequent rise in metal concentrations in environmental compartments, the 1990 flows and accumulations of the metals pose long-term risks to human health and ecosystem health. In contrast to the apparent general view that these metal flows are well under control, the conclusions of this case study point in a different direction.

The increase in emissions takes place despite high efficiencies and substantial functional recycling rates. The non-functional recycling flows are, although small compared to functional flows, a major cause of diffuse emissions to air, water and agricultural soil. This implies that a further increase of efficiency and functional recycling may be difficult to achieve and might not be effective, moreover. In fact, relatively low concentrations in specific flows in the economy cause a marked increase of risks through a closed-loop accumulation process, as in the example of Cu and Zn in fodder. A management strategy must therefore look in other directions.

A 'moderate' scenario comprising relatively undisruptive measures does not appear to conform to sustainability. Although for zinc there is a significant reduction of risk ratios, for copper the problem remains, especially for aquatic ecosystems. In order to conform to environmental quality standards, a 'stringent' scenario, including serious changes in society, is required. Agricultural practice should change significantly, building materials should be substituted on a large scale, and waste management techniques should be adopted that are at present non-existent, not only in the Netherlands but also in upstream Rhine and Meuse countries. The environmental impacts resulting from such changes are not addressed here, but might also be considerable. The same can be said regarding the costs and economic impacts of such changes.

Developing a solution for these problems is therefore an example of an unavoidable clash between the economy and the environment. Most of the emissions considered might be reduced adequately by technical means. For these it is merely a question of being prepared to pay a certain amount of money. Cleaning up the water is another matter however, and implies changing the whole nature of food production as well as that of residential building and waste processing. It is then a question of choice: do we choose to solve the problems to the degree laid down by the various environmental quality standards, or do we choose to keep basic societal practices more or less as they are at present? In the short term, the possibilities for reshaping the management regime in a more sustainable direction are limited. In the long run, however, more drastic changes are indicated, since the environmental problems related to metals seem to be long-winded indeed.

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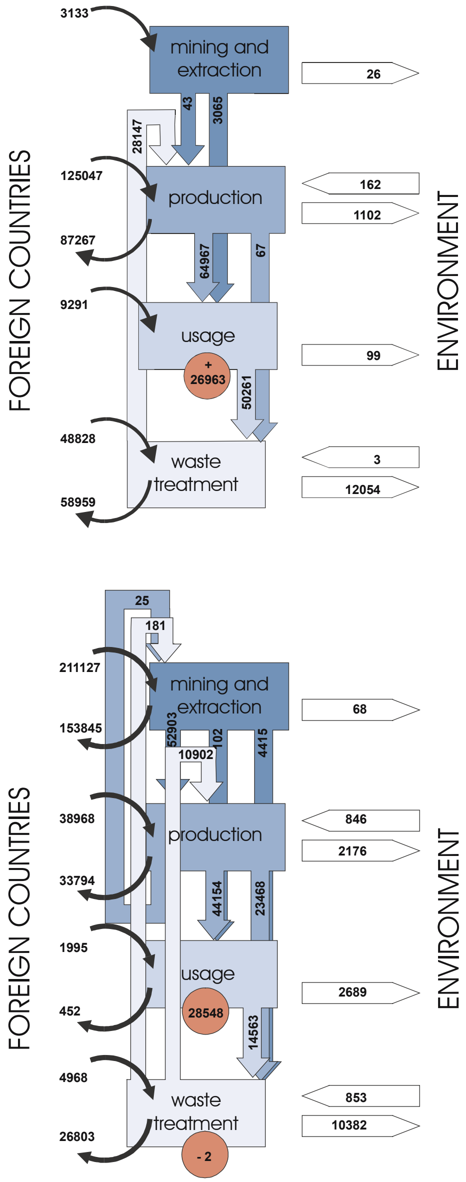
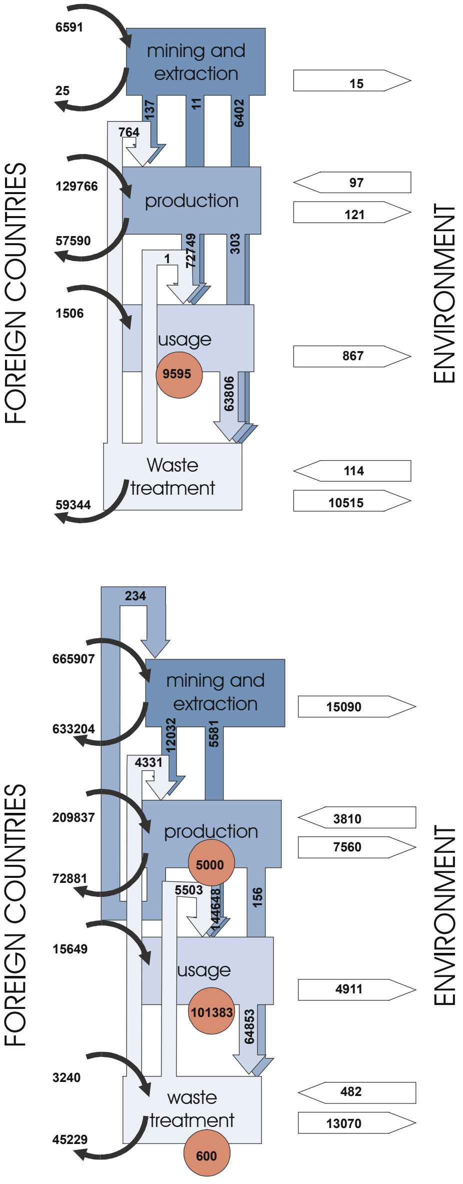
APPENDIX - FLOWS OF COPPER, ZINC, LEAD AND CADMIUM IN THE NETHERLANDS, 1990.



Copper (top) and zinc (bottom) flows in the Netherlands, 1990 (ktonnes/year).



Lead (top) and cadmium (bottom) flows in the Netherlands, 1990 (ktonnes/year).

Chapter 16

TOXIC EFFECTS OF METALS AND METAL COMPOUNDS

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1. OCCUPATIONAL DISEASES

The Italian physician Bernardino Ramazzini (1633 – 1714) systematically described the diseases of workers (Ramazzini 1998). The chapter “The diseases of miners” reads as follows:

> *“The diseases of miners and similar workers are mainly laboured breathing, consumption, stroke, paralysis, cachexy, swelling of feet, degeneration of teeth, gingival ulcers, pain of joints and trembling movements of the limbs. Lung and brain of such workers are being considerably damaged, especially the lung as it breathes the evaporations of the minerals with the air, and is affected in first instance.*
>
> *If these vapours are taken up by the centers of life and are mixed with blood, they alter and poison the natural water of the brain and the nervous system, which leads to convulsions, drowsiness and the above mentioned diseases.*
>
> *For these reasons the mortality of miners, who transport the minerals in pits, is in most cases very high and the women, who marry these men, marry again and again.”*

Ramazzini does not describe in detail the type of work that was performed by the workers, which he called “miners and similar workers”. At that time extraction of minerals and ore should also have been of considerable importance. It therefore can be assumed, that at least part of the diseases described by Ramazzini were caused by metals.

This assumption is not refuted when the diseases designated by Ramazzini are compared with the diseases that can be caused by chronic exposure to metals

A. von Gleich et al.(eds.), Sustainable Metals Management, 393-402.

according to the ordinance on occupational diseases (Berufskrankheiten – Verordnung, BeKV, tab. 16-1).

Table 16-1. Diseases of miners according to Ramazzini and diseases caused by chronic metal exposure according to the ordinance on occupational diseases (BeKV)

diseases according to Ramazzini (miners) *	**metal as causative agent according to BeKV**
laboured breathing	Cd / Be / Al
paralysis / convulsion	Pb / Hg / Cd / Mn / As
cachexy	Pb /Hg / Cd / Mn / Tl / Be
pain of limbs	Hg / Mn / Tl
damage of teeth	Pb / Hg
drowsiness	Pb / Hg / Mn

* modified

Despite some uncertainties in the allocation of diseases and symptoms, table 16-1 shows that the descriptions of Ramazzini match rather well with the occupational diseases that can be caused by metals. One therefore can take for granted that diseases caused by metals have been known for a long time.

In spite of considerable efforts nowadays many accidents at work and occupational diseases occur. They are the cause of important economic losses (table 16-2).

Table 16-2. Accidents at work, occupational diseases and expenses in 1998 in Germany (from: Arbeitssicherheit '99, Bundesministerium für Arbeit und Sozialordnung).

number of accidents at work:	about 1.8 million
number of recognised occupational diseases:	about 20,000
expenses of accident insurance funds:	about 23 billion DM
expenses for occupational diseases:	about 3 billion DM
work related loss of production (estimated):	about 16 billion DM

In 1998 about 20,000 occupational diseases were recognised by the German accident insurance funds. Nearly half of them were caused by physical factors (noise, vibration, carrying of loads). Only 3% were attributed to chemical factors, of which "metals/ metaloids" form a subgroup (fig. 16-1). The official name of the occupational diseases that have been used in fig. 16-1 in an abbreviated form, do not in every case denote the specific cause of an occupational disease, as not only causes but also clinical symptoms are used to name occupational diseases. It is known, for example, that skin diseases are also caused by metals and their compounds (e.g., chromium-eczema). They are not listed under "metals/metaloids" but under "skin". The specific causes can only be elucidated by a detailed analysis of the documentation of the individual cases (Wardenbach, 1989).

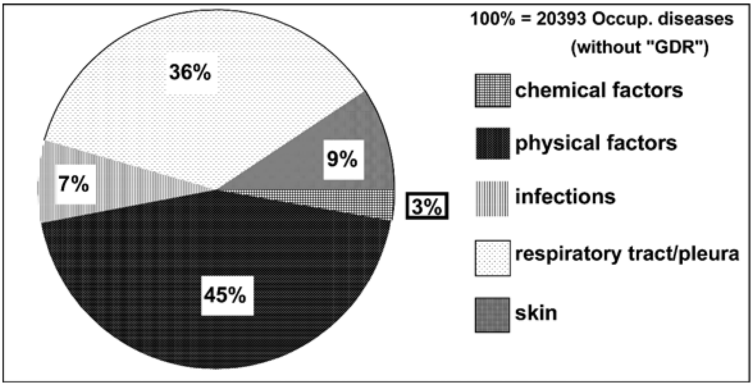

Figure 16-1. Causes of occupational diseases in 1998 (from: Arbeitssicherheit '99).

For that reason the segment "metals" of figure 16-2 contains only those occupational diseases for which the name directly points to metals or their compounds as the underlying cause. A total of 108 cases of occupational diseases induced by metals were recognised in 1998 in Germany. Because of the aforementioned limitations, this number has to be regarded as an approximation.

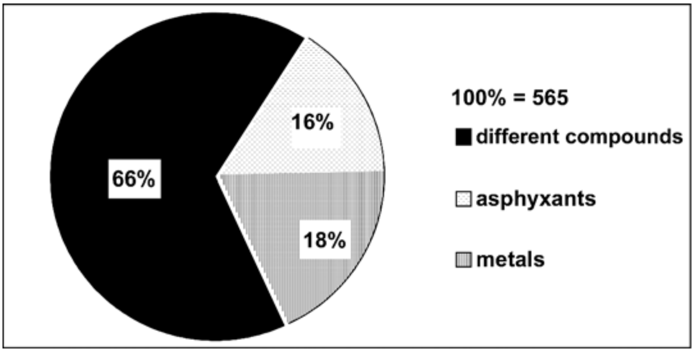

Figure 16-2. "chemical factors" and occupational diseases in 1998.

2. TOXICITY OF METALS

In comparison to synthetic chemicals, metals and their compounds possess some peculiarities. As an element they are not metabolised and broken down in the organism, unlike several organic compounds. Their oxidation state can change, which can lead to a different toxicity of the same metal. (Chromium-VI-compounds are carcinogenic, Chromium-III-compounds are not carcinogenic).

Some metals have the potential to accumulate in the body, others are an essential part of the organism (e.g., metal-containing enzymes). In the latter case deficiency and overdosing can disturb health with differing symptoms. Deficiency of cobalt, for example, causes anaemia, whereas cobalt exposure at workplaces induces heart diseases. (Marin, 1967).

It also has to be taken into account that the effect of a metal can be modified by simultaneous exposure to another metal. With metals, this fact is called interaction. Some of the known interactions are depicted in fig. 16-3. An arrow from metal A to metal B indicates that metal A reduces the toxicity of metal B or low levels of metal A increase the toxicity of metal B. Potassium and thallium ions share a common cellular receptor. Thus, potassium deficiency augments the toxicity of thallium, which in turn can be reduced by the application of potassium.

As can be seen from fig. 16-3 there exist abundant possibilities for interactions. In principle, this also holds true for other chemicals. However, with metals it is of greater importance, as it is common that several sources of exposure occur simultaneously (food, environment, workplace).

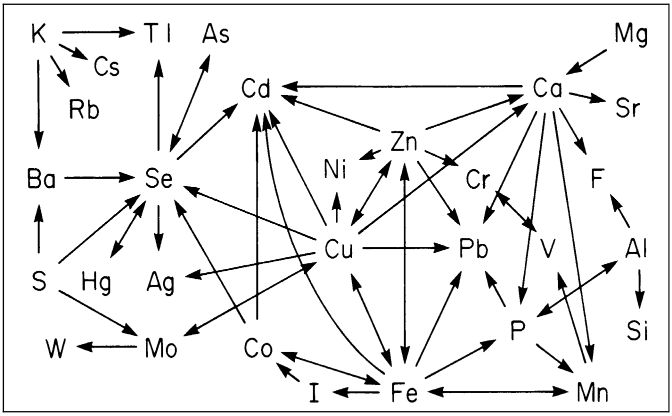

Figure 16-3. Interaction of metals (from Seiler, 1988).

Practically every organ can be damaged by one or several metals at appropriate exposurest. Often, several organs are impaired by the same metal. The entire spectrum of toxicities is present (acute/chronic toxic; sensitising, carcinogenic, mutagenic, toxic to reproduction). Exemplarily, certainly not complete and without taking into account modifying factors, table 16-3 summarises the toxicity of metals after chronic exposure. The kind of toxic effect in the respective target organ (e.g., lung cancer or lung fibrosis) and whether the toxic effect is caused by the metal itself or its compounds were disregarded.

Table 16-3. Target organs of some metals and their compounds after chronic exposure

target organ	metal													
	As	Be	Pb	Cd	Co	Cr	Cu	Fe	Hg	Mn	Mo	Ni	Se	Tl
liver	X							X			X			X
respiratory tract	X	X		X	X	X		X				X		X
blood	X		X				X						X	X
nerves			X						X	X				X
kidney	X		X	X					X		X			X
skin	X	X				X						X		
reproduction			X										X	
heart					X			X						X

One also has to consider that different ways of exposure can lead to different toxic effects. For example, oral dosing of cobalt containing cemented carbide does not induce severe damage, whereas inhalation causes lung fibrosis with severely limited lung function. Inhalation and oral intake of cobalt chloride (it was used for the stabilisation of the foam on beer!) can provoke damage to the heart muscle.

3. SOLUBILITY AND TOXICITY

In general, the toxicity of a metal is the consequence of the action of free metal ions on target cells. Thus is it plausible that the toxicity of metals and their compounds depends on their capability to release metal ions by dissolution. It is self-evident that solubility does not represent a fixed value. It varies depending on the solvent or physiological environment surrounding the metal or its compound, respectively.

Approximately 75% of the human body is made up of water. As a first approximation one might presume that increasing water solubility is equivalent to an increasing toxicity. But this does not apply.

In table 16-4 the water solubility of some nickel compounds according to usual handbooks on chemistry and physics are listed.

Table 16-4. Water solubility of nickel compounds

Compound	water solubility
nickel acetate	soluble
nickel sulphate	75.6 g/100 ml
nickel chloride	254 g/100 ml
nickel subsulphide	insoluble
nickel carbonate	insoluble
nickel metal	insoluble
nickel oxide	insoluble

If the toxicity is largely determined by water solubility, then insoluble compounds would be virtually non-toxic. However the aqueous phase of the organism contains different salts and proteins, which are able to influence the solubility considerably.

In fig. 16-4 the solubility of metal containing dusts in solutions with varying salts is depicted. Solubility was measured by a standardised procedure (Fritsche 1987).

"Saliva" and "lung" denote aqueous solutions, whose salt content approximates the inorganic part of saliva or lung cells with respect to type and amount. Depending on the "solvent" and dust sample, there exist in part considerable differences in the release of metal ions (logarithmic scale!). These differences can be reinforced if additional physiological components, especially proteins, are added to the "solvent" (see fig. 16-5). In doing so, the in-vivo situation will be reproduced better and better.

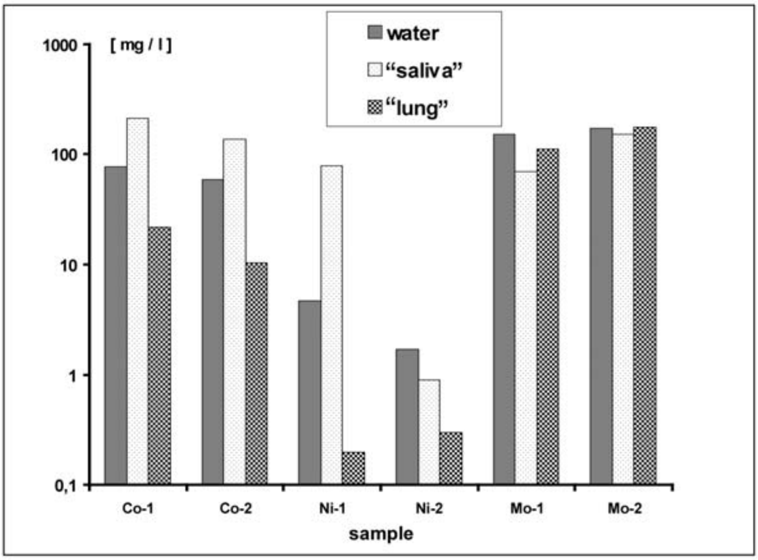

Figure 16-4. Solubility of metal containing dusts in water and salt solutions (from: Fritsche, 1987).

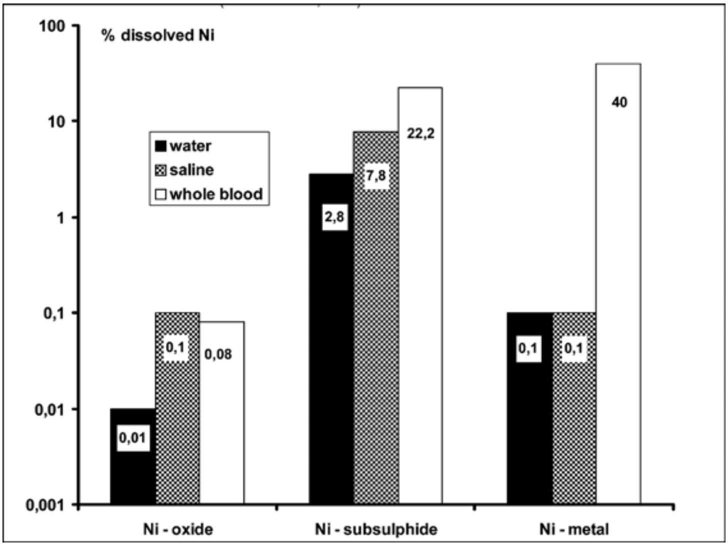

Figure 16-5. Solubility of nickel compounds in water, saline and blood (from Anderson, 1980).

Increasing solubility or bioavailability does not mean the chronic toxicity also increases continuously. As a first approximation, one can assume that easily soluble metal components, which are rapidly resorbed by the organism, are equally rapidly eliminated. This means they have a low probability to exert their damaging effect. Only a few ions are released by very sparsly soluble compounds and thus there exists only a low probability of damage. Hence, medium but sufficient solubility or bioavailability respectively, should result in the largest probability of damage, if the metal compounds stays in the organism sufficiently long. In this way, a continuous strain on the organism by metal ions results. This holds true especially for the inhalation of corresponding dusts, as their residence time in the human lung is several hundred days (the half time in humans is about 400 days). This contrasts with the time necessary for the gastro–intestinal passage, which after oral application, is only several hours.

Such a relationship between bioavailability ("solubility") and toxic effect was established for nickel compounds in carcinogenicity studies after intraperitoneal application (see fig. 16-6). In these studies the readily soluble nickel compounds (acetate, sulfate, chloride, carbonate) showed a relatively low carcinogenic potency, which was more pronounced with compounds of lower solubility (sulphide, oxide, metal, alloys with the high nickel content of 66% and 50%) and was again lower with alloys with a low nickel content (29% nickel). It is not known whether the varying potency of the nickel alloys is the result of the varying nickel content or if the remaining components of the alloys (Fe, Al) influence the release of nickel ions.

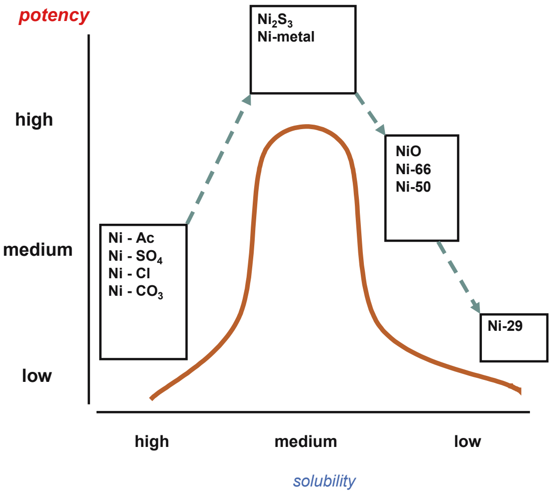

Figure 16-6. Carcinogenic potency of nickel compounds (from: Pott, 1991).

The existing human data confirm this picture: nickel oxide and nickel sulphide have been classified by the European Union as human carcinogens. Their carcinogenic potency is sufficiently high to be detected by epidemiological methods. The easily soluble nickel salts were classified as being suspect for carcinogenic activity. It has to be stressed however, that there exist indications of a carcinogenic effect in humans after inhalation of aerosols of easily soluble nickel salts (nickel electrolysis). At present, the evaluation of these data has not been finalised but they elucidate that an increased risk for substances with a low potency can be detected by epidemiology if exposure is sufficiently high.

4. AN APPLIED EXAMPLE FOR THE CLASSIFICATION OF ALLOYS

In many applications metals are not used in a pure form but as alloys, in which kind and amount of the individual metals varies widely. At present, discussions are ongoing as to how alloys should be classified with respect to their health hazards. This is of importance as in many cases classification is a prerequisite for regulatory actions for the protection of human health. In this case, classification means a health hazard has been proven or can be predicted reasonably well.

Because there exist many different kinds of alloys, it certainly will not be possible to perform a complete toxicological investigation for every alloy. Perhaps it is possible to form groups of alloys. However, the criteria for the allocation of individual alloys should not follow their technical properties but their health hazards.

In a simplified way, an alloy can be regarded as a mixture of different metals. Mixtures belong to the so-called preparations. (Definition according to Directive 1999/45/EC: preparations mean mixtures or solutions composed of two or more substances). The leading principle of this system consists in the classification of preparations according to the toxicity of their components if the percentage of one of the components exceeds a given concentration limit.

For alloys it is known that the availability of an individual metal can be changed by varying the nature and amount of the remaining metals. For example, this knowledge was taken into account when nickel-containing alloys were developed for the use in jewellery, in order to reduce the incidence of nickel allergies. (Menné, 1992). In the meantime, the European Union prohibited the use of nickel-containing metals intended to be used for jewellery or articles of consumption if they release too much nickel ions. (European Parliament, 1994).

In the context of the above-mentioned preparations directive, Germany proposed that alloys could be classified by a divergent procedure, if appropriate tests demonstrate that the critical metal does have a sufficiently low bio-availability. These tests should take into account different exposure routes (skin, lung, gastro intestinal tract), as in these compartments a differing bio-availability may exist.

Allowing for additional aspects, especially the possibility to detect severe toxic effects, the following proposal was put forward:

- In principle, alloys are classified according to the existing procedure (percentage, toxicity).
- Classification can be changed on the basis of tests for bio-availability.
- Tests for bio-availability take into account the foreseen route of exposure (oral, dermal, inhalation) and the critical toxicity of the metallic components.
- It is not allowed to conduct animal experiments with alloys that contain metals which are carcinogenic, mutagenic, toxic to reproduction, chronic toxic or accumulating.
- Grouping of alloys is possible on the basis of bioavailibility and toxicity of the metallic components.

Beside others, this proposal is at present being discussed on a European level in order to finally develop a system for the classification of alloys with respect to their toxicological properties. Before such a system can be applied, appropriate tests for the determination of bioavailibility will have to be developed.

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Chapter 17

METALLURGICAL PLANTS AND CHEMICALS INDUSTRY AS CHALLENGES TO ENVIRONMENTAL PROTECTION IN THE 19TH CENTURY

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1. THE METALLURGICAL INDUSTRY AND ITS EMISSIONS IN THE 19TH CENTURY

Industrial emissions in the 19th century have characterised the processing models used in certain technical disciplines, which define the environmental debate headed by technology (A. Andersen, 1996).

When dealing with emissions and the hazards arising from emissions, the metallurgical industry as a whole relied on a shift in the time and space dimension. In doing so, they relied on a shift from acute and local hazards to long-term global effects. The objective of this was defined two-fold: firstly, any type of emissions also signified a commercial loss, which had to be minimised; secondly, the expenses incurred for compensation were to be externalised. However, this was only possible if the legal requirement of clear causal evidence was not able to be furnished.

To illustrate this point, I should like to compare this branch of industry with perception of risks in the chemicals industry, which as a new industry – as will be demonstrated – has developed and has been able to develop a completely different way of tackling such risks (A. Andersen, 1999)[1].

To begin with, I should like to examine some events, which took place in the kingdom of Saxony. In 1845 fourteen inhabitants of the town of Halsbrücke and the municipal aldermen protested to the local authorities in Freiberg about expansion plans for the state-operated metallurgical plant:

> “The fruit tree only produces meagre fruit and once it finally produces and brings forth blossoms, the smoke from the metallurgical plant only needs to cover the blossoms slightly in order to poison them. The cattle fodder is also

A. von Gleich et al.(eds.), Sustainable Metals Management, 403-416.

poisoned and we were lucky that we noticed that the fodder was spoiled in sufficient time at least to prevent our cattle from becoming seriously ill as a result of eating such fodder."(StA Dresden, ASt Freiberg)

The petitioners also described the causes in detail that this was the result of the new inventions and installations (i.e. a new furnace design) as well as the fact that firewood was replaced by hard coal.

The decline in ore qualities in Saxony and increased international competition forced the management of the metallurgical plants to rationalise the smelting process and to increase ore throughput rates in order to continue producing corresponding quantities of precious metals. It was not until a new furnace technology was introduced that mass processing of lower-grade silver ores became possible. Within a period of eight years (i.e. from 1847 until 1855) the quantities of ores being processed increased two-fold (cf. fig. 17-1).

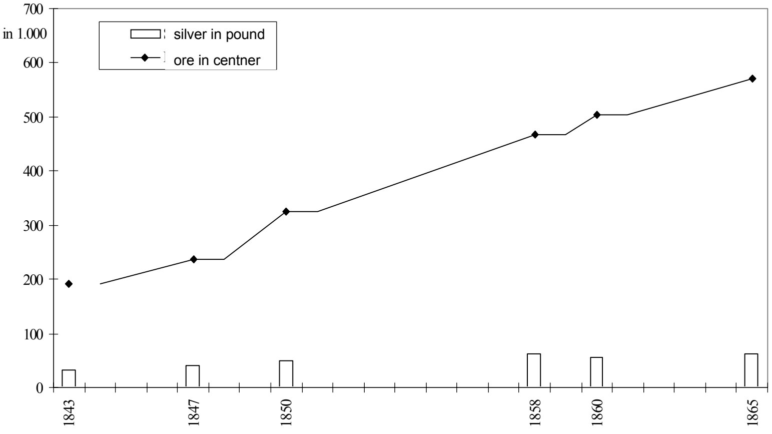

Figure 17-1. Ore processing and silver yield in metallurgical plants in Saxony (Jahrbuch für das Berg- und Hüttenwesen im Kgr. Sachsen)

Massive protests by neighbouring farmers, and later by forestry farmers sparked off a unique debate surrounding the consequences of non-ferrous smelting.

There were two crucial reasons as to why this debate could become a paradigm case not only in the German context. The key significance of ore mining for the state of Saxony meant that the risks entailed with this branch of industry had to be dealt with in a particular way. In the ensuing dispute involving experts two institutions, whose contemporary reputation went far beyond the borders of Saxony, stood out: the *Bergakademie* (Minig Academy) in Freiberg and the *Akademie für Forst-und Landwirtschaft* (Academy for Forestry and Agriculture) in Tharandt.

The *Bergakademie* co-operated closely with the metallurgical plants located in the area, which was also reflected in (technical) strategies and proposals to minimise smoke-related damage. The situation in Tharandt was marked primarily by Julius

Stöckhardt, a student of Liebig, who had the first chair of agricultural chemistry in 1847 and was considered to be the founder of the scientific study of smoke-related damage due to his tests and expert's reports. As both the parties causing the damage and the damaged parties were looking for support in other scientific disciplines – from veterinary science to chemical technology – a culture of expertise was developed as a result of the debate concerning the emissions from the metallurgical plants in Freiberg, which was unique for the latter half of the 19th century. As part of this culture of expertise the state-operated metallurgical plants in Saxony were able to occupy a leading position, at least as far as the German Reich was concerned, both in the field of metallurgical smelting and also in combating emissions from metallurgical plants. In Prussia the problems relating to industrial immissions were more diverse with the result that concentration on one branch of industry did not take place and non-ferrous smelting only played a secondary role in this.

In the wake of the protests since 1845, the official complaints of numerous towns commencing around 1847 opposing expansion of the metallurgical plants at Halsbrücke brought the Ministry of the Interior into the arena as the approval body. The ministry instructed Stöckhardt to compile an expert's report concerning the consequences of expanding the metallurgical plant.

In his expert's report Stöckhardt demonstrated that sulphur dioxide emissions were the main cause of damage to agriculture (Stöckhardt, 1988)[2]. This was the first direct evidence of damage caused by SO_2 in the world. Nevertheless, the Ministry of the Interior approved expansion of the metallurgical plant without any further provisos. The liberal verdict of freedom of trade demanded as little state intervention as possible in the production process. The Ministry of the Interior feared that (restrictive) immission prevention regulations would place the well-being of state-operated metallurgical plants in Saxony at risk. The only solution was to pay compensation to those affected.

The damage caused by smoke from metallurgical plants and the petitions from victims for assistance or at least for appropriate compensation were the subject of debates at the state parliament of Saxony seven times between 1855 and 1870 (First published on 4.5.1854, cf. Mittheilungen über die Verhandlungen des Landtages, 1855). After initial longstanding resistance by the management of the metallurgical plants, which endeavoured to evade its responsibility either by using the argument that the victims had been aware that they had settled near to a metallurgical plant or by using the criticism that the farmers were to blame themselves, as they had not cultivated suitable crops, as a result of massive public pressure it was forced to cut the emissions from the two state-operated metallurgical plants near Freiberg.

Three possible solutions were adopted (A. Andersen, R. Ott, E. Schramm, 1986):

1. retention of acidic gases and dusts containing heavy metals by condensation chambers, filters or using catalytic methods;
2. reduction of noxious gases by converting them, e.g. using a sulphuric acid processing unit;
3. by means of dilution via tall chimneys.

In doing so, the Halsbrücke metallurgical laboratory co-operating with the *Bergakademie* examined all metallurgical processes that were applied at that time or were presented in metallurgical and engineering periodicals as effective solutions for reducing emissions from metallurgical plants. This extensive “technology assessment” did, however, come up against its limitations in the commercial profitability calculation required by the administrative board of the metallurgical plant. This position was illustrated by the representative of the Ministry of Finance, Finanzrat Freiesleben, in a debate in the 1st chamber of the state parliament of Saxony in 1867. Representatives of the metallurgical plant had examined condensation facilities in Belgium, France and England. However, they also had the experience that some viable facilities could “only be created by sacrificing profitability of existing production facilities” (LA, 1866/68). For this reason, of these findings “only a few... were brought to completion in our area”.

These predominantly commercial criteria for immission protection resulted in the abandonment of an extensive technical experiment, the objective of which was to absorb sulphuric acid gases using lime (StA Dresden, ASt Freiberg, 1856). The costs for the required volumes of lime and for transportation appear to be too high and in addition there was no market for the massive quantities of gypsum resulting from this process. Therefore, flue gas desulphurisation using lime, which from a contemporary standpoint is a simple yet promising process, was no longer pursued and developed at the metallurgical plants in Freiberg for economic reasons.

Attempts to obtain sulphuric acid using the lead chamber process, were more rewarding. A sulphuric acid factory was established in Halsbrücke in 1857; its products were able to be sold at a profit (Jahrbuch für das Berg- und Hüttenwesen, 1873). However, the expected positive effects on SO_2 immissions did not occur, as only roaster gases with a sulphuric acid content of 4% could be processed (E. Drösser, 1908). Those gases containing less sulphuric acid arising during the smelting process continued to be emitted.

As the damage continued to increase in the 1860s despite all technical installations and eventually comprised an area of approximately 5000 ha, parliamentary debates centred on ways to counteract this damage. Since the first petitions in the mid 1840s, those affected had demanded a return to metallurgical technology and the scope of production in metallurgical plants prior to 1846. Not least of all due to these demands and because of this debate, the Trade Regulation Act of Saxony dated 1861 was ratified to guarantee the continued existence to authorised plants even if they caused a nuisance at a later date. Victims could thus not demand that the plant be modified, but rather could only submit claims for compensation. This standard procedure, which in addition to the Trade Regulation Act of Saxony was also adopted by the Norddeutscher Bund (North German Federation) in 1868, remains the basis for state authorisation policies today (R. Wolf, 1986).

The residents in the vicinity of the Freiberg metallurgical plants thus only had the right to claim compensation. For the administrative board of the metallurgical plants the relation between immission protection and profitability was thus redefined. Protective installations were only used if they proved to be more economical than compensation payments. In 1861 one plan was to construct a 60 m chimney in order to dilute pollutants to a large extent and distribute them over an extensive area so that they did not cause any more acute damage. However, the experiment failed and damage increased throughout the area to such an extent that this chimney had to be shut down again in 1863 (E. Schröter, 1908), as the operators feared that the protests would spread.

After every conceivable immission protection measure was tried out in metallurgical plants in the 1850s, the Ministry of Finances appointed an interdisciplinary commission comprising metallurgical experts, agricultural chemists, veterinary scientists, agricultural experts and forestry scientists, who examined the precise effects of emissions from metallurgical plants and were to establish limits for the major pollutants as a way of still containing damage (StA Dresden). This working group was and remained until well into the 20th century the only attempt to arrive at a technology assessment on an interdisciplinary level. Even though the smelting process itself was never the subject of debate and always remained the internal concern of the metallurgical plant, results were nevertheless obtained, which defined research into immission damage for more than fifty years. Two aspects should be noted: on the one hand, the desire of the state treasury to manage emissions from the metallurgical plant meant that only individual substances were estimated, synergy effects were not the subject of the debate, which is still a problem encountered in the discussion surrounding environmental protection and occupational safety with a certain level of powerlessness. On the other hand, the agricultural chemist Stöckhardt demonstrated the problems involved in defining limiting values in gassing experiments with spruce trees, as he reached the conclusion that a "threshold for noxiousness could not be stated in specific figures" (A. Stöckhardt, 1871).

On the basis of this fundamentalist statement concerning the harmfulness of even minute quantities of SO_2, Stöckhardt and thus the entire body of forestry and agricultural scientists at that time thus circumvented a social debate concerning the technical consequences of non-ferrous smelting. If smelting of sulphurous ores is considered to be uncontested and necessary by society, it would have been all the more necessary to discuss the conditions for this production. He did not even expand his theory that chronic poisoning is equivalent to acute poisoning in the long term. It could have become an important argument of principles against any chimney policy and subsequent theories concerning dilution – also in the field of waste water policy. It could even have made it possible to overturn the burden of evidence, as the proponents of the dilution theory would have been forced to establish that each of their limiting values were not harmful by carrying out extensive tests. However, the way was thus open for a positivistic approach with definitions of limiting values – only if something proved to be harmful are new limiting values required. The problem of weighing up different commodities and that of finding a compromise for conflicting interests ceased to exist behind the feigned objectivity of limiting values. Here the focus was not the limits of harmlessness, but rather (relative) cost-benefit comparisons, where the level of acceptable costs (for compensation payments and/or technical emission protection) was defined.

So tall chimneys became the favoured solution again in Saxony for the time being.

Although Robert Hasenclever, who ran a sulphuric acid factory, stated in 1879 that tall chimneys had not proven to be suitable for the purpose of neutralising acidic vapours (R. Hasenclever, 1879)[3], the plant in Freiberg relied on precisely this technology in spite of its co-operation with Hasenclever.

The reason why the administrative board of the metallurgical plant constructed this chimney, which at the time cost 300,000 Marks and once completed in 1889 was the tallest chimney in the world measuring 144 m (fig. 17-2), was primarily to reduce legal claims for compensation (O. Hüppner, 1890), as compensation payments were clearly linked to a causal context. The height of the chimney was thus determined by the fact that the smoke trail was just able to pass over the range of hills surrounding the valley around Freiberg. In addition to diluting the emissions, a decisive factor was the fact that no claims for compensation could be upheld against the metallurgical plant, as other factories located in the vicinity also emitted sulphur dioxide and it was thus no longer possible to furnish causal evidence relating to any one single plant.

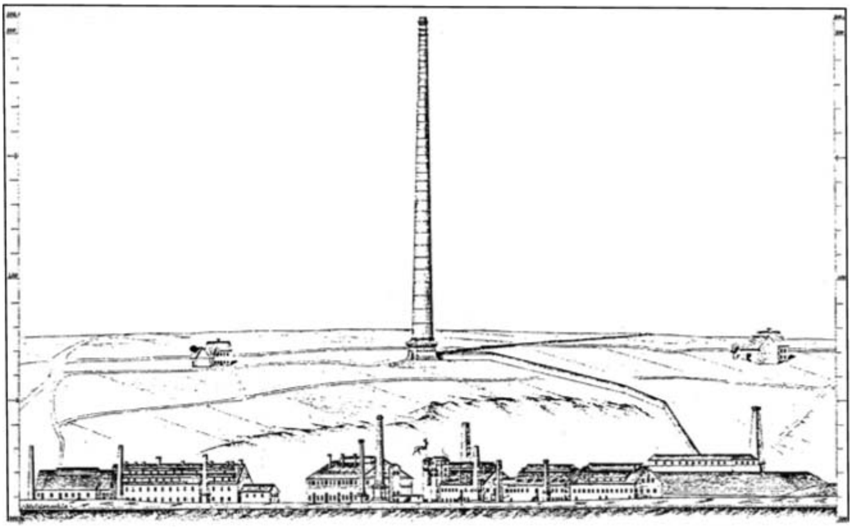

Figure 17-2. Tall chimney dated 1889

It very quickly became evident that construction of chimneys was a fallacy, as the damage did not vanish at all. On the contrary, the damaged area extended to a radius of more than 10 km. The detriment had now become manageable for the state-run administrative board of the metallurgical plant over and above (minimum) compensation payments until at least 1935 (StA Dresden). Despite warranted criticism of tall chimney technology, this method was still generally recognised as a means of counteracting immissions. However, this was due less to its actual effect than the powerful cultural effect of these industrial sculptures, which were regarded as a symbol of progress. The contemporary sociologist Hugo Münsterberg, who made a name for himself as an industrial scientist in the 1920s, summarised their significance fittingly in 1908. “Where a chimney smoked and now a thousand smokestacks bear witness to diligent work, legitimate progress has been made, which has made the world a better and more valuable place.” (H. Münsterberg, 1908)

2. CHEMICALS INDUSTRY AND RISK AWARENESS

I should now like to leave the assessment of risks in the metallurgical industry for the time being and to examine those of one of the most dynamic branches of industry in the German Reich, the chemicals industry.

While the debate concerning water legislation in Prussia was taking place, which prohibited discharging substances that were health hazards, the representatives of the chemicals industry also stated in 1894: “The belief that everything that may be harmful must be prohibited is unacceptable. A slate that falls from a roof is capable of killing someone, but nobody would consider banning roof slates.” (Society of Applied Chemistry, 1894) This statement is thus a paradigm definition of risk situations in this branch of industry. Barely twenty years later in the debate on water legislation in the German Reich the director of Bayer, Carl Duisberg, formulated the economic premises contained in this concept of risks: “We should not face any difficulties as a result of the Reich waste water legislation, as everyone is aware that the chemicals industry cannot operate without discharging its waste and we are nevertheless responsible for creating considerable economic value…” (C. Duisberg, 1923)

The ways of dealing with the dangers involved in this industry were described by the president of BASF, Carl Bosch, during the remembrance service for almost 570 victims of the explosion at Oppau in 1921 (fig. 17-3), which was the largest industrial disaster in German history to date:

> “This stroke of fate demonstrated to us in a terrifying way that all our efforts are merely vain human actions, that the secrets of the forces of nature cannot be tamed using levers and bolts… The human struggle with the forces of nature has always claimed the lives of countless victims, in most cases though in a less spectacular way, as they were not really brought to our attention. However, in this case in view of the magnitude of the disaster, this struggle becomes apparent in its full and shocking tragedy. The struggle is not a voluntary one, it has to be fought, and even today, standing at the open graves, the relentless compulsion forces us to continue fulfilling our duties.” (BASF, 1921)

The fundamental principle which all three statements have in common (Society for Applied Chemistry, Duisberg, Bosch) is the fact that this branch of industry is prepared to take risks and, related to this, identifies acceptable risks. The risk awareness, which Bosch demonstrated in 1921, was symptomatic. The objective was to discover existing weak points in the production process in order to overcome them. A technology assessment, which would at least have identified all social, ecological and health hazards, was not in the conception of the chemicals industry.

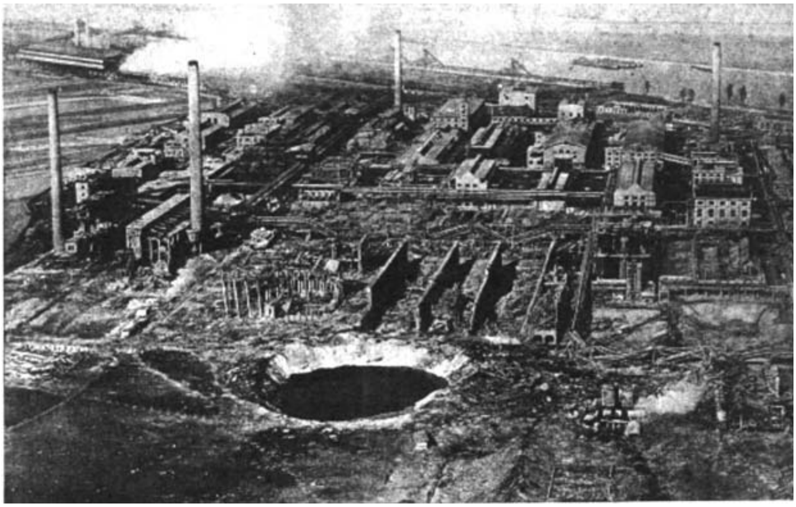

Figure 17-3. Explosion accident site in Oppau 1921

Accidents were indications that the production process was not functioning flawlessly and provided an incentive to make the production process more reliable and to optimise it from a commercial aspect.

Let me illustrate this point using an example.

The transformation of tar, which was a vile smelling and problematic by-product of gas production, into numerous bright paints, i.e. the beginning of synthetic paint production, was the source of considerable fascination for people in the 1860s and 1870s.

In view of this perception, the production process and its consequences for the environment and workers became of secondary importance. The mass material balance of fuchsine production alone is alarming (F. Fischer, 1893). Only scarcely 30% of the anilines used and the arsenic acids needed at that time were included in the final product, i.e. the remaining more than two thirds of parent substances were waste products or were discharged in sewage or in the atmosphere. Responding to the criticism of the Social Democrats that the workers involved in the paint production process at BASF were "terrifying figures covered in red, blue and green paint," (W. Breunig, 1976)[4] the company responded:

> "that workers involved in the production of paint do have splashes of paint on their clothing and on exposed parts of their bodies, which is just as usual as a miller being covered in white and a chimney-sweep being covered in black." (FA BASF)

Of course protests concerning neighbourhood rights from residents along the river, who needed a source of pure water for their production processes. However, these conflicts remained local or in the best of circumstances were restricted to the regional context, but did not cause any modifications to be made in the production processes. These processes were rather modified as a result of accidents, in which third parties outside the factories were injured.

In an accident in Basle in 1864 several people suffered from arsenic poisoning (M. Hämmerle, 1976 & M. Meier, 1988). The production of aniline on the basis of arsenic acid was prohibited in the city of Basle. As a direct result of this, paint manufacturers such as Ciba moved outside the city limits.

At the time of this ban the Germany company Meister, Lucius & Brüning, which was the forerunner of the Hoechst paint factory, had developed a process for aniline production in which arsenic acid was replaced by nitrobenzene (A. von Brüning, 1873). The intervention of the Basle city government made it possible modify the aniline production process faster than would have been likely without state sanctions, seeing as the new process was slightly more costly to begin with. Those involved at that time cannot be blamed for the fact that this modification did in fact replace one evil with another, as nitrobenzene is considered to be highly carcinogenic, although this did not become common knowledge until the 20th century. This example is one of the very few in which state bans were applied at all and brought about a change. Otherwise, the authorities mainly relied on voluntary action or prescribed environmental technologies like tall chimneys or catalytic converters, which did not alter the production process itself.

The bad mass material balance in the paint production process already mentioned was obviously also a thorn in the flesh of the chemicals industry. Irrespective of the shift from arsenic to nitrobenzene processes as a result of several disasters, the industry endeavoured to optimise the production process. Firstly, optimisation of chemicals technology comprised switching from manual stirring to automatic stirring machines and also developed closed production circuits, thus also reducing the acute risk of accident and poisoning.

Secondly, this was the starting point for the development of extensive production trees, in which initially unused waste materials became the base material for new products, which in turn produced waste materials that were likewise used for other new products.

The "technology assessment" merely described how the residual materials could be further processed. An ex-ante risk assessment or an interdisciplinary discourse, as described in the case of the metallurgical industry in Saxony, did not take place.

I had already referred to the myth of the chemicals industry; to be accurate it should be pointed out that its implementation process – as demonstrated by the Basle arsenic disaster – was not continuous. However, around the turn of the century the chemicals industry was considered to be a guarantee of progress. Even the water pollution caused by the industry could still produce some positive results. One of the most popular trivial fiction writers of the German empire, Rudolf Herzog, thus described the dirty state of the River Wupper in 1905 as "the decoration humans attributed to both it and themselves, which signifies: this is a centre of work; working people live here! This demands respect." (R.Herzog, 1905)

3. COMPARISON OF RISKS BETWEEN THE CHEMICALS INDUSTRY AND METALLURGICAL PLANTS

Let me summarise the different procedures relating to the production risks in these two branches of industry:

In the public debate industrial emissions ranked almost entirely behind problems of general urban hygiene. (Large-scale) industrial production promised improved social prosperity for all classes; its still existing local/regional hazards were considered to be a general sacrifice, which society at large had to make. From a legal aspect, this was seen as a factor of “normal local environmental burden”. The tall chimneys were thus less of a technical solution for the emission problem, but rather a symbol of the progress achieved (cf. Münsterberg 1908).

While industrial emissions at the end of the empire and in the Weimar Republic – outside individual regions – no longer played a role in social debates, nevertheless the processing models did characterise certain technical disciplines in both branches of industry, which have defined the debate on environmental protection – headed by technology – to date.

Both the metallurgical industry and the chemicals industry relied on a shift in the space and time dimension. They thus relied on a change from acute and local hazards towards long-term global effects. Their objective in doing so was defined in two dimensions, on the one hand emissions of any type also signified a commercial loss, which had to be minimised; on the other hand, the expenses incurred for compensation were to be externalised. However, this was only possible, if clear causal evidence, which was a legal requirement, could not be furnished.

The chemicals industry and metallurgical plants pursued different paths here. The debate surrounding emissions from metallurgical plants in Saxony constituted two technical principles in Germany: the end-of-the-pipe technology and tall chimneys. They combined with this the development of a policy of limiting values in Germany. While Stöckhardt rejected any limiting value for gases containing sulphuric acid as being non-definable for causing hazards at the beginning of the 1860s, courts and politicians demanded specifications for orientation purposes or in accordance with which they could approve new industrial installations. The limiting values were considered right from the start as a level of emissions that was accepted by society.

Despite the more extended social effects of industrial emissions – caused especially by the construction of tall chimneys – a customised technological development was the sole instrument of the enterprises. The technical consequences were the subject of public discussion, while the subsequent technical development did not take place in society. In combination with this the legal context was created by the Trade Regulation Act of Saxony, which still applies to the present immission protection legislation with regard to its initial protection for authorised installations. For the enterprises this signified an absolute legal certainty: in case of subsequent damages the operator could not be forced to modify technologies that had already been authorised. The only option available was to claim compensation under civil law. In this area, too, the Civil Code of Saxony dated 1863 provided for the first regulations governing immissions in German law, which later became part of the Civil Code (§ 906). This rendered every technology assessment relating to the technology, which was conducted by an enterprise, obsolete; it has remained a private matter to this day.

While expansion of the damage zone relating to reduction of immissions per m^2 proved to be a decisive factor for the metallurgical industry in averting claims for compensation, the time dimension was the prevalent factor for the chemicals industry. This was due to the shift in risk from the environment to the workplace. Within the definition of the clear causal cause-and-effect relation, in the case of metallurgical plants a vegetation period was considered to be the maximum time period. Although early forestry examinations in the 1860s had in fact revealed certain declines in growth lasting for an extensive period, these could nonetheless not be dealt with using the existing range of legal instruments with the result that even the losses in harvest occurring in the course of one full year were still evaluated according to an immissions concept based on acute damages. The permanently higher SO_2 content of the air in the vicinity of the metallurgical plants as compared with pure air zones, which had certain long-term detrimental effects, was defined as basic industrial environmental burden, which was excluded from claims for compensation due to the legal construction of “normal local environmental burden”. This example of an argument was not applicable to the chemicals industry, as environmental burdens at the workplace could not be characterised in accordance with vegetation periods. Therefore the time horizon in the chemicals industry, having passed stages of acute poisoning and accidents, was moving towards infinity. Possible effects of work-related, toxic environmental burden could manifest themselves throughout the life-time of a worker and did not stop when the worker retired.

While smoke from metallurgical plants “dissolved” into a general smoke epidemic around the turn of the century, from the start the chemicals industry referred to the organic, for the most part municipal discharges. In this case acute health-related hazards could not be excluded, as the Hamburg cholera epidemic in 1892 again demonstrated emphatically. After the problem of arsenic was resolved, the discharge of chemicals, on the other hand, proved to be at best a regional aesthetic problem as a result of the discoloration it left behind. In view of the positive image of the chemicals industry, this attitude was also capable of achieving a public majority.

Both branches of industry examined succeeded in most cases to at least master the acute hazards under normal operating conditions by making new and further developments within existing lines of technical development. Precisely this reinforced the optimistic spirit of industrialism in relation to progress especially by developments in the chemicals industry. However, the parties involved at that time were aware of the fact that this way of dealing with problems was at the same time restricted by a quantitative extension of the production process. Their reaction to this could only be conceived again within existing technical disciplines.

Irrespective of certain critical tendencies in relation to the industry in the field of nature preservation and local environment preservation, contemporary “technology assessment” identified very vital problem areas, which have become the subject of social debate and technology evaluation today. In view of the fact that "environmental" conflicts in the examination period from 1845 to 1930 were merely controversies surrounding various proprietary rights and uncontested free usage of natural resources, such as air and water, possible bans on production and technology or relevant authorisations did not, however, have any chance. The ban on arsenic in the paint manufacturing process was merely one exception. This was, however, a classic poison, the hazards of which were uncontested. "Environmental" protection and occupational safety otherwise had to be measured against the yardstick of commercial profitability. Only those actions that overcame this obstacle had a chance of being successful.

However, it was not until the changed natural conditions in society since the 70s were discussed as a central theme that the opportunity was created to examine calculations of commercial profitability as a theme for socio-ecological economic accounting.

NOTES

[1] Regarding the myth of progress in the chemicals industry itself cf. A. Andersen

[2] This was submitted to the OHA on 2.3.1850 (StA Dresden, ASt Freiberg, OHA GG 32, vol. 1, pp. 21-49). As the manuscript is identical to the text contained in the *Centralblatt*, my quotation originates from this publication. The expert's report was published in 1850 simultaneously in the *"Zeitschrift für deutsche Landwirthe"*. This enabled Stöckhardt to present his examinations to both parties, i.e. engineers/technicians as well as farmers. In other authorisation procedures, such as e.g. in the case of the Hamburg copper works (Elbkupferwerke) in the 1850s, direct reference was made to Stöckhardt.

[3] R. Hasenclever had published a series of articles *"Über die Beschädigung der Vegetation durch saure Gase"* in "Chemische Industrie". This sequel article appeared as an independent publication the same year and was supplemented by colour lithographic prints of damaged vegetation

[4] Weidemann, who was a union representative, from whom this statement originated, was sentenced to 14 days in prison for inflammatory speeches despite the fact that the content of his accusations was proven to be founded.

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Chapter 18

COPPER MINING AND METALLURGY IN PREHISTORIC AND THE MORE RECENT PAST

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1. INTRODUCTION

The origins of copper extraction must be looked for in Asia Minor. The know-how arrived in Europe via the Aegean. Our knowledge of the first copper mines in Europe is slight (see table 18-1 and figure 18-1).

Table 18-1. The origins of copper mines in Europe

Rudna Glava	Serbia	Oxide ore	4500 - 4000BC
Ai Bunar	Bulgaria	Oxide ore	4500 - 4000BC
Chinflon	Spain	Oxide ore	3000 - 2500 BC
Mitterberg	Austria	Sulphide ore	1700 - 1000 BC
Mount Gabriel	Ireland	Oxide ore	1600 - 1500 BC

Other mining areas might exist but the traces have been destroyed by more recent mining. There is no written evidence. The oldest copper mines were founded upon copper-oxides that were reduced with charcoal. The deposits were easily recognisable due to the green and blue coloured copper mineral.

In Mühlbach (Mitterberg deposit) the conditions are and were different. Sulphides constitute the primary minerals – chalcopyrite and pyrite. Both have a golden luster and could have led the miners of that time to believe that it was gold. But it was not possible to produce metal by reduction smelting.

Pure copper is a soft metal, not useable as a tool. Several copper deposits also contained nickel (Ni), arsenic (As) and antimony (Sb), which were not so easy to extract from the copper. However, they did stabilise and harden the copper. Table 18-2 contains a series of these natural copper alloys. Bronze and brass is also listed, which can only be produced by the joint smelting of copper and tin ore / zinc ore.

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Figure 18-1. European copper deposits in the Bronze Age (Jovanovic, 1980)

Table 18-2. Bronze Age copper (Cu) alloys

Natural alloys					
	BC	**Cu**	**% As**	**% Sl**	**% Ni**
Pure copper	2500	> 99.0	< 0.5	<< 0.1	-
Arsenic bronze	2000	95	< 5	< 0.1	< 0.5
AsSl bronze	1500	85	< 5	< 10	< 0.5
NiAs bronze	1500	> 88	< 5	< 1	< 0.5

Specifically manufactured alloys					
	BC	**Cu**	**% Sn**	**% Sb**	**% Zn**
Sn bronze	2000	> 85	< 15	< 1	-
Sn bronze	500	> 70	< 10	< 20	-
Brass	From 800	> 70	< 10	< 10	< 20

2. COPPER MINING SINCE THE BRONZE AGE

2.1 Mühlbach

The deposit at Mühlbach am Hochkönig lies south of Salzburg, above Bischofshofen (see figure 18-2).

Figure 18-2. Map of Mühlbach

In the Bronze Age smelting took place at the pit face, 150 years ago it took place in Mühlbach, and 100 years ago until 1931 in Außerfelden in Salzachtal. Table 18-3 shows a chronology of copper mining and extraction.

Table 18-3. Copper mining and extraction in Mühlbach am Hochkönig (Mitterberg) (Re. Günther et al, 1995).

1700 - 1000 BC	pre - historic mining and copper production
1827	re-discovery of the deposit
1829	start of mining
1848	construction of Mühlbach copper smelter
1882	construction of copper smelter in Außenfelden/Mitterberghütten
1908	contruction of a modern processing plant
1911	contruction of an electrolytic refinery
1931	closure of mine and smelter
1938	re-opening of mine and production of concentrates
1972 - 1976	experimental hydrometallurgical processing of the concentrates
1977	final shut-down of all smelter

The Bronze Age mining was followed by 2800 years quiet. Only by chance at the beginning of the 19th century were the deposits re-discovered. This was quickly followed by the re-opening of the mine and construction and operation of a copper smelter. 30 years later the copper smelter could no longer meet demand. A larger and, for its time, modern copper smelter was built in Außerfelden/Mitterberghütten in Salzachtal. In 1908 a modern processing plant was constructed in Hochkönig while in 1911 an electrolytic refinery was built in Außerfelden. The Great Depression at the beginning of the 1930s spelt the end initially. In 1938 mining and ore dressing was re-started in order to exploit the domestic reserves.

In 1972 an attempt was undertaken to extract copper. The experiment had to be ended in 1976 as the mine could not produce the requisite amount of concentrates. All work was finally shut-down in 1977.

Data about the deposit is shown in table 18-4.

Table 18-4. The deposit.

Deposit seam with a length of some 11km, a depth of 0.2 – 4m. Numerous faults		
Principal ore:	Chalcopyrite	$CuFeS_2$
Minor component:	Gersdorffite	NiAsS
	Fahlerz	$(Cu, Fe)_{12} (Sb, As)_4S_{13}$
Also:	Pyrrhotite; pyrite, haematite, quartz, dolomite, magnesite, anhydrite, gypsum,	

It is a chalcopyrite deposit with a certain amount of As and Sb, as well as pyrite. Unfortunately the ore contained almost no silver or gold.

Table 18-5 shows the entire copper extraction in Mitterberg. Annual production in the Bronze Age was well above 20 t Cu, for which 1000 t of ore had to be mined and processed, without drilling equipment or dynamite.

In the 19th century 300 t Cu per annum were mined, in the 20th century production rose from 1000 t to 1500 t and finally to 2000 t Cu per annum.

Table 18-5. Cu extraction in Mitterberg

Time Period	Amount of crude ore	Cu-content
1700 -1000 BC	approx. 800,000 t*	17,000 t Cu*
1827 – 1906	1,750,000 t**	23,400 t Cu**
1907 – 1930	1,460,000 t	29,200 t Cu*
1942 – 1961	1,831,700 t	33,160 t Cu
1962 – 1976	2,360,000 t	33,560 t Cu
In total	8,200,000 t	136,300 t Cu

* Estimate / ** Converted value

2.2 Mining

Numerous traces of mining remain, especially day drifts and glory holes. Figure 18-3 illustrates how the mine in Mühlbach would have looked. Tools were stone hammers that weighed 2-5 kg, as well as wedges made out of animal horn. The ore was also mined by setting fires and then breaking it up by quenching it with water. Figure 18-4 illustrates the fire setting procedure. Neither drilling machines nor dynamite were known.

Meanwhile, day drifts and paths had to be dug in the same way. Under these conditions the average daily mining performance was 4 t of ore.

Figure 18-5 illustrates the mining boundaries of the Hochkeil mine. The horizontal and vertical scales are not the same. However, it is clear that the veins along the entire upper area of the deposit have been worked and tunnels run for several hundred metres. There is also evidence of some 200 smelting places next to the day drifts.

2.3 Ore dressing and metallurgy in the Bronze Age

From numerous samples we can build a fairly exact picture of ore dressing and metallurgy at that time.

The extracted ore was hand picked, the tailings were discarded. The lumps of ore were reduced in size with hammers and then crushed. The crushed copper was washed and the sediment dumped. Concentrates (slime), granular ore and grit were subjected to heap roasting.

Heap roasting also marks the transition to the metallurgy of copper. The partially roasted product was smelted with sand, charcoal and rich slag in small shaft furnaces. This was done in batches. The products were black copper, copper matte and slag. The black copper (carbide) was roasted together with the copper matte before it was finally reduced with charcoal and then sold. The copper collected at the bottom of the shaft furnace as a flat cake weighing 4-8 kg. The resulting matte was repeatedly roasted, melted and treated as before. The rich slag (> 2% Cu) then underwent the roast reduction process once more. The final slag has between 0.3 and 0.5% Cu. Figure 18-8 shows one of the shaft furnaces as used in Mühlbach. Tuyere remains were also found.

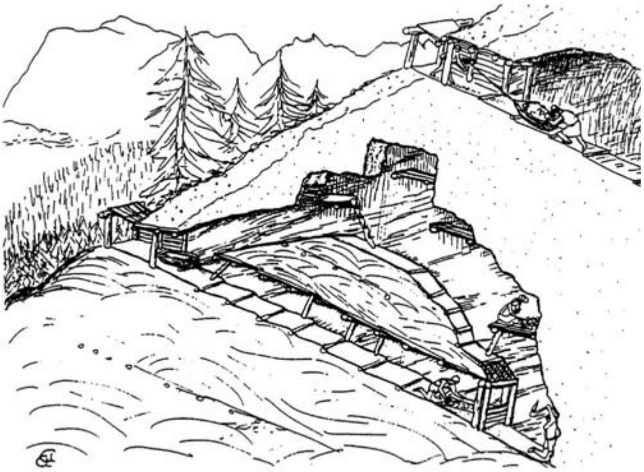

Figure 18-3. Copper mining in "Firststreckentechnik mit Bergeversatz" (stope engineering with dirt paths)(Günther et al., 1995)

Figure 18-4. Underground fire setting (Agricola, 1978)

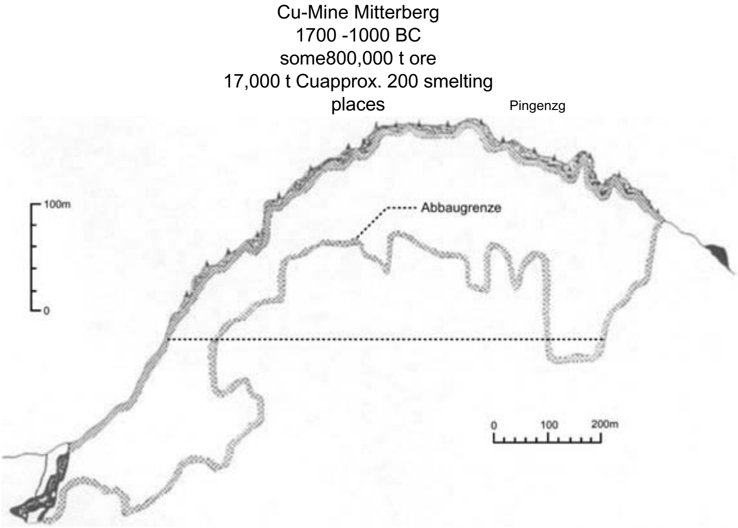

Figure 18-5. Mining boundaries of the Mitterberg mine in the Bronze Age (ref. Kyrle, 1912)

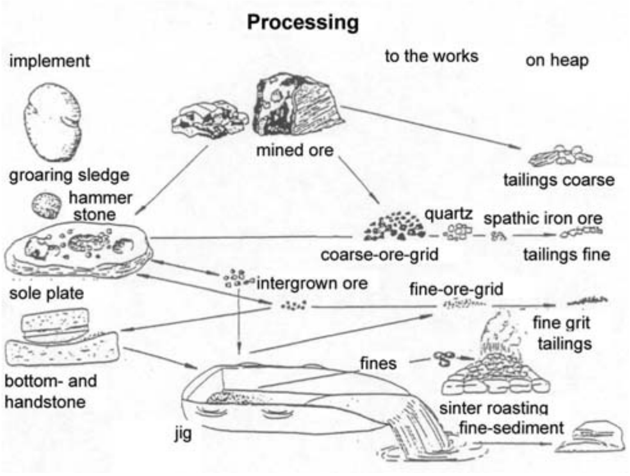

Figure 18-6. Illustration of ore dressing in the Bronze Age (Günther et al, 1995)

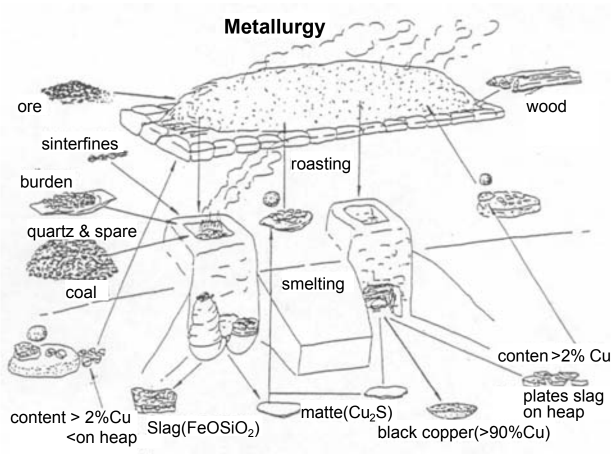

Figure 18-7. Illustration of smelting in the Bronze Age (Günther et al, 1995)

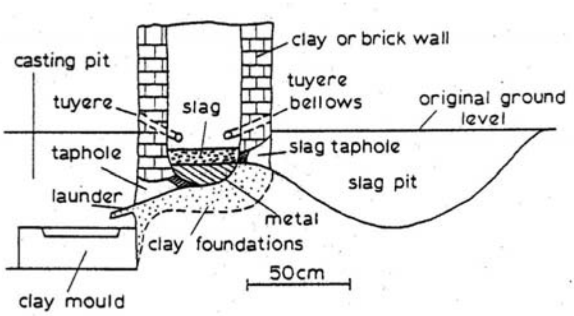

Figure 18-8. Example of a smelting furnace to produce copper (Tylecote, 1992)

Table 18-6 shows analysis of the resultant copper cake. The metal was traded in this form and composition.

Table 18-6. Analysis of copper remains from the Bronze Age mining district in Mitterberg (ref. Kyrle 1912)

No.	Object	S	Fe	Ni	Cu	As
1	Cast cake (CA 1412)	1.74	2.53	0.74	94.18	Analysis by KYRLE
2	Cast cake (CA 1720)	0.99	0.32	traces	97.54	
3	Cast cake (CA 1721)	0.97	0.57	traces	97.91	
4	Cast cake (CA 1408)	1.48	0.89	0.34	96.54	
5	Cast cake (CA 1414)	0.36	1.42	0.57	97.14	

(continued)

No.	Object	S	Fe	Ni	Cu	As
6	Pure copper from picked slag fragments	0.09	-	-	98.46	
7	Cast cake (CA 1413)	0.28	0.23	0.00	98.2	0.19
8	Copper cake (CA 1722)	0.33	1.18	2.19	95.46	0.65
9	Copper cake (CA 6232)	0.52	0.46	0.10	98.8	0.0

2.4 Metallurgy 100 years ago

Table 18-7 shows the set-up of the copper smelter in Mühlbach and Außerfelden/ Mitterberghütten. In 1880 neither converters nor electrolytic refineries had been invented. A huge operation was required to produce some 200 t Cu per annum. The technology was almost unchanged from the Bronze Age.

Table 18-7. Smelting and roasting capacity of the copper smelter (Günther et al, 1995)

Copper smelter Mühlbach (approx. 1880)	
1 cylindrical shaft furnace 2 arched furnaces	Ore and slime smelting
7 double heaps 1 roasting shaft furnace 1 roasting reverb. furnace	Roasting of lowgrade and enriched matte
2 copper refining hearths 1 refining furnace	Copper refining
Output of smelter 230 t/a Cu	
Copper smelter Mitterberghütten (approx. 1925)	
2 Dwight-Lloyd machines	Roasting
2 shaft furnaces	Smelting
5 drum converters	Converting
1 electrolysis	Refining
Output of smelter 4,000 t/a Cu	

The picture changed in 1926. Fine ore/concentrates were roasted on sinter hearths, while lump ore and sinter were melted to matte and removable slag in shaft furnaces. The copper matte was pre-refined in a converter, and then the copper was electrolysed. Converter slag was de-copperised in the shaft furnace. Thus the entire operation was significantly simplified. The resulting SO_2 was mostly processed into H_2SO_4. But neither the mine nor the smelter survived. The site was much too small.

Metallurgy in the 19th century is already very carefully documented. Table 18-8 and figure 18-9 provide further details. Figure 18-9 shows more clearly than table 18-8 how protracted and laborious copper extraction from sulphidic ores was before the introduction of the converter process. The final slag resembles final slag today, but the copper quality was far from that demanded today.

Table 18-8. Composition of batch mixture and products (1st half 19th century) (Günther et al, 1995)

	(all data in weight percent)				Distribution by product (%)
	Cu	Fe	S	SiO_2	
Batch mixture I	13	28	22	23	100
Lowgrade matte	23	42*	28*		53
to be dumped slag	0,3	27	1	46	40*
Batch mixture II 75% roasted lowgrade matte 10% sand, 15% slag	20*	38*	10*	17*	100
Enriched matte	55	16	21		33
Slag	1	51		26	63*
Speiss	80	5	2		1-2*
Batch mixture III 58% roasted highgrade matte 27% slag,15% sand	35*	21*		27	100
Black copper	95	0,5	0,5		35*
Return slag	2,5	34		48	56*

*estimated

2.5 Sustainability of early copper extraction

If one poses the question about the sustainability of copper extraction in the Bronze Age and later, obviously one cannot assess it using today's objectives. Metal production was, according to today's standards, very small, so the yield was very important. Energy consumption and emissions played no role. Mining was so laborious that once the ore was dug up from the mine a 100% copper extraction was targeted. That was also achieved. There is no doubt that for as long as drilling and blasting were unknown concepts in mining, metal recycling was always more cost effective than copper extraction from primary raw materials. Back in ancient times, in order to produce good quality metal, around a third of the material input was added scrap metal, as described by Plinius [1989]. But this form of extraction had a very high energy demand, which was met over the millennia by using timber and charcoal respectively. Open-air roasting only became a problem as production began to rise. Then (around 1850-1880) the first H_2SO_4-plants were built, but they were often very temperamental. This was due to the comparably low and irregular supply of SO_2. Table 18-9 is interesting as it illustrates the ore dressing and smelting. Thereafter, ore dressing was considerably improved due to better grinding processes and very selective flotation reagents. However, in metallurgy copper losses were always low.

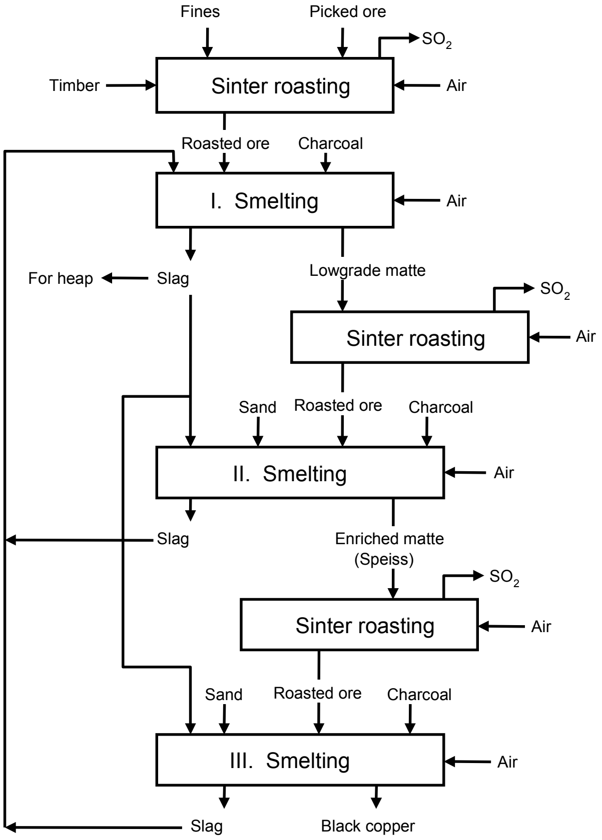

Figure 18-9. Copper production in Mühlbach (1st half 19th century) (Günther et al, 1995)

After the resumption of mining in 1829 the processing plants (stamping mill, washing plant and shaking table) were still driven by hydro-power, a total drop of 225m was available. Lump ore and the resultant concentrates were taken to the valley by carts in summer and by sledges in winter.

The energy expenditure was considerable. In the mine, rocks were extracted by setting fires. Some 0.4-0.8 t of rock could be prised away with 1 t of timber. The heap roasting required 0.25 m^3 of timber per t of ore. For the entire copper smelter some 10 tonnes of charcoal per tonne of copper was needed in 1877, after the installation of a converter in 1907 a further 2.3 tonnes of coke per tonne of copper was required; 1911 after the start of electrolysis only a further 0.85 tonnes of coke per tonne of copper was needed, in addition to the expenditure of energy for the electrolysis (≤ 400 kWh/t Cu).

Table 18-9. Copper production losses in Mühlbach/Mitterberghütten (according to smelter statement / estimates respectively) (Günther et al, 1995)

	Ore dressing	Copper smelter	according to smelter statement
Bronze Age			
Tailings/slag	~ 0.5 % Cu	0.3– 0.5 % Cu*	
Loss	~ 25 %	~ 3 %	
19th Century			
Tailings/slag	0.25 % Cu	0.3 % Cu	in total 25 %
Loss	12 %	~ 3 %	
until 1925			
Tailings/slag	0.15 % Cu	~ 6 %	in total 10 %
Loss	0.3 % Cu	< 2 %	
until 1976			
Tailings/slag	0.07 % Cu	3 % Cu	no copper smelter
Loss	~ 3 %	≤ 1 %	on site

* Lump ore with 15 – 25 % Cu, fines with 7 – 10 % Cu

The purification of waste gases was initially limited to particulate collection. Only when the Außerfelden copper smelter was built was the neutralisation of SO_2-containing waste gases undertaken, and this imperfectly. Finally, a small H_2SO_4-plant (10 t H_2SO_4/d) was built in 1920, leading to 0.0025 % SO_2 in the chimney gas.

Conclusion: The copper yield always corresponded to the state-of-the-art technology; the expenditure of energy would accordingly be quickly adjusted to the latest operational development. Waste gas purification alone only reached the state-of-the-art in the final phase of the copper smelter. The small production until 1880

by 1850 ≤ 100 t Cu/a
by 1880 ≤ 200 t Cu/a

meant that waste gas purification did not appear urgent.

Further, the overburden dumps and slag heaps did not pose a problem to the environment with regard to either the amount or their composition. The total size of these dumps from the start to around 1900 represented a 100 m x 100 m x 100 m cube, but was spread over a wide area. The actual copper extraction was so designed that the waste dumps and slag heaps contained very little copper.

3. COPPER EXTRACTION SINCE THE MIDDLE AGES

3.1 The Mansfeld / Sangerhausen sites

The Mansfeld deposit stretched from Gerbstedt over Hettstedt, Mansfeld, Helbra, Wolferode to Helfta. The Sangerhausen deposit comprises Sangerhausen, and the villages of Niederröblingen, Allstedt, Nienstedt (see figure 18-10). Table 18-10 shows a chronology of the Mansfeld mining and copper smelter. Mining and smelting began around 1200. After 1400 there were a total of 9 smelter with a smelting capacity of 180 t Cu/a. Around 1500 the mine was already so deep (30 m) that the first day drift was required, to allow the resulting water to run off. In around 1700 fire setting was replaced by black blasting powder, dynamite followed in 1870. Around 1500 the so-called “Saiger process” was so far developed that 70% of the silver could be extracted. 20 years later, some 106 smelting furnaces were already in operation and achieved a capacity of approx. 1000 t Cu/a. Before 1500 the smelting capacity reached charges of 1.5 t per day and per furnace. 10 years later the smelting capacity rose to 4 t/d per furnace; due to improved bellow construction.

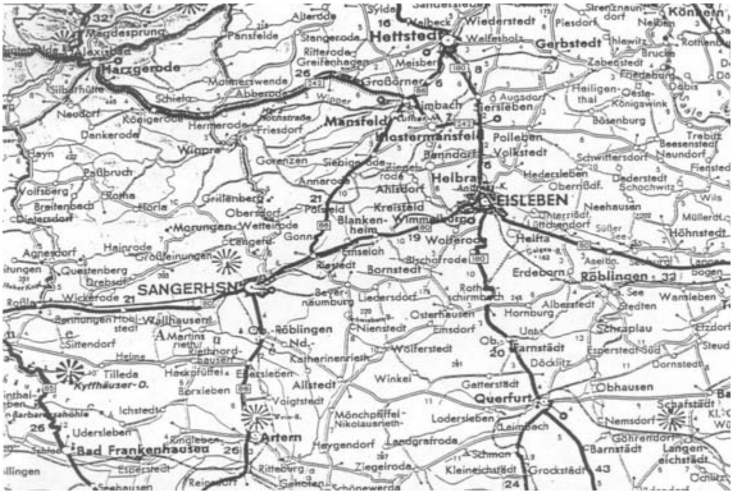

Figure 18-10. Map of Mansfeld/Sangerhausen

Capacity rose to 18 t/d per furnace in 1860 and jumped to 150 t/d per furnace for the first time in 1870 due to blast heating to 300 °C. Shale burning could be halted in 1915; after 1960 the daily throughput of the smelting furnaces was 800 t/d. The final implementation of the converter operation only took place in 1926. This was because silver was extracted using the so-called “Ziervogel process” which required fine copper matte as charging material. Between 1926 to 1938 only a small amount of the copper matte was refined to produce metal, most of it was refined just to produce fine copper matte, which was then desilverised using the “Ziervogel process”. Only with the introduction of the electrolysis in 1938 was the entire matte production refined into metal and then electrolysed. 1933 saw the highest silver production and the highest copper production was achieved in 1967.

In the 1960s the Mansfeld pits were exhausted and closed. The closure of the Sangerhausen pit and smelter followed in 1990.

Table 18-10. Chronology Mansfeld (ref. Hoffmann, 1925; Hüttenwerke, 1904; Jankowski, 1995; Mansfeld, 1999)

Approx. 1200	Start of mining and smelting works
1430	Eisleben 5 smelter with 10 furnaces – 100 t Cu/a Hettstedt 4 smelter with 8 furnaces – 80 t Cu/a
Approx. 1500	First day drifts documented (they were 30 m deep and reached the ground water table) 70 % of the silver was extracted
1520	Eisleben 24 smelter with 64 furnaces Eisleben 10 smelter with 24 furnaces Hettstedt 18 furnaces
From 1700	Gun powder replaced fire setting Mine depth 50 – 100 m
1785	Mine depth 130 m Initial use of steam engine powered pump drive
1832	Initial use of steam engine for shaft transport
1870	Initial use of dynamite Mine depth 250 m
1926	Implementation of converter process
1933	Highest silver extraction at 187 t
1938	Launch of Cu-electrolysis
1967	Highest copper extraction at 30615 t
1990	Closure of copper mine and crude smelting operation

Table 18-11. Extraction of by-products (ref. Hoffmann, 1925; Hüttenwerke, 1904; Jankowski 1995, Mansfeld, 1999)

Approx. 1500	Improvement of silver extraction (“Saiger process”)
From 1850	Manufacture of nickel products
1858	Initiation of H_2SO_4-production
From 1865	Manufacture of paving stones from slag (1938 42 x 10^6 large paving stones, 16.5 x 10^6 small paving stones)
1887	Construction of leadsmelter
From 1910	Ferrous-molybdenum, nickel and cobalt production from furnace sow (Ofensauen)
1928	Introduction of waelz kiln operation and clinker from flue dust to produce ZnO and $ZnSO_4$
From 1940	Production of V_2O_5
From 1950	Production of rhenium
From 1958	Production of selenium

Copper and silver were the only products until the mid 19th century. Then the product range was significantly widened, as illustrated in table 18-11. This was done to improve the economics of the operation (Ni, Pb, ZnO, V_2O_5, Rh, Se), for environmental reasons (H_2SO_4), from a strategic point of view (furnace sow) and to use available materials (slag brick).

3.2 The deposits

The deposits stretched over large parts of Germany to Poland, but only a few were worth mining, they are listed in table 18-12. The largest deposits were found at Lüben with an annual production of over 20,000,000 tonnes of ore.

Table 18-12. Deposits overview

Spatial extent: ~ 600,000 km^2	~ 600,000 km^2	
Commercially usable:	*Richelsdorf (Hessen)* *Harzvorland (Sachsen-Anhalt)* *Spremberg (Brandenburg)* *Bunzlau (Niederschlesien)* *Lüben (Niederschlesien)*	
Depth in Harzvorland	0.3 – 0.4 m and less	
Main minerals:	*Bornite* *Chalcopyrite* *Fahlerz* *Galena* Sphalerite	$Cu_5Fe\ S_4$ $Cu\ Fe\ S_2$ $Cu(As, Sb)_4S_{13}$ PbS ZnS
Miscellaneous:	copper sulphides Cu_2S, CuS	
Also:	Pyrite, pyrrhotite, haematite, magnetite, calcite, barite, quartz, anhydrite in total 52 elements are represented	

In Harzvorland the depth was just 0.3 - 0.4 m but it also fell to only 0.1 m. The main minerals are bornite, chalcopyrite, fahlerz, galena and sphalerite. The extracted ore contained 2.4 – 3 % Cu, 1 – 3 % Fe, 2 – 5 % S, 0.01 – 0.02 % Ag, 10 – 17 % bitumen, as well as 29 – 30 % SiO_2, and 11 – 15 % of CaO and MgO. The ore contains little iron and sulphur, but does have high bitumen content.

3.3 Metal content and production

The Mansfeld/Sangerhausen region is a polymetal deposit with the principal metals being copper and silver. Increasingly from 1850 onwards efforts were made to extract the minor metals. This was mainly due to considerations to improve the commerciality of the site, but self-sufficiency motives also played a role at that time. The reserves of the most important metals are given in table 18-13 below. Table 18-14 shows the amount of Cu and Ag extracted over a period of 700 years. According to which, 2/3 of the total amount of documented copper and silver have been extracted.

Table 18-13. Metal content of the Mansfeld/Sangerhausen deposits (ref. Mansfeld, 1999)

Copper	3,750,000 t
Lead	750,000 t
Zinc	650,000 t
Vanadium	65,000 t
Arsenic	27,000 t
Molybdenum	23,000 t
Silver	20,000 t
Nickel	14,000 t
Cobalt	11,000 t
Selenium	3,900 t
Rhenium	3,300 t
etc.	
Gold	5 t

Table 18-14. Cu-Ag production balance sheet of the Mansfeld/Sangerhausen mining district (ref. Mansfeld, 1999)

		Cu	**Ag**
Mansfeld mining district		2,9 %	0,015 %
Sangerhausen mining district		2,4 %	0,006 %
Period	**Ore (t)**	**Copper (t)**	**Silver (t)**
1200 - 1699	7 000 000	205 000	1 025
1700 - 1749	480 000	14 000	74
1750 - 1799	1 160 000	34 100	166
1800 - 1849	1 290 000	37 200	200
1850 - 1899	14 380 000	456 300	2 593
1900 - 1950	41 110 000	1 064 100	6 062
1951 - 1990	43 480 000	818 300	4 093
In Total	**109 000 000**	**2 629 000**	**14 214**

Thus Mansfeld/Sangerhausen had the largest copper deposits in Germany. Silver extraction also far exceeded the other German pits.

3.4 Mining

Mining began in small pits that produced little before the use of drilling equipment and explosives (see table 18-15). This was made more difficult by the height of the mine face that meant that all underground work could only be carried out when lying down. Despite this mining and smelting was profitable around 1500; figure 18-11 shows what returns could be derived from mining and smelting.

Table 18-15. Mining in Mansfeld (ref. Jankowski, 1995; Mansfeld, 1999)

Approx. 1500	Pit occupancy 4—10 men per shift Production 2—5 t shale per week **Longwall height 40—50 cm**
Approx. 1900	Pit occupancy 1100 – 2000 men Production 1200 t shale per week **Longwall height 40—50 cm**
Approx. 1920	Pit occupancy 3000 -4000 men Production 14,000 t shale per week + 20,000 t dead rock per week **Longwall height 80 cm**
Approx. 1960	Pit occupancy 1000 - 2000 men Production 10,000 t shale per week + 20,000 t dead rock per week **Longwall height 80 cm**

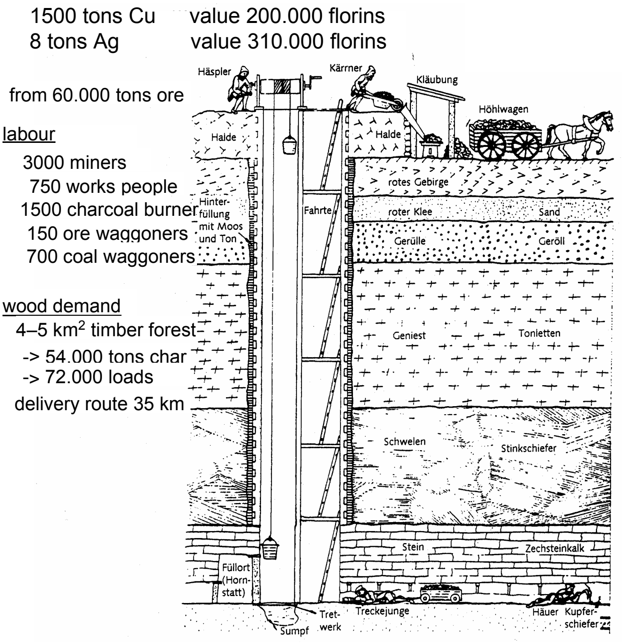

Figure 18-11. Mansfeld production data from 1530 (Jankowski, 1995; Mansfeld, 1999)

In this context it is quite remarkable that the value of the silver production exceeded that of copper. In total some 6000 people were engaged in processing the requisite 60,000 t ore, producing the necessary charcoal and in transportation. As smelting was not carried out during the entire year, 400 coal trips were made to the smelter and the same number of return journeys along the coal road (today the B 242) in the summer half-year. As the journeys were slow, the vehicles were on the move day and night within sight distance. Especially in Mansfeld, fire setting required good weather due to the bitumen. A shaft was sunk approximately every 10 m; the shale was mined out of this radial (see figure 18-12).

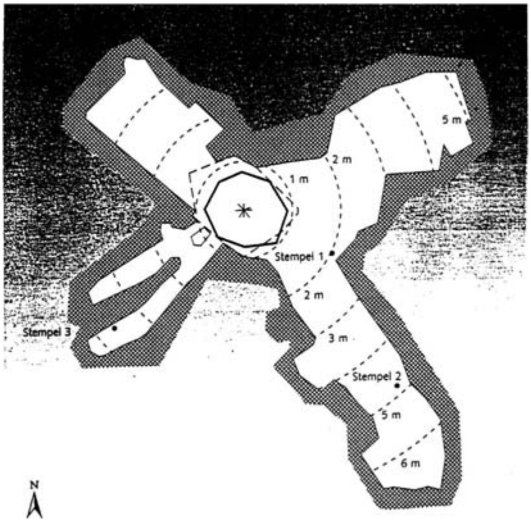

Figure 18-12. Underground situation of shaft 1 at Sangerhausen (Jankowski, 1995)

The seam was only 20 cm wide; the longwall height was 50 cm, whereby part of the dead rock was used immediately as packing. Around 1920 the situation changed dramatically (see table 18-15). A certain level of mechanisation in mining led to fewer large pits, plus the longwall height had to be raised to 80 cm. Naturally this resulted in a lot more dead rock being mined. Figure 18-13 illustrates this. Table 18-16 shows the amount of layered dumps and conical heaps that is still available today. Their metal content is so low that metallurgical processing is not possible.

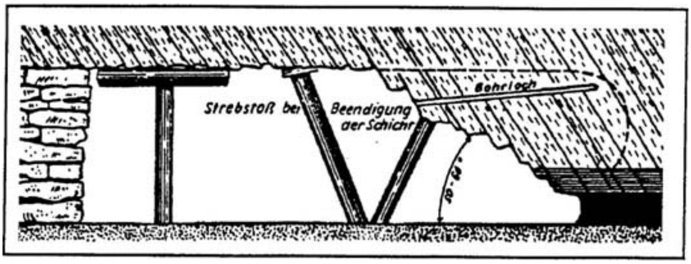

Figure 18-13. Model of the so-called "excavation mining with props" of the longwall in 1920 (Mansfeld, 1999)

Table 18-16. Mining heaps (ref. Mansfeld, 1999)

<table>
<tr><td colspan="2">Conical heaps</td><td colspan="2"><i>Sangerhausen</i> $21 \times 10^6\ m^3$
<i>Mansfeld</i> $24.4 \times 10^6\ m^3$</td></tr>
<tr><td colspan="2">Layered dumps</td><td colspan="2"><i>Sangerhausen</i> $0.2 \times 10^6\ m^3$
<i>Mansfeld</i> $31.8 \times 10^6\ m^3$</td></tr>
<tr><td><i>Metal content</i></td><td></td><td><i>(too poor) copper shale</i></td><td><i>Tailings</i></td></tr>
<tr><td></td><td><i>Copper</i></td><td><i>(Ø 0.36 %)</i></td><td><i>(Ø 0.23 %)</i></td></tr>
<tr><td></td><td><i>Lead</i></td><td><i>(Ø 0.54 %)</i></td><td><i>(Ø 0.33 %)</i></td></tr>
<tr><td></td><td>Zinc</td><td>(Ø 1.16 %)</td><td>(Ø 0.06 %)</td></tr>
</table>

3.5 The Spremberg deposit

Between 1958 and 1964 a seam at a depth of 900-1650 m was found during prospecting for copper shale. In 1977 the Mansfeld collective combine published research that envisaged production at the Spremberg seam. Table 18-17 highlights key data. The plans did not come to fruition. Here for the first time a copper concentrate would have been produced. This would have significantly cut the high energy demand of raw ore smelting.

Table 18-17. Spremberg copper shale deposit (Mansfeld 1999)

Project work 1977	*Area:*	*17.4 km*^{2}
	Depth	*900 — 1600 m*
	Quantity of ore	*98,600,000 t*
	Copper content	*1,490,000 t*
	Production	*3,350,000 t ore per annum*
	Concentrate production	*302,000 t/a*
	Copper content	*42,200 t/a*
	Investment level	4.6×10^9 *GDR mark*
	Production start	1990

3.6 Ore dressing

Until 1960 the raw ore was enriched by hand-picking, however, only by a factor of 2. This meant that there was still a large amount of inert material to smelt. Around 1980 a flotation experiment was carried out in Freiberg that resulted in a threefold copper enrichment. An industrial beneficiation plant was never built and raw ore was smelted even in the last 30 years. In the early 1970s a flotation experiment was conducted in Gleiwitz with Spremberg ore that was manifestly more successful. Table 18-18 summarises the results.

Table 18-18. Ore dressing (Mansfeld, 1999)

Ore handpicking until around 1960 by 300 - 400 people	
Ores	*~ 1 - 2 % Cu*
Handpicking	*2.5 – 3.2 % Cu*
	~ 7.5 % bitumen
Experimental testing to produce concentrates	
Concentrates (Freiberg)	*5 - 5.3 % Cu*
Cu-yield	*0.33 % Pb*
90 %	*0.62 % Zn*
	0.05 % Ag
	11 % $C_{org.}$
Concentrates (Gleiwitz)	*14 % Cu*
from Spremberg	*0.5 % Pb*
	0.6 % Zn
	0.025 % Ag
	3.8 % Fe
	7.0 % S
	7.9 % $C_{org.}$

At this juncture it should be mentioned that by the Middle Ages ore dressing had already reached a high level of development; as illustrated in figures 18-14 and 18-15, which contain details about processing plants in the Middle Ages. Comminution and gravity separation are depicted.

3.7 The Mansfeld smelting process until the end of the 18th century

The handpicked shale was burnt to remove the bitumen. It was then smelted using charcoal. Figure 18-16 shows two shaft furnaces to smelt matte.

The resulting copper matte had to be roasted several times (at the end with additional charcoal) to remove the sulphur. Figure 18-17 shows such open air roasting furnaces. The roasted material was smelted in a shaft furnace with charcoal to produce black copper and slag. The resulting matte and slag were recycled.

Silver separation was achieved by smelting with lead and the so-called "Saiger process", whereby the latter is shown in figure 18-18. The copper was then pyrometallurgically refined to produce refined copper. The resulting dross was specially processed.

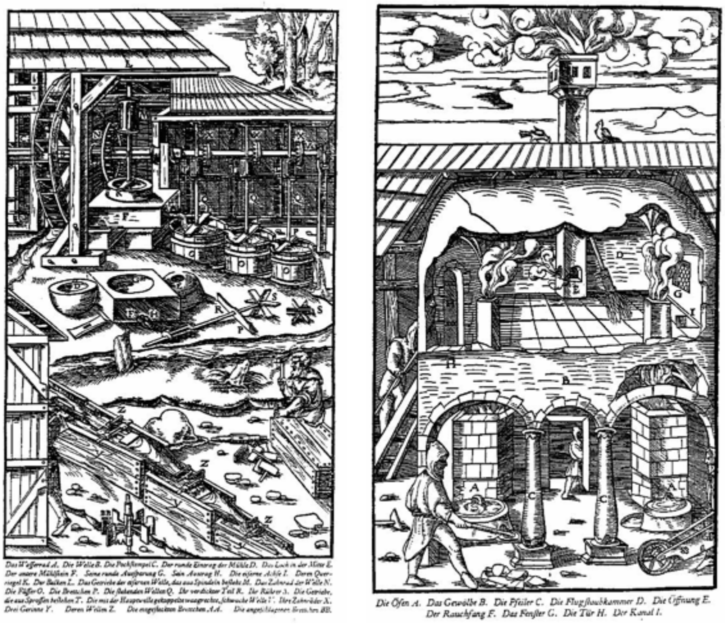

Figure 18-14/16. left picture (figure 18-14) - Ore dressing plant in Agricola's Age (Agricola, 1978), right picture (figure 18-16) - Shaft furnaces to smelt matte (Agricolas, 1978)

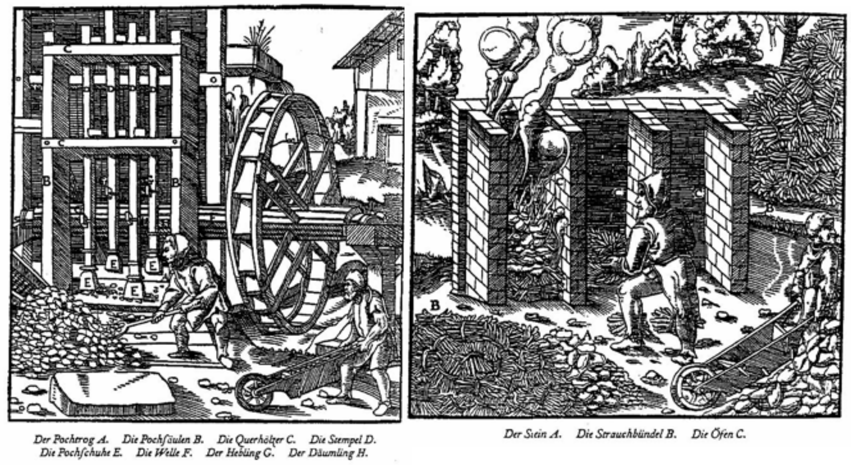

Figure 18-15/17. left picture (figure 18-15) - Comminution in Agricola's Age (Agricola 1978), right picture (figure 18-17) - Shale and matte roasting (Agricola 1978)

Figure 18-18. The PbAg-Cu "Saiger process" in "Saiger furnaces" (Agricola, 1978)

The entire process is shown in figure 18-19, but in an extremely summarised form. Two old depictions of the Mansfeld copper smelter close this chapter. Figure 18-20 shows the back view of the Hettstedt *Kupferkammerhütte* (1833) with the open air roasting in the foreground and the shaft furnace buildings to smelt the matte and black copper behind. Agricola has also portrayed a similar picture. Figure 18-21 shows less clearly the so-called "Saiger smelter" in Hettstedt (1837).

The effect on the environment was limited as the total production of all the smelter together seldom reached 1000 t Cu/a before 1850. Only the "Saiger smelter" process to remove silver from copper resulted in measurable lead emissions. The "Saiger smelter process" was finally replaced by the "Ziervogel procedure" in 1847. After 1850 copper production (see table 18-14) rose, in 1858 the first H_2SO_4 plant came on stream, and in 1916 a further H_2SO_4 plant was built.

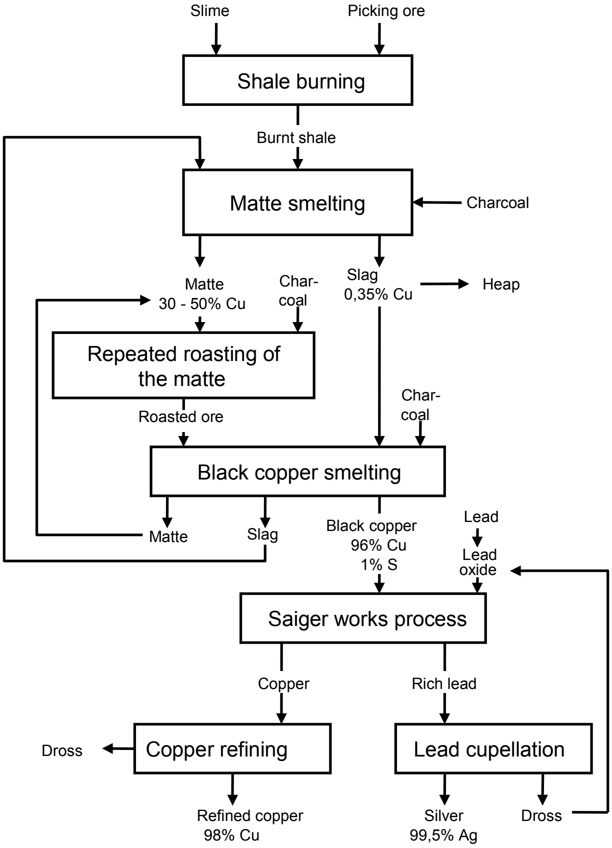

Figure 18-19. The smelting of copper shale to produce copper and silver until approx. 1800

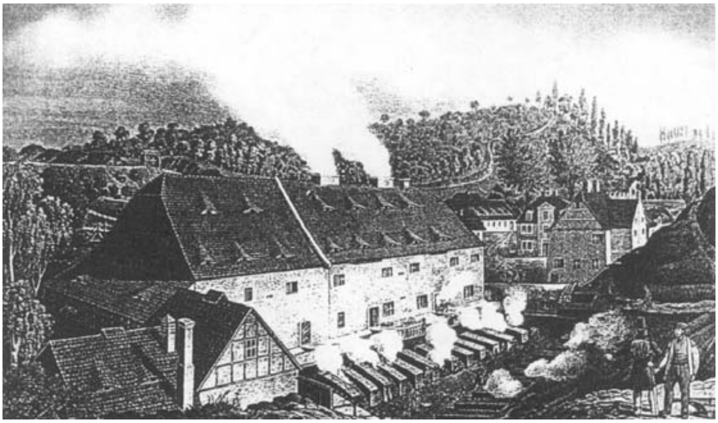

Figure 18-20. Back view of the *Kupferkammerhütte* in Hettstedt

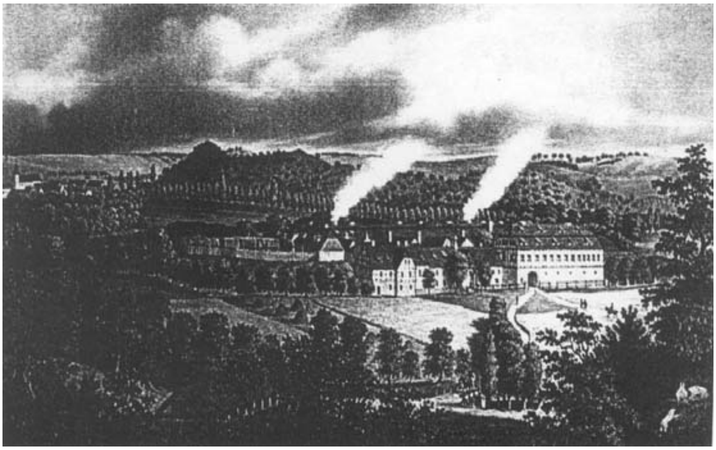

Figure 18-21. View of the “Saiger smelter” in Hettstedt

3.8 The Mansfeld AG, the VEB Mansfeld Kombinat Wilhelm Pieck

The 19th and 20th centuries brought decisive changes for copper production in Mansfeld.

- From 1835 coke replaced charcoal.
- An important step was the implementation of the “Ziervogel procedure” in 1847 to extract silver. This increased both the silver yield and the quality of the

copper. At the same time the lead, as an input to the "Saiger process", and the lead extraction process with all the lead emissions could be omitted. Only in 1938 was the "Ziervogel process" made redundant by Cu-electrolytic refining.
- Since 1850 hot blast air has been used intermittently in the shaft furnaces.
- Since 1865 the slag has been used increasingly to manufacture slagstones.
- The realisation of furnace roasting enabled the generation of H_2SO_4 (1858).
- The derived flue-dust resulted in the extraction of concomitant metals such as lead (1887) and ZnO (1928)
- Around 1900 the first large-scale pit was erected with a several thousand strong workforce.
- Since 1910 the resulting iron buildup (furnace sow) has been processed to produce Mo, Ni and Co.
- The open air sulphur process was finally superflous (burning of shale no longer necessary), when the direct smelting of shale in shaft furnaces was possible (from 1922). The cleaned shaft furnace gases were burned in power plants and used to generate electric power (1905, 1912), while since 1901 they had been used to drive gas engines.
- 1926 the converter process replaced the roasting procedure.
- 1938 copper refining electrolysis was implemented for the entire copper production. The "Ziervogel process" was halted.

Table 18-19. Development of the Mansfeld-Group (Mansfeld, 1999]

The Mansfeld AG 1902	10 production pits 4 primary smelter with 14 shaft furnaces 2 roasting plants with H_2SO_4-factories with 154 roasting furnaces 2 reduction smelter 1 desilvering plant 2 copper refining smelter 1 electrolysis plant Production 18600 t Cu 98.4 t Ag 18300 employees
The Mansfeld AG 1921	8 production pits 2 primary smelter 2 roasting and reduction plants 1 refinery Production 11,800 t Cu 56.7 t Ag 15800 employees
The Mansfeld Kombinat 1965	4 production pits 2 smelter Production 29,000 t Cu 140 t Ag approx. 13000 employees

The development of the Mansfeld-Group since 1900 is shown in table 18-19. The number of pits declined, but the number of smelter fell more sharply. The size of the workforce also shrank. Figure 18-22 shows the process applied in 1902. The copper shale ores were still burnt in the open-air to remove the bitumen. The burned copper shale was smelted to form low-grade matte, furnace sow (Ofensauen) and slag, the low-grade matte was roasted, the slag processed to make slagstone. The ore to be roasted was smelted with the low-grade matte to form white metal. This was then roasted under controlled conditions to extract the silver. The residue was reduced by smelting, refined and sold as refined copper. Analysis of the various materials in this process model is shown in table 18-20.

Figure 18-22 shows only the copper, silver and H_2SO_4 extraction. There is no mention of the auxiliary plants.

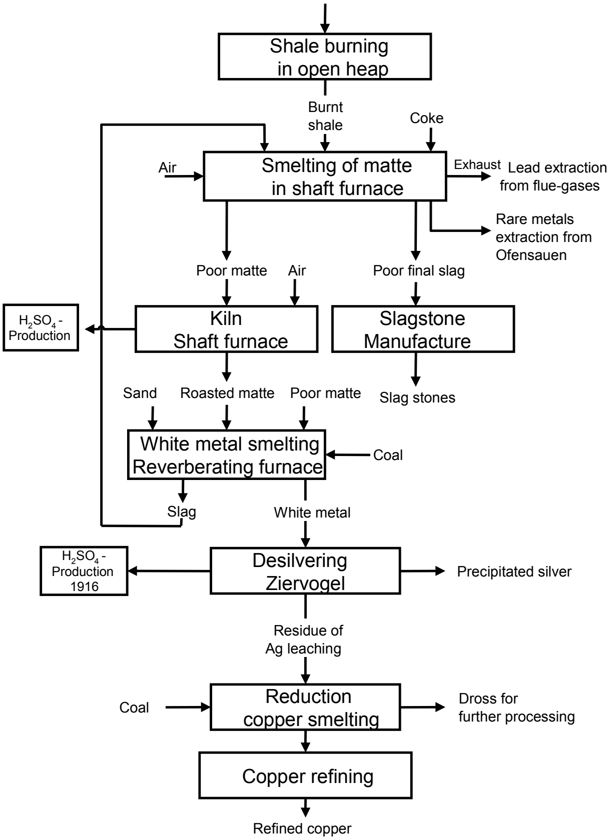

Figure 18-22. Smelting in Mansfeld (1902)

It has already been mentioned that more and more secondary components were extracted to improve profitability. Production in 1962 is shown in table 18-21. To this belongs the operational flow chart in figure 18-23 with all the auxiliary plants.

Tables 18-20 and 18-21 and the figures 18-22 and 18-23 show the complexity of the operations of Mansfeld AG and the Mansfeld collective combine respectively.

Nevertheless, only the slag production was really significant (see table 18-21). This was, however, responsible for the high expenditure of energy. Almost all other operations (excluding Ag) were too small for profitable production.

Table 18-20. Composition of the charged material and intermediate products from the copper and silver extraction (approx. 1902) (Hoffmann, 1925; Hüttenwerke, 1904; Treptow, 1900) (all data in weight per cent)

	Copper shale	***Copper shale burned***	***Low grade matte***	***Low-grade matte slag***	***White metal***	***White metal slag***	***Ofen sau***
Cu	*3 – 2,8*		*45 – 50*	*0,18*	*73,8*	*12,4*	*5 – 12*
Ag	*0,02 – 0,01*		*0,23*		*0,43*	*0,04*	*0,03 – 0,04*
Fe	*3 – 1*	*6*	*22*	*3,2*	*2,7*	*39*	
Ni (+Co)				*0,03*	*0,46*	*0,22*	*2 – 4*
Pb					*0,68*	*0,25*	
Zn				*1,4*	*0,90*	*1,9*	
Co				*s. Ni*	*0,18*	*s. Ni*	*1 – 3*
S	*5 – 2*		*25*		*20*	*2,2*	*3 – 4*
Bitumen	*17 – 10*			-	-	-	
SiO_2	*29 – 39*	*53 – 49*		*46*	-	*18,7*	
Al_2O_3	*16 – 11*	*15 – 18*		*16*	-	*2,9*	
CaO	*15 – 11*	*10 – 18*		*21*	-	*4,3*	
MgO	*5 - 2*	*3 - 5*		*2,2*	-	*1,0*	
Mo							*1 - 8*

Table 18-21. Production of the Mansfeld collective combine 1962 (Mansfeld, 1999)

30,000 t	Copper
124.3 t	Silver
26 kg	Gold
35,100 t	H_2SO_4
28,300,000	Slagstones
88,200 t	Coarse crushed slag
3,000 t	Soft lead
24.2 t	Selenium
500 t	Nickel sulphate
61.7 t	V_2O_5
3,150 t	ZnO
4,000 t	$ZnSO_4$
160 kg	Rhenium

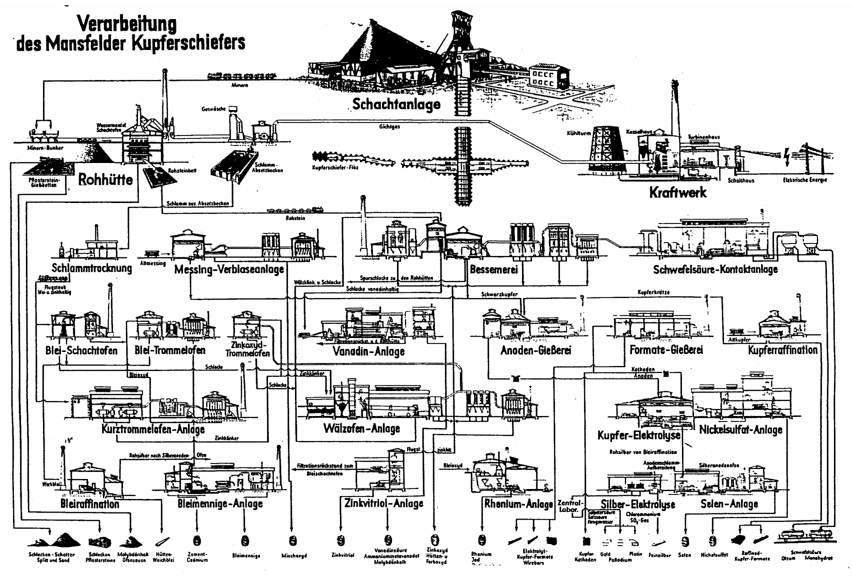

Figure 18-23. Processing of the Mansfeld copper shale (approx. 1962)

The small sulphur content in copper shale produced furnace sow when smelted, but the volume remained low, at 0.3 kg/ t copper shale. The more powerful smelting techniques of the 20th century led to a greater volume of furnace sow (2 - 3 kg/t). This furnace sow could be seen as a collector of numerous rare metals. To be processed this buildup had to be crushed, melted and granulated before it was processed in other locations (until 1947 in H.C. Starck in Goslar, between 1977 and 1987 by Outokumpu in Finland). (see figure 18-24).

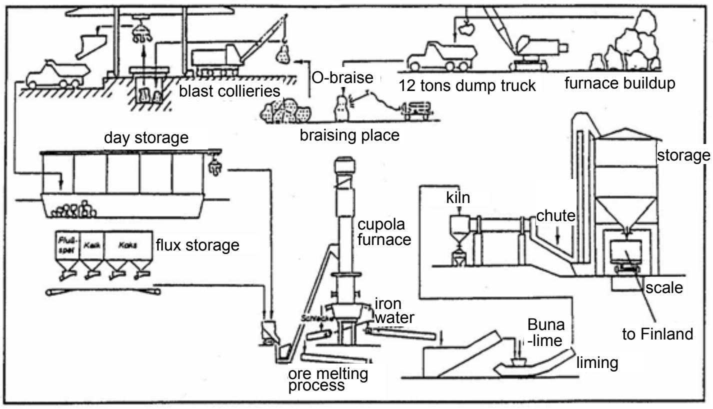

Figure 18-24. Technological flow chart of the iron processing and smelting procedure of Ofensauen (Mansfeld, 1999)

3.9 The end

Copper mining and extraction was profitable until the beginning of the Great Depression in 1930, if one excludes the 30 Years War. If the German Reich had not intervened in 1933 it would have spelt the end for Mansfeld AG, which had exhausted its financial reserves.

Initially the state subsidy was only modest, but it reached such a scale between 1950 and 1970 and then again from 1975 that it led to the closure of the copper mine in 1990.

Table 18-22. Subsidies for Mansfeld AG, Mansfeld collective combine respectively (Mansfeld 1999)

1933 - 1946	< 20 x 10^6	Reichsmark/p.a.
1947 – 1968	Ø 100 x 10^6	GDR mark/p.a.
1969 – 1974	Ø 70 x 10^6	GDR mark/p.a.
1975 to	115 x 10^6	GDR mark/p.a. rising to
1988	320 x 10^6	GDR mark/p.a.

The primary smelter also did not have a chance of survival. At a cost of more than 500,000,000 DM the secondary copper production and processing operation were modernised after 1990. Table 18-23 shows how the costs and revenues had drifted apart since the 1930s, despite the fact that the GDR kept domestic copper prices far higher than world prices.

Table 18-23. Development of costs and revenues [Mansfeld 1999]

	Total production costs*	Copper price	Copper price
	Mansfeld	GDR	World market
	M/ t Cu	M/ t Cu	M/ t Cu
1913	1792	1400**	1400
1938	1747	550**	550
1948	7267	1500	1545
1967	9813	4500	4900
1984	26165	12500	4000
1988	56000	12500	4600

* Mining + Smelting smelter / ** German Reich

The main reasons for the lack of profitability are as follows:

- The shallow depth of the copper shale seam demanded excessive costs and yielded too low productivity respectively.
- The inability to produce concentrates necessitated raw ore smelting.

The total costs (mining and smelting) broke down into mining 65%, smelting (matte smelting) 30%, refining (converter operation, anode refining, electrolysis) 5%. There was no chance of survival for this mine and smelter.

3.10 Sustainability of copper extraction in Mansfeld

The Mansfeld copper shale comprised very fine disseminated complex ores with high bitumen content. The ore dressing by flotation was only partially successful and was very costly (see section 3.6). The raw ores processing led to a large amount of slag with a high expenditure of energy. The lack of ore dressing meant that for ore with 1.8% Cu, some:

- 62 t ore had to be mined, transported and smelted together with
- 14 t coke to extract
- 1 t Cu from the copper matte and
- 45 t slag.

Still 9 t coke was required for hot blast air. The development over the centuries is shown in table 18-24. Although significant savings have been made over the years the low Cu content remained a decisive cost factor.

Table 18-24. Process data of the Mansfeld lowgrade matte smelting furnace down the centuries (Mansfeld, 1999)

	furnace throughput per day		Coal/coke requirement kg/t charge
Approx. 1500	2 — 4 t	Charcoal	600
Approx.1700	4 t	Charcoal	410
Approx. 1800	4.2 t	Charcoal	300
Approx. 1820	8.5 t	Charcoal	225
From 1865	20 t	Coke	225
Approx. 1880	100 t	Coke hot blast air	175
Approx. 1910	200 t	Coke	190
Approx. 1935	up to 800 t	Coke	220
Approx. 1975	up to 350 t	Coke hot blast air	145

Until 1785 hydraulic and horse power served both above and underground to operate the waterwheels and capstan responsible for the extraction, transport, water pumping, crushing and air supply to the mine and copper smelter. The first steam engine was built in 1785. In the 19th century operations above and underground were fully converted to steam. From 1905 onwards electric power was increasingly used for these functions. The Group's own power station was operated for this purpose, which, in part, was supplied with blast furnace gas.

The yield was held to be good in all years, whereby the insufficient ore dressing was a disadvantage. Mining extraction losses (see also table 18-16) were 10%, smelting losses are put at between 10 – 15%. Cu-content in the slag of 0.35 % at around 1800 and 0.18 % around 1900 is proof of the expertise of the copper plant workers. The high percentage smelting losses are attributable to the large slag volume per tonne of copper.

The gaseous emissions could never be reduced to an acceptable level. At the end of the running time (1990) the clean gases still contained 200 - 300 mg/Nm^3 of dust. At this time copper smelter in the Federal Republic Germany had maximum limits of 20 to 10 mg/Nm^3 dust respectively, which was achieved without exception. The burning of shale continued in the open air until it was shut down (after 1920). The SO_2-containing roaster gases were collected from 1858, but not the SO_2-content from the shaft furnaces. Lead and zinc emissions were always regarded as critical. A real advance was the halting of the "Saiger procedure" and its replacement with the "Ziervogel process". However, the flue-gases from the other processes remained a source of emissions. Therefore, in the mid 1970s the lead and zinc plants were shut down. After the closure of the smelter in 1990 the waste dumps and the sludge of the Theisen disintegrator remained. Their reprocessing is difficult to envisage as the PbZn content is not very high and is slightly radioactive. Therefore reprocessing is not worthwhile, only sealing the waste dump can be considered.

The Mansfeld AG employed some 12,000 people in the 1930s. 1987 around 18,000 were employed in the copper mine and smelter. 1989/90 the entire mining and lowgrade matte smelter were shut down. The copper silver smelter (KSH) and the copper processing plant (WWH) remained operational in Hettstedt, today they form the Mansfelder Kupfer und Messing GmbH (MKM). It would never have been possible to operate the mine at break-even. There was a lack of maintenance for the primary smelter, while the operational technology was outmoded. Only the recycling smelter and the processing smelter had a chance of survival, but they also required investment in the order of 500,000,000 DM. Large scale redundancies were the result. The entire region has still not recovered today. But strictly speaking this is the result of a long term mis-guided policy of subsidisation.

The workforce development since 1990 can be seen in table 18-25.

Table 18-25. Payroll of copper smelter in Mansfeld (Mansfeld 1999)

	1990	***1992***	***1994***	***1995***	***2001***
Mine	*5.300*	-	-	-	
WWH	*7.900*	*2.970*	*1.350*	*1500**	*1.100**
KSH	*2.000*	*870*	*500*		

*MKM, the employees of its hived off repair and supplier operations must also be included

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Chapter 19

SOCIAL AND ECOLOGICAL CONSEQUENCES OF THE BAUXITE-ENERGY-ALUMINIUM PRODUCT LINE

Steps Towards Sustainable Metal Management

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1. ORE PRODUCTION AND PROCESSING IN DEVELOPMENT THEORIES

During the second half of the twentieth century, raw material mining and metal working increased at an exponential rate[1] (Metallstatistik, 1985-95 & Metallstatistik 1988-98). In the case of many raw materials, it has become clear that continued and sustained mining will exhaust supplies within a relatively short time. Attitudes towards these commercial activities have changed over the past 50 years. The various development theories dating from the post-war period have highlighted various aspects of raw material mining and metal working and yet, blind spots still remain today.

In his theory on the stages of development, Walt Rostow (Rostow,1962 & 1990) asserted that economic growth through the input of capital is the main prerequisite for development. In this context, the mining and processing of raw materials contribute to capital accumulation and, consequently to economic growth. In addition to Rostow, there are a number of other authors who advocate "growth theories" and, like Rostow, start from the assumption that "catching-up development" is possible in any country.

In Latin America, around twenty years after the end of the second world war, when the effects of capital export were becoming apparent, the precepts of the growth theorists came under criticism. "Catching-up development" was not deemed possible and furthermore the gulf between developed and developing countries was widening. Critics deemed development processes to be characterized by relationships of dependence, not only between the North and the South, but also between upper and lower classes in individual countries (Cardoso & Faletto, 1979).

A. von Gleich et al.(eds.), Sustainable Metals Management, 449-482.

Economic growth was only seen to benefit those with capital to invest – usually transnational groups and banks. In other words, wealth is not distributed, meaning that the previously asserted “trickle down effect” is not triggered by this development. On the contrary, rather than growth being distributed, they noticed an increasing concentration of wealth, whilst at the same time, disadvantaged social groups are marginalized. Society and economy were therefore increasingly seen to be characterized by “structural heterogeneity”. Each time a country’s added value is increased, for instance by processing the mineral into metal in the country containing the raw material itself it becomes less dependent. This in-country processing was initiated by the aluminium industry worldwide at the end of the 70s and beginning of the 80s (Paulo de Sá, 1990),. The dependency theorists – one of the most prominent of whom is the former Brazilian president Fernando Henrique Cardoso – did not yet include the ecological dimension in their analyses at that time. Nor have they been concerned with the question of reconciling the conflicting interests of users.

The advocates of the neo-liberal economic theory, known as the Chicago Boys (Hayek, 1967&1976; Friedman, 1976&1980) because some of the main exponents taught at that university, came on the scene at the beginning of the 70s, not only in Latin American faculties, but also as advisers to and ministers of the authoritarian governments in Latin America. According to them, all citizens can be involved in the market in their capacity as economic entities. Their first priorities for development consisted in liberalizing the market, cutting subsidies and gradually dismantling the state. In this context transnational groups gained power. On the other hand, the opening up of borders resulted in a loss of support for trade unions, farm workers, landless, minorities and neighbourhood organizations, as they became exposed to the prevailing terms of competition on the world market for raw materials, wages and prices. The dominance of economic science and the neglect, or even abolition, of social science in Latin American universities are concomitants of this period.

Social impoverishment and ecological devastation, investigated in the Brundtland Report, “Our Common Future”, by the North-South Commission (Hauff, 1987), were the basis for the United Nations Conference on the Environment and Development (UNCED,1992). The result of the UNCED was Agenda 21 as well as conventions for climate protection and biodiversity. These results were also the motivating force behind new theories. The termination of the generation contract and the threat to the “global commons” are the starting points for and motive behind a number of theories, which emerged from various disciplines (Hübner, Dröge, Meyerhoff, Petschow, 1998; Enquete, 1994 & Gensch, 1992). The dominant themes are justice between generations and within generations, which demands that economies and societies should create the conditions required to conserve natural assets. The conditions for future sustainable development are referred to in newly emerging theories. First and foremost, the Indian economist and Nobel prize-winner Amartya Sen (Sen, 1999 & Ulrich, 1986,1997) shows that the social prerequisite for economic prosperity is democracy. He asserts, “Seeing development in terms of the substantive freedoms of people has far-reaching implications for our understanding of the process of development and also for the ways and means of promoting it. On the evaluative side, this involves the need to assess the requirements of development in terms of removing the unfreedoms from which the members of the society may suffer. The process of development, in this view, is not essentially different from the history of overcoming these unfreedoms. While this history is not by any means unrelated to the process of economic growth and accumulation of physical and human capital, its reach and coverage go much beyond these variables." (Sen, 1999).

2. ORE MINING, ENERGY PRODUCTION AND EXTRACTIVE METALLURGY: SOCIAL AND ECOLOGICAL CONSEQUENCES IN COMPANIES AND REGIONS WITHIN THE AREA OF TENSION

Sustainable development of metal production requires consideration of all the stages of production in the countries of origin. All too often, ecological and social considerations are "forgotten", as advertisers expound the positive energy saving and reusability properties of metals (Audi A2, 2000).[2]

First, we will look at the social and ecological consequences of bauxite mining, energy generation and aluminium production in the largest rainforest region in the world, the northern Amazon (Orinoco) region, situated in the Guayana shield, which is rich in bauxite deposits (Mori & Adelhart, 1998).

Table 19-1 lists the various stages in aluminium production and their ecological effects.

Table 19-1. The most important stages in aluminium production

Production stage	The ecological consequences in the country of origin
1. Open-cast Bauxite mining	Deforestation, emissions, dust and noise (UNEP,
2. Bauxite washing	Water pollution (bauxite mud)
3. Drying	Emissions, depending on the energy source, dust
4. Loading/ Transport/ Loading	Emissions, contamination of water, dust
5. Alumina production Bayer process	Red mud contaminated with caustic soda, dust (WHO, 1997 & IPAI, 1991)[3]
6. Energy production	Depends on the energy source. Most major aluminium companies (Gitlitz, 1993) are supplied by specially built large hydroelectric power plants: flooding, emissions (WDC, 2000 & IUCN, 1997)
7. High-voltage transmission line	Clearing the line (World Bank, 1991)[4]
8. Aluminium production: Söderberg and the Hall-Heroult processes respectively:	Fluoride emissions, formation of heat (WHO, IPAI)[5]

In the course of developing this economic sector, there has been clear progress in the state of environmental technology: for instance reducing the formation of dust by installing electrostatic filters when drying bauxite in Porto Trombetas, Pará, Brazil; pumping water back into the operating cycle from the red mud lake formed during the production of alumina near the factory; and extracting fluoride produced in the smelter when melting aluminium, etc. There is still a question mark over the extent to which these innovations eliminate the pollution problems they are designed to combat. The need to take environmental, social and economic factors into consideration is discussed below.

The impacts of the bauxite-energy-aluminium product line therefore depend on the respective production processes, the state of environmental technology and the size of the plants. Each of these factors should be specifically analysed according to the ecosystems and forms of settlement and cultivation in the regions selected as mining, energy or industrial sites. That means we are interested in the ecological, as well as the economic and social consequences of bauxite mining, energy production and metal processing.

The product line analysis (PLA) is an instrument that enables us to assess all impacts (Projektgruppe Ökolog. Handeln, 1987; Eberle, Gießhammer, 1996 & Baumgärtner, Rubik, Teichert, 1989). [6] The economic and social consequences are included in the product line matrix in addition to the ecological impacts shown in the above table (Plantenberg, 1988,92,96,98,99; Gawora, 1994, Moser, 1994, Gemeinsame Konferenz Kirche, 2000).

This cross-border, multi-dimensional way of looking at a product "from the cradle to the grave" was defined as a product line as early as 1985 by the Öko-Institut in Freiburg. Co-operation between actors in the different stages of the product line can optimise processes and promote sustainable development. According to the Freiburg Öko-Institut, this enables producers and consumers to assume full responsibility for these products.

The key concepts of product line analysis are:

a) A focus on needs. The first step is to examine the need for a product[7] the environment in which the product is located.
b) Vertical examination. A product is examined over its entire life cycle, that is from the extraction and processing of the raw material to transport, production, trade and marketing, consumption and disposal. This is what is termed a product line.
c) Horizontal examination: The individual life cycle phases of a product line are examined with regard to their effects on nature, society and the economy. A criteria grid is developed for each dimension to demonstrate the effects of product line variables.
d) Comparison of variables: As product line analysis should be an instrument to promote a socially and ecologically orientated economy, the comparison between different products, services and production processes can indicate which is the most acceptable from an ecological and social perspective. This may result in a decision not to produce certain products.

A product line matrix links the vertical examination to the horizontal examination and the life cycle or product line to the three dimensions. The entire product line is set out below to clarify the method. However, we only look at those stages that are usually not taken into account in Europe. First we have a look at the Brazilian Amazon region in more detail: nature, the new economic sectors, the regional economy and the social groups? First of all, here is an overview of keywords (cf. table 19-2) (➔indicates a fact ➚ indicates an upward trend ➘ indicates a downward trend).

A little later we will look at the special dimension of the product line in the following rainforest countries: Brazil, Suriname and Venezuela.

Table 19-2. Bauxite-energy-aluminium product line matrix – (1) a detailed view of the Brazilian Amazon region

Bauxite mining/recultivating	**Nature**	➔Demarcation of nature reserves ➔Black community territories overlap with mining concessions and nature reserves ➔Extensive clearing ➔Water polluted with bauxite mud ➘Fish population ➔Uncertain quality of the partial reforestation ➔Road and railway construction, construction of a town in the forest ➔Emissions (depending on the energy source e.g. diesel) ➔Dust ➔Noise
Washing		➔Partial filling of the bauxite mud lake that accumulates during washing. Clouding of rivers by bauxite mud ➘ Fish population
Drying		➔Emissions from burning oil
Transport		Trombetas Region ➔Isolated stagnant water along the road and railway through the forest. Transport in the planned mining area of Paragominas ➔Plans for roads that cut into the Indian territories
Alumina production		➔Waste materials: water polluted with red mud containing caustic soda endangers: -small animals in the mangroves -Crabs, etc. -Fish, which are important for nutrition in the region ➔Dust ➔Emissions(depending on the energy source)
Energy production		➔Flooding of the tropical rain forest ➘Biodiversity ➚CO_2 + methane emission ➚Felling of trees around the lake, on the islands ➔Change in the fish population, no fish ladder ➚Mosquito problems ➚Risk of mercury ➚Road construction

High voltage line		➚Deforestation ➚Use of defoliants
Aluminium production		➔Fluoride emissions(cf. economy) ➔Emissions of polycyclic aromatic hydrocarbons ➘Flora, fauna, air, earth, water polluted
Further processing		
Trade		
Consumption		
Disposal Recycling		

Table 19-3. Bauxite-energy-aluminium product line matrix – (2) a detailed view of the Brazilian Amazon regional economy

Bauxite mining/recultivating	**Economy**	*Multinational group* ➚Bauxite mining ➔Transferring the washing equipment to mine in order to prevent polluting the water ➔Environmental technology to decrease the amount of dust caused by drying the bauxite *Regional economy* ➔Dependent on MRN (Mineração Rio Norte) ➔River traffic regulation by the governmental environmental agency, IBAMA ➚Food imports -marketing problems -attempts at diversifying (fruit-growing) ➘Fishing. Problem caused by IBAMA ban on cultivation, hunting and fishing.
Washing		➘The abundance of fish was essential for feeding the regional population ➔With the large scale mining of bauxite, Brazil becomes able to produce aluminium in the Amazon
Drying		➔Drying is done using energy produced with oil, and not water power as originally planned (the fluctuation of the water level is too great, etc.)
Transport		➔Transport on large ships for further processing inland (Bacarena and São Luis) and abroad
Alumina production		*Multinational group* ➔Faster building of large production capacity ➔Investments to seal off the red mud lake (alumina, PVC) ➔Investments to pump water from the red mud lakes back into the operation cycle *Regional economy* ➘Fishing. Loss of livelihood for many ➔Attempt at diversification (quarrying, fruit-growing, etc.) ➚Dependence on the transnational group Alumar

(continued)

Energy production		*State-owned energy group* ➔Dependency of the price per kWh on the price of aluminium on the world market ➔Lack of profitability ➔Interrupted river traffic ➚Brazil's large debts *Regional economy* ➔Change in fishing: drastic reduction and threat to livelihoods below the dam. Change in the composition of the fish population above the dam ➔Change in economic conditions after relocation
High voltage line		➔Transfer losses
Aluminium production		*Multinational group* ➔Faster building of a large production capacity ➔No longer any Brazilian partners ➔Establishment of the smelter in 1984, taxes have been paid since 1995 ➔Exhaust gas cleaning equipment available at the plant *Regional economy* ➚Partial destruction of fruit-growing and fishing around the factory ➚Dependency on the transnational group Alumar
Further processing		
Trade		
Consumption		
Disposal Recycling		

Table 19-4. Bauxite-energy-aluminium product line matrix – (3) a detailed view of society in the Brazilian Amazon region

Bauxite mining/recultivating	**Community**	*Mining enclave* ➔Psychological problems *Regional community* Weakening of the sustainable economy and black community livelihoods Restrictions by IBAMA Displacement Uncertain land ownership conditions - introduction of legal recognition of black community territories Lack of public health service for the regional population Lack of transparency Coordination issues between the three state institutions: IBAMA, ITERPA (Pará Land Institute), INCRA (National Colonisation and Land Reform Institute)
Washing		➔Fishing communities' catch decreases whenever washing results in bauxite mud polluting the river and killing fish ➘Supply

Drying		➔The drying bauxite is stored in temporary shelters ➔Half of the bauxite is treated in drying plants
Transport		➔Railroad construction for transporting the bauxite planned in Paragonimas/Pará ➔Repercussions on the Indian territories
Alumina production		*Factory* ➘decreasing number of permanent employees at the factory ➚increasing number of short-term employees (➚Outsourcing) *Regional community* ➔Displacement of 20,000 people when the aluminium industry was established ➚Two-fold increase of child mortality in the slum areas ➚. Diseases. Insufficient public health service. See section 3 below ➘Fishermen without protection ➘Reliability of diet ➔Lack of transparency
Energy production		➔Displacement of 30,000 people ➔Colonisation ➚Mosquito problems ➚Timber traders ➔Lack of compensation ➚Diseases: malaria, bilharzia, etc. ➚Mercury effects on human health ➚No services: health care
High voltage line		➔Damage to health due to chemicals used ➔Health risk due to low frequency electromagnetic radiation ➔Cuts through Indian territories
Aluminium production		*Factory* ➔Job insecurity ➘Decreasing number of permanent employees in the factory ➚Increasing number of short-term employees (outsourcing) ➔Industrial accidents, illnesses, see below ➔Company advertising *Regional economy* ➔Displacement of 20,000 people when the factory was built ➔Illness: skin irritations, etc., insufficient public health service, see section 3 Dependence on TNC[8] Endangering food security ➔No transparency with regard to health and environment-related data
Further processing		
Trade		
Consumption		
Disposal Recycling		

3. REPERCUSSIONS OF ALUMINIUM PRODUCTION ON EMPLOYEE HEALTH AND THE ENVIRONMENT

Now we will take a retrospective view of the stages of this process that have been most intensively studied over the past 25 years, in relation to the effects of aluminium production on health and safety in aluminium factories[9]. What interests us most is who has negotiated what and how, in whose interests and with what consequences.

3.1 Repercussions of aluminium production on health - IPAI 1977/1981

In 1977, the International Primary Aluminium Institute (IPAI, 19777), which is based in London, held an international conference on health issues in the aluminium sector. Participants at the seminar, entitled “Health protection in primary aluminium production”, included industry directors and managers, professors of medicine, ergonomists, works doctors and local managers as well as representatives of the World Health Organisation (WHO, 1997) and the United Nations Environmental Programme (UNEP, 1992) (cf. table 19-3).

The aim of the seminar organised by the IPAI in 1977 in Copenhagen was to discuss possible effects on health due to workplace exposures in aluminium smelters, preventive health measures and occupational health care (IPAI, 1977/81). Questions were raised about the impacts of the smelters (pot rooms), heat, dust and polycyclic aromatic hydrocarbons on employee health. The seminar went on to discuss preventive measures in the workplace. Risks to health and safety were analysed and quantified, and random sampling, the duration of exposures and measuring methods were discussed. The debate also covered industrial hygiene in aluminium smelters as well as ergonomic considerations.

The implementation of industrial hygiene measures, which require exact data as the basis for a preventive strategy, was felt to be a particularly important area for employee training. However, neither employees nor local residents were invited to this conference, even though these social groups are the ones most directly affected and therefore have a special interest in the subject. Environmental and development organisations, in particular the United Nations, currently demand the involvement of social groups in discussions about regional questions concerning them. The conference proceedings were not, however, made accessible to the general public and could not therefore be used to push for preventive measures.

The composition of participants at these meetings says a lot about how much needs to be learned about promoting sustainable and modern management. It would have undoubtedly helped to develop preventive management if representatives from trade unions, residents’ organisations and state authorities had been invited to participate.

Table 19-5. Effects of alumina – aluminium production and adverse effects on health (IPAI)

Type/place of pollution	**Effects**	**Diseases**	**Description/studies**
Smelter: fluoride	-Increase in the mineralization of bones -Calcification of ligaments -Bone deformities -Infertility (cf. animal experiments)	"crippling fluorosis" -osteosclerosis -exostosis -Calcification of ligaments	H.C. Hodge, '77 Slow but steady increase of fluoride in the bone
Smelter: heat	-Cramps -Exhaustion	-Heat stroke	M.O. Colwell, '77 Horvath, S.M. '1981 Rodahl, K. '1981 Worker-training, replacing water and salt loss, getting enough rest, wearing proper clothes, etc.
Smelter: pot room **Respiratory physiopathology: ventilation**	Lung expansion	Bronchial-asthma Chronic bronchitis Emphysema	J.R. Vale '77 M. Smith '81
Smelter: pot room, dust	Pneumoconiosis (particle size, water solubility of gases)	-Bronchial - muscle-spasms Cell change - Change of respiratory tract and alveoli	B.Johansen '77 Air checks in pot rooms
Smelter: pot room	Test of lung functions to prevent disease	Test of lung functions	J.R. Vale '77 M.Smith '81
Smelter: pot room	Respiratory diseases -Loss of lung elasticity -Increase in sensitivity of bronchial tubes -Restricted airways		J.R. Vale et al '77 M.M. Smith et al '77 H-Johannessen '77 H.C.v.Voorhout '77 B.D. Dinman '77 H.C. Hodge '81 M. Chan-Yeung '81 G.B. Field '81
Smelter: pot room	Cancer	Lung cancer	Andersen '81 G.W. Gibbs '81
Smelter: PAH	Occurrence and measurement of polycyclic aromatic hydrocarbons	Cancer	Alf Björseth '81 A. Steinegger '81

Source: IPAI (1977): Health Protection in Primary Aluminium Production, London.
IPAI (1981): Health Protection in Primary Aluminium Production, Vol.2, London.

3.2 Repercussions of aluminium production on health and nature (NIOH, 1994)

In 1994, at the invitation of the National Institute for Occupational Health (Oslo, Norway) and the Secretariat for Health, Environment and Safety (Oslo, Norway), 142 seminar participants and 15 advisors from 25 countries, and from all continents, met in Bergen, Norway. During this International Conference on "Environmental and health aspects related to the production of aluminium", 33 articles (and 21 summaries) were discussed, which were later published in the journal entitled "The Science of the Total Environment" (Arnesen, Abrahamsen, Sandvik, Krogstad, 1995). In comparison to the IPAI conference, held seven years previously, a much broader range of participants was now involved. Environmental issues were actively included in the debates. The lectures were given by members of medical, agronomical and horticultural university institutes, state-owned forest institutions, independent ecological and social research institutions and clinics. The topics discussed demonstrated a broad knowledge base (cf. table 19-4).

In spite of the link being made between aluminium and dementia, exposure to aluminium was not the main focus here. Fluoride and the hydrofluoric acids of the cryolite (Na3AlF6) bath used for the electrolytic reduction of aluminium were deemed more important.

Polycyclic aromatic hydrocarbons used in electrodes also held greater concerns both for the environment and for health.

Aluminium-related asthma was deemed more important than fluorosis in this conference. A somewhat greater risk of lung cancer had already been substantiated.

Work in the pot rooms with the Soderberg electrodes was associated with a greater risk of cancer of the bladder, with an increased risk of leukaemia and with cancer of the pancreas. The neuro-toxicity of aluminium was discussed – but no report was given on this.

Certain health effects were established as scientifically sound, even though they had been refuted just a short time previously.

3.3 Environmental and health criteria for aluminium (WHO 1997)

Since 1987, the United Nation's World Health Organisation (WHO), the International Program for Chemical Safety (IPCS), the United Nations Environmental Program (UNEP) and the International Labour Organisation (ILO) have been studying the scientific basis for the risks posed to human health and the environment by chemicals. In 1997, they published the results in "Health, Environment and Aluminium", in order to strengthen national capacities to properly manage chemicals.[10] (cf. table 19-5)

Of course there have been numerous other publications and conferences, in particular by trade unions and standardisation organisations addressing the same topics, but these are not universally available.[11]

Table 19-6. Effects of alumina – aluminium production and adverse effects on the health (National Institute of Occupational Health Oslo & Nordic Aluminium Institute)

Type/place of pollution	**Effects**	**Diseases**	**Description/Studies/Biomonitoring Suggestions (cf.T. Norseth (ed.)(1995))**
Smelter: Polycyclic aromatic hydrocarbons PCA	Biological index for effects at work (BEI)		Levin 1995, L. et al ՙ95 B. Schoket et al ’95
Refinery and smelter : dust	Respiratory ailments		J.H.Vincent 1995 Industrial hygiene standards -dust breathed trough the nose or mouth -Proportion of the breathable dust that can get into the lungs to the ramification of the trachea -proportion of that which is breathed in that can get into the lungs and penetrate the alveoli
Smelter: pot room	Testing of the nervous system		R. Bast-Pettersen ’94 (Bast-Pettersen, Drabløs, Goffeng, Thomassen & Torres, 1994)
Smelter	Breathing in gaseous fluoride particles	Chronically progressive limitation of lung functions, asthma	Th. V.O’Donnell ’95 -regular tests (screening) -obligatory respiratory protection
Aluminium smelter, Polycyclic aromatic hydrocarbons PCA	Cancer	Lung cancer, cancer of the bladder, leukaemia, cancer of the pancreas	B. Armstrong 1994 A. Rønneberg 1992
Smelter: fluoride, arsenic, sulphur, heavy metal	Effects on the forest’s ecosystem	Serious damage to the flora and fauna	B.Mankovskáa ’95 Eva Vike, Atle Håbjørg ’95 Richard Horntvedt
Smelter	Effects on the soil		A.K.M.Arnesen ’95
Smelter	Water, fish, fauna		I. Rodushkin et al ’95 K. Naes et al ’95 J. Knutzen ’95

Source: Tor Norseth (ed.): Environmental and Health Aspects Related to the production of aluminium, in: The Science of the Total Environment, Vol. 163, 1995.

The WHO regards this issue as a priority for future studies, since no exhaustive research exists as yet on the question of possible adverse effects of occupational exposure to aluminium on workers' health.

Nevertheless, the findings made by a number of studies indicate that aluminium plant workers often suffer from diseases of the respiratory tract (WHO, 1997). They cite the studies of Dinman (Dinman, 1988) regarding lung diseases associated with alumina and Abramson's study (Abramson,, Wlodarczyk & Saunders, 1989), which deals with the connection between aluminium smelters and lung diseases. Furthermore, Jederlinic examined lung X-rays and lung function of workers exposed to alumina for around 25 years. He found concentration of metals, particularly alumina, that were several times over the limit in three out of nine workers. The authors deduced that alumina was the most probable cause for the development of interstitial fibrosis among these workers. Whilst asbestos could be excluded, it was clear that exposure to "mixed dust", including silica could be seen as a possible explanation. In addition to this example, other examples of exposure to "mixed dust" were cited (WHO, 1997).

For the past 35 years, reports have been published on so-called "pot room asthma" which occurs in aluminium smelters. For example, a study by O'Donnell and others (O'Donnell TV, Welford & Coleman, 1989), showed that reduced ventilation increased bronchial susceptibility. The condition was probably caused by the irritant effect of particles and vapours from cryolite (sodium aluminium fluoride), gaseous hydrogen fluoride and other active substances that can be absorbed by aluminium. In studies by Kongerud, a close connection was shown between the degree of fluoride exposure, which can result in the inhalation of several irritating substances, and work-related asthmatic symptoms in pot room workers. In 1994, Söyseth (Söyseth, Kingerud, Ekstrand & Boe, 1994) and others reported a connection between fluorides and increased bronchial susceptibility.

A study of 2086 people employed at a large aluminium industry in Arkansas, established that extended exposure to dust leads to a decrease in lung functions amongst active refinery and smelter workers. A follow-up study by the same authors (Townsend, Enterline, Sussman, Nonney & Rippey, 1985) showed that there is a connection between inhaling dust in the workplace and lung function.

In Hosovski's study (Hosovski, Mastelica., Sunderic & Radulovic, 1990), 87 workers at an aluminium smelter who had been exposed to aluminium concentrations of between 4.6 und 11.5 mg/m^3 in the air at work for at least six years were compared to a control group of 60 workers of the same age, occupation, company employment and social status. With the help of psychomotor and psychometric tests, a significant difference was established in reaction times and oculomotor coordination.

Table 19-7. Effects of alumina–aluminium production and adverse effects on health (WHO)

Type/Place of pollution	Effects	Diseases	Description/Studies
Aluminium industry	Effects on the respiratory tract		Dinman 1988 Abramson 1989
Aluminium industry: mixed dust containing silica	Restrictive pulmonary diseases	-interstitial fibroses	Jederlinic 1990 (Nederlinic ; Abraham ; Churg, Himmelstein, Epler & Gaensler)
Smelter and others **Fluoride exposure** **Exposure to dust in general**	Restrictive pulmonary diseases	-Asthma	Associated with inhalation of aluminium sulphate, aluminium fluoride and potassium, aluminium tetrafluoride, and found to occur within the complex environment of primary aluminium production, especially in pot rooms O'Donnell 1989 Kongerud 1990/1 Söyseth 1994
Refinery and smelter	Storage of dust in lung tissue, decreasing degree of pulmonary functions	-Pneumoconiosis -Chronic bronchitis	Saia 1981 Townsend 1985 Sjörgren & Ulfvarson 1985
Aluminium industry	Effects on the central nervous system	Impairment of the cognitive functions Motor dysfunction and peripheral neuropathy	Sjögren (1990/1994) Hosovski (1990) Longstreth (1985) White (1992) McLaughlin (1962)

Source: WHO (97): p. 148-157, 203-207.

3.4 Gradually confirming the connections between factory work and disease...

Whilst certain problems are the most significant initially, such as fluorosis, others are becoming increasingly significant over time, such as the effects of polycyclic aromatic hydrocarbons.

Initially, cancer could not be connected with aluminium production. However, this connection was regarded as certain at the conference held in 1994. Nevertheless, this disease was not mentioned in the WHO volume published in 1997. Studies on the topic were merely indicated in the appendix. All three publications emphasized the need for further investigations. Companies regard measuring and standardising as their responsibility, side by side with national institutions. In the work mentioned, however, no overview is given of how regular measurements are carried out and checked and whether they are published. Therefore, evaluations of prevention and the results of ergonomic optimisation processes are not transparent. This means that it is not evident where these have already been carried out and with what results.

3.5 ....but the affected public is excluded

Government and company experts took part in the debates. The implementation of training courses, measurements and ergonomic measures has generally remained restricted to the companies.

If companies do not comply with government standards, the government may take the lead in promoting changes and preventive measures. However, not all countries have effective health and safety enforcement policies.

The technical debate about the effects of alumina and aluminium production on workers and regional ecosystems has been taking place without the inclusion of the people who are most directly affected. The results of the implementation of preventive measures have not yet been systematically followed up. The affected groups could themselves attempt to locate and document the specialist knowledge more accurately, thanks to their knowledge of the geographical and temporal processes present in the environment and their own legitimate interests are at stake.

3.6 There is still no debate on the impact on the regional population

The debate only focuses on **one** issue: aluminium production and workers. The Norwegian conference also examined the effects on flora, fauna, water and soil. This holistic approach at least leads to questions being raised about the impact on affected social groups.

To sum up, we can say that information about the social impacts of metal working is available, but it has not been disseminated further than to employers and specialists. Trade unions at a Brazilian and a Suriname plant I visited did not have any information relating to company operations and the effects on workers. Trade unions at some plants either had very little power or were forbidden altogether.

To date, the effect of bauxite-energy-aluminium product lines on regional population groups has not been dealt with in scientific literature. So involvement by a broader range of production personnel at technical conferences would be extremely important for promoting the transparency of cause and effect. The participation of civil society organisations is essential, as only they know how to manage their region – in this case, the tropical rainforests – and protect their livelihoods. It does not take a great deal of imagination to see that greater transparency could led to essential preventive measures. The economic, social and cultural interests and capacities of the regional population, as well as international climate-related interests, should be more strongly represented. I will come back to this point later.

4. PRODUCT LINE DIMENSION IN RAINFOREST COUNTRIES WITHIN THE GUAYANA SHIELD

Let us first obtain an overview of the spatial and temporal dimensions of this product line in the countries within the Guayana shield (cf. figures 19-1, 19-2 and 19-3 and tables 19-6 and 19-7).

4.1 Brazil

The above analysis of the spatial and temporal dimensions of the product line stages (Müller-Plantenberg, 1996) provides the following image of Brazil (figure 19-1). Once the Trombetas bauxite mine is exhausted, the plan is to use the deposits in Paragominas. A railway line, already designed for this purpose, will link to the existing iron ore project railway line in the Carajas region. This will cut through the Indian territory of Awa Gurupí. Dams that are currently under construction will provide energy. . There are also plans to expand production capacities at the refineries and smelters in Barcarena and São Luis. 80% of their current production is exported, but the social and ecological consequences remain "open questions" in the region and they contribute to increasing the greenhouse effect (cf. tables 19-7 and 19-8).

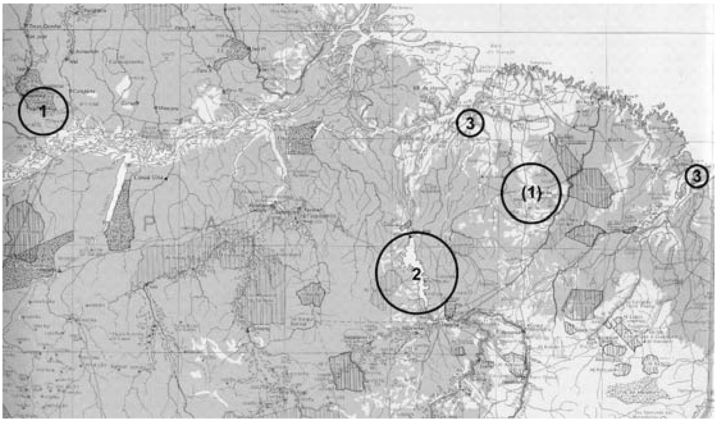

Figure 19-1. Bauxite-energy-aluminium product line in Brazil.
1/(1) – bauxite mining / bauxite mining planned; 2 – power generation; 3 – alumina and aluminium production

Source: according to CIMI, CEDI, IBASE, GhK eds: Areas indigenas y grandes projetos Brazil, Berlin 1986; We added the circles to indicate the location of the various production facilities and planned bauxite mining sites. There are recent plans for further bauxite mining near Santarem and hydroelectric power station projects, but these are not taken into account here.

4.2 Suriname

Once the mines that are currently being worked have been dismantled, there are plans to use the Backhuis bauxite deposits in the west of the country (Colchester, 1995 & Müller-Plantenberg, 1997) (cf. figure 19-2). The Kalina and Lokono Indian communities as well as the Apeura, who are already threatened by the Indonesian timber trade company MUSA, would be affected by this (Forest Peoples Programme, 1997). For years, there have also been plans to build another hydroelectric power station here, with two dams and reservoirs. This is the Kabalebo project, for which a two-phase extension has been planned (250MW, 500 MW) in the Kabalebo water catchment area (Norconsult/Norway & Electrowatt/Sweden, 1975 & Klaassen, 1982) (cf. tables 19-7 and 19-8).

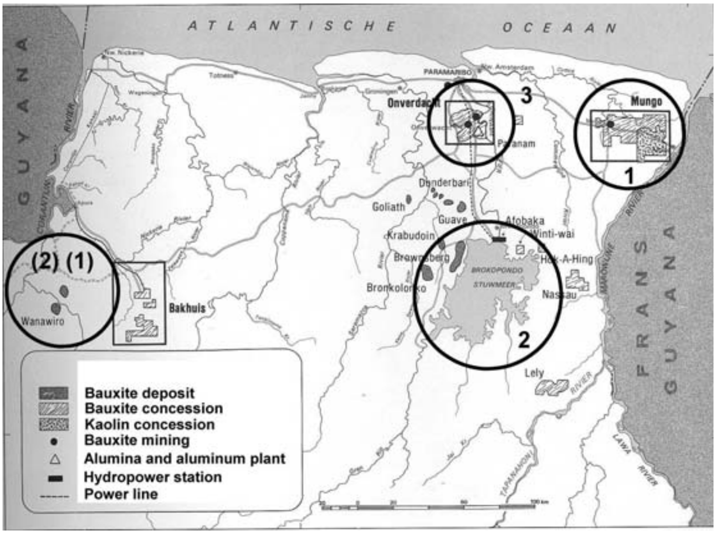

Figure 19-2. Bauxite-energy-aluminium product line in Suriname
1/(1) – bauxite mining / bauxite mining planned; 2/(2) – power generation / power generation planned; 3 – alumina and aluminium production

Source: The National Planning Office of Suriname, Washington D.C. 1988, p. D1, F1; We added the circles to indicate the location of current and planned bauxite mining sites. There are plans for more hydroelectric power stations in the west of the country, west of the Bakhuis concession. These are not taken into detailed account here and are merely indicated by the number two in brackets (2) on the map.

4.3 Venezuela

The most important mine in Venezuela (Guillen, 1997), a country with an aluminium boom and relatively low energy costs per kWh, is at Pijiguaos, in the western Orinoco region. It is connected by rail to a port from where the bauxite is shipped (cf. figure 19-3). The Guri reservoir is the largest "aluminium reservoir" on the Latin American continent. It extends over 4,260 km². There are plans to increase hydroelectric power by rerouting rivers (not marked on the diagram). This would certainly affect the territories of the Yekuana and Sanema Indian peoples, which consist of around 5,000 members, as well as the tropical rainforest areas. There are a large number of other bauxite deposits in the tropical rainforest region, which could be exploited by mining companies in future, such as in the eastern Guayana rainforest region of Cerro Impacto near El Palmar (cf. tables 19-6 and 19-7).

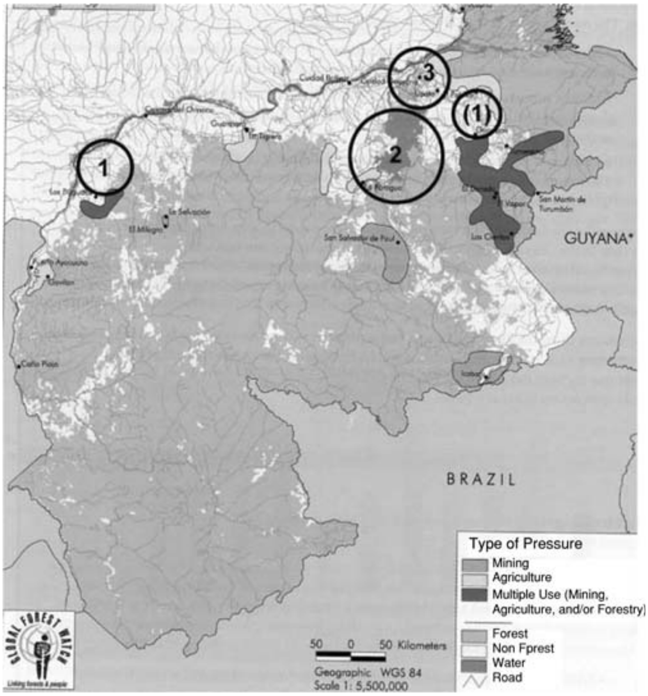

Figure 19-3. Bauxite-energy-aluminium product line in Venezuela.
1/(1) – bauxite mining / bauxite mining planned; 2 – power generation / power; 3 – alumina and aluminium production

Source: Global Forest Watch: The State of Venezuelan Forests, World Resource Institute, Washington 2002, p. 68; We added the circles to indicate the current and planned location of bauxite mining sites. Existing plans for hydroelectric power were not taken into account here.

Table 19-8. Bauxite-energy-aluminium product lines in Suriname, Brazil and Venezuela

Country	**Current and *planned bauxite deposits***	**Current reservoirs km^2, MW, km^2/MW and *planned reservoirs*/**	**Alumina and aluminium production, current and *planned***
Suriname	Mungo, Bakhius, Lelydorp, Headly Reef, Gros Rosebel, South Benzdorf - *mines planned in the west*	Brokopondo 1560km^2 flooded in 1964/180 MW 8.67km^2 / MW *Kabalebo reservoirs planned/*	Paranam
Brazil	MRN mine in the Trombetas, *mine planned in Paragominas and near Santarem*	Tucurui reservoir 2430km^2, flooded in 1984; 7600 MW; 0.32km^2 / MW *further expansion and more dams planned at Tocantins*	Bacarena and São Luis currently have a refinery and smelter at each of the locations
Venezuela	Pijiguaos, *the exploitation of further deposits has been planned, e.g. Cerro Impacto Near the town of El Palmar and at the border of Guyana*	Guri reservoir 4260km^2/ 10300MW/ 0.41 km^2/MW *diversion of the river planned in the Guri lake/*	Puerto Ordaz Alumina and aluminium production

Table 19-9. People affected by the "bauxite-energy-aluminium product line" in the Guayana shield

Affected by what	Who	Where		
		Suriname	Venezuela	Brazil
Bauxite	American Indian peoples	X	Mapoyo, Guahibo, Panare, Piapoco and Piaroa	
	Black communities			6000 people
	Agricultural worker organisations	X	X	X
Energy production	American Indian peoples		X	Gaviao, Parakana Assurini
	Black communities	6000 people		
	Agricultural worker organisations		X	30,000 people
Alumina and aluminium production	American Indian peoples			
	Black communities			
	Agricultural worker organisations	X	X	20,000 people

X: exact figure not determined

5. THE INTERESTS AND POTENTIAL INFLUENCE OF AFFECTED GROUPS OF PEOPLE (GKKE, 2000)

The absence of transparency and democracy, and the consequent lack of information on the economic, social and ecological consequences of bauxite mining, energy production and aluminium production, means that the people affected are only able to express themselves in a highly inadequate manner. In a project led by the *Gemeinsame Konferenz Kirche und Entwicklung* (Joint Conference of Church and Development - GKKE), and involving over 100 non governmental organisations in the Carajas region (Forum Carajas/Brazil) and the *Aluminium Zentrale* (ALZ), the groups affected analysed and documented their situation over a four-year period. They identified the following priorities with regard to the bauxite-energy-aluminium product line in Brazil.

1. **The black communities[12] displaced by bauxite mining focused on:**

- A binding regional management plan;
- The land rights to which they are entitled to, according to the Brazilian constitution;
- The submission of a management plan for the natural reserve by the nature conservation authority IBAMA; criticism of IBAMA and its former unlawful ban on cultivation, fishing and hunting.

2. **The smallholders displaced by the reservoirs / hydroelectric power stations demanded:**

- Participatory regional planning,
- Establishment of a regional fund,
- Extractive reserves,
- An environmental impact assessment on the second expansion stage of the Tucurui hydroelectric power station
- Electrification of the villages.

3. **The fishermen, whose fishing has been adversely affected by the pollution of water by red mud residue from alumina production, the construction of ports and the expansion of water routes, demanded:**

- The dredging of canals that have been filled in,
- The establishment of an economic diversification fund;
- An extractive reserve;
- Participation in a monitoring committee formed by representatives of the state, the company and the community.

4. **The employees of the refineries and smelters demanded:**

- A representative committee to monitor working conditions,
- Information and training;
- An interdisciplinary health centre.

A representative of groups in the four most important regions of the product line (bauxite mine at Trombetas, energy production in the Tucurui reservoir region, alumina and aluminium production both in Barcarena at Belem and in São Luis) participated and discussed what was needed to ensure their livelihoods. They demanded that their interests be taken into account by civil society.

The satisfaction of their demands presupposes that they know their legal rights and that they can develop contacts and communicate with supporters. In view of the extensive lack of information and transparency at the beginning of this cooperation process, the demands of these groups can only be implemented gradually, after careful information-gathering and organisational work (OECD, 1995). Legal action is possible wherever democratic rights are deemed to be legally enforceable. In the thinly populated Amazon region, obtaining better information and transparency 15 years after a 21-year dictatorship cannot be taken for granted as yet. On the contrary, learning about democracy is the order of the day. International contacts with human rights and environmental organisations play a mayor role as well as the cooperation with the parliaments of those countries where company shareholders are based.

5.1 Entrepreneurial interests and standardisation

Since the International Conference on the Environment and Development took place in Rio de Janeiro in 1992, when AGENDA 21 was drafted by non-governmental organisations and international conventions were adopted on rainforest preservation, biodiversity and climate, investors and companies have started to try and gain comparative advantage by creating a corporate identity that takes these issues into account.

An entrepreneur, Stefan Schmidheiny, of the Economic Council for Sustainable Development justifies the interest in ecological production in the following way (Schmidheiny, Fritsch, & Seifritz, 1994):

- Consumers want cleaner products,
- Insurance companies would rather insure clean companies in order to prevent having to make payments for environmental damages and accidents,
- Banks would rather lend money to those companies that avoid polluting the environment so that they are not obliged to pay for expensive clearance work or legal proceedings,
- The best and smartest employees prefer to work for companies that take responsibility for the environment.
- Environmental regulations are becoming more strict.

However, Schmidheiny only represents a small fraction of employers.

Others, such as Stefan Glimm, managing director of the Aluminium Trade Association of Germany (Gesamtverband der Deutschen Aluminiumindustrie e.V.), in 1998, demand that environmental targets be established at the most senior levels. "In view of scarce budgets, political, industrial and environmental organisations should take an interest in shifting environmental policy targets to a central level in order to liberate resources for other tasks...In the medium term, however, the environment, consumers and the economy would benefit from this type of change in environmental policy and from the end of eco-control."(Glimm, 1998)

Other entrepreneurs only act at those production locations where organised social groups forcefully demand the improvement of working and living conditions. This also involves government pressure (like in Jamaica) or international support.

Various companies' Chief Executive Officers (CEOs) have recently starting talking more frequently about ethical principles. For example, Paul O'Neill, CEO of ALCOA, for a long time the largest aluminium group, gave a detailed talk about climatic problems at the Spring meeting of the Aluminium Organisation in 1998 (O'Neill, 1998). Today there are hardly any corporate groups left that have not – for PR purposes at least – drawn up a code of conduct. "If a company code, which is up to the minute, is subject to effective and independent monitoring, it can play an important role in furthering and protecting human rights. However, voluntary codes of conduct can never be a replacement for the systematic monitoring of company behaviour through local authorities, national governments (both the home country's and host country's governments) and the international community. Independent monitoring is essential, so that codes of conduct make sense, but they should not divert attention from the effective implementation of national laws and international standards." This is according to a representative from a major oil company at a seminar about best practice in this industry (Evangelische Akademie Mülheim, 2000) [13]. Even *Misereor* and *Brot für die Welt*[14] consider this a starting point for increasing the social and environmental sustainability of production and trade (Piepel, 2000).

Regardless of their differences, companies created the International Standardisation Organisation (ISO), which certifies company environmental and quality management standards (ISO 9000 and ISO 14000). These are optional standards, therefore they cannot be legally enforced. Up to now, they have merely been environmental standards. The possibility of introducing health and safety standards was discussed during the above-mentioned ISO Conference in 1996, but this has not yet been taken further. Press and media awareness of these standards is high, though I noticed in Latin America that workers and the general public have almost no knowledge of these standards. The trade unions vote at the 1996 ISO Conference was clearly in favour of the standards. . Company compliance with these standards should be regularly monitored.

5.2 National legislation – transparency, democracy, monitoring

National environmental and social laws are enforceable. As a rule, they are already the product of social regulatory requirements. They were frequently enacted as the result of social conflicts and disputes. For example, an environmental impact assessment decree was enacted in January 1986, immediately following the end of the 21-year Brazilian dictatorship in 1985. This provided for the assessment of ecological consequences before economic plans are approved, with the participation of the public.

Laws were also enacted in the course of implementing international conventions.

The right of citizens and social organisations can file a suit is a fundamentally important aspect of democracy and makes every one equal "in the eyes of the law".

However, if the laws are unknown, it is impossible to monitor social and ecological standards. If it is impossible to monitor these standards, democracy is itself in danger.

5.3 EU and OECD guidelines, UN conventions and global governance

In Europe, ethical production and consumption are also monitored by “Fair trade and labour standards” (1988) as well as by the establishment of EU standards “For European groups in developing countries” (European Commission, 1999).

United Nations agencies have also drawn up international conventions on social and environmental issues for ratification by governments. However, they are not binding and cannot be enforced. Complaints are examined in lengthy procedures in the International Labour Organisation, but those against whom complaints are successful cannot be forced to take remedial action. Nevertheless, they take on great significance wherever national regulation is inadequate, such as with the treatment of minorities and environmental issues. They set an example, since the governments that ratify them must enact laws accordingly. Wherever there was insufficient protection at national levels, international human rights and environmental organisations have built international bridges to protect national and regional population groups. The main debating point has been with regard to the observance of the following conventions and guidelines:

- Economic, social and cultural rights (ECOSOC of the UN)(El Ejercicio, 2000),
- Convention 169 for the rights of indigenous and tribal peoples (ILO, 1989) [15],
- The right to development, in the Rio statement (UNCED, 1992),
- Mining and environmental standards (UN-DESA, UNEP, DSE/CDG, 1999) and
- Guidelines of the World Dam Commission (WCD, 16.11.2000) [16]

In view of the reduction in the power of states as part of the globalisation process, people have started to talk about ‘global governance’ by UN organisations or international human rights and environmental organisations. However, it remains doubtful as to whether international regulatory mechanisms could effectively complement national regulations. This question requires urgent and detailed attention (Müller-Plantenberg, 1999).

6. STATE-SOCIETY-COMPANIES: PROJECTS AND INSTRUMENTS

Sustainable development is jeopardized wherever large-scale mining projects penetrate rain forest regions. Approval should certainly depend on the results of an environmental impact assessment, conducted with full public participation. There have been various attempts to improve such procedures, including better provision of information, training courses, monitoring, dialogues between the state, companies, communities in which all sides have equal rights and the establishment of jointly administered funds. Companies are urged to help communities continue to pursue their mode of production, including after the end of the mining project.

When a large company penetrates the Amazon or other rural regions of Latin America, it is essential for communities with sustainable economies to re-design their own regional plan to take account of the presence of the company, in order to continue their livelihoods on a long-term basis and avoid migrating to the slums of the big cities.

The concept of “stakeholders”, i.e. groups of people affected by company activities, is gaining in significance. The term implies that these people must be included in the process. In Canada, remarkable concepts have emerged to promote such participation:

- Canada’s White Horse Mining Initiative, which dates from 1992, ensures that the state, companies, indigenous peoples, environmental groups and trade unions are involved in mining negotiations (Whitehorse Mining Initiative, 1994).
- Local round-tables which facilitate planning and decision-making at community level (Local Round Tables, 1994).
- Dialogue between the companies and the indigenous communities in the CDG-COICA project (Fiero, 2000).
- Monitoring and dialogue between the state, society and company are emerging in many places, such as the aluminium dialogue that took place at the end of the 1990s between Brazilian communities , the Joint Conference of Churches and the Aluminium Zentrale; (cf. figures 19-5 and 19-6) (GKKZ/ALZ-Bonn, 2000).

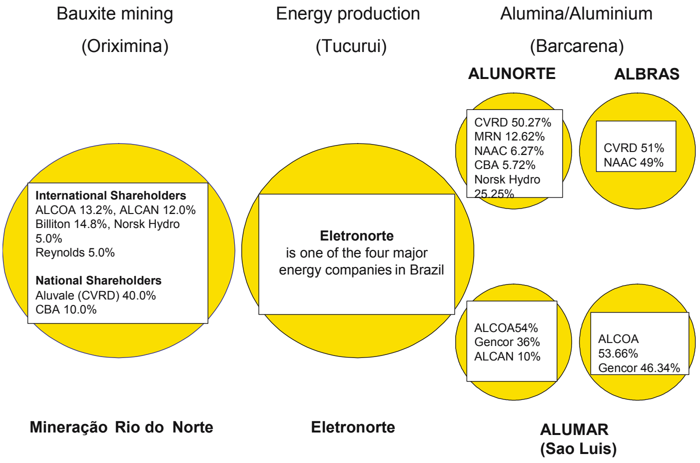

Figure 19-4. The Producers

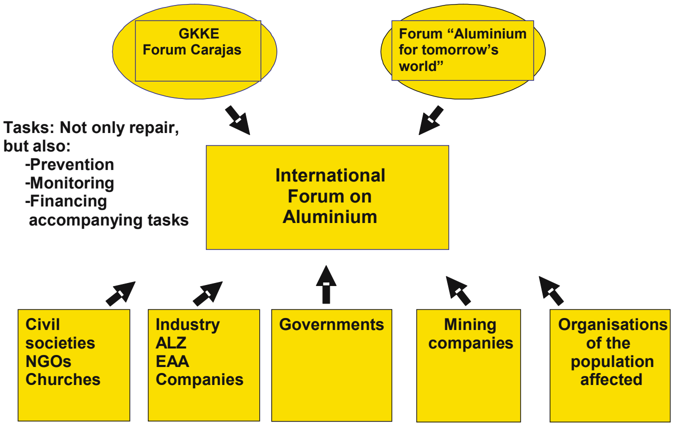

Figure 19-5. Perspective for further developing the aluminium dialogue

Source: GKKE/ALZ Ev.Ak.Mühlheim: Internationaler Dialog über Aluminium: Globale Verantwortung von der Rohstoffgewinnung bis zum Verbrauch, hier: AG1, Berichterstatter Dieter Gawora, Materialien der GKKE Heft D 24, Bonn 2000, p. 57.

6.1 The Interests of Transnational Corporations (TNCs) – Instruments under their control

With the demands of an accelerating world market, the global environmental crises (climate change, biodiversity), the increasing concentration of wealth and growth of poverty, companies are increasingly moving away from a one-sided focus on their shareholders. They are increasingly discovering their responsibility towards and interest in those whose interests they affect (stakeholders; workers, people affected in the region, customers, environmental groups, human rights groups, etc.) (Vincent, 1990; Weiss, 1994; Pittinger, 1998; Biesecker, 1998 & Rat von Sachverständigen, 1994).

At the same time, there has also been more work done on human rights and the environmental problems caused by multinational groups, as was documented in the report of the working group on transnational companies - part of the UN subcommission for the promotion and protection of human rights (Sociétés transnationales, 2000) and the report of the international seminar on "Controlling Corporate Wrongs" (IRENE, 2000).

The OECD even revised their guidelines for transnational corporations, taking account of social and ecological issues (OECD, 2000).

Companies can undoubtedly use product line analysis (PLA) as an instrument for providing a more comprehensive overview of the stakeholders of their production process and as a basis for promoting cooperation with the people involved. It will also undoubtedly be advantageous for companies in the long term, by improving their competitive market position, and allowing them to anticipate developments and take precautions.

6.2 Instruments for state control of projects

If states wish to pursue a sustainable development plan, they must seek to improve the dialogue between companies and society about the social and ecological impacts of mining and metal processing. It is strategically important for environmental impact assessments to be developed into a democratic, preventive instrument, in which the role of the public is strengthened, the strain on courts relieved and the independence of advisors increased. Lessons can be learned from the policy and debates promoted by the UVP (Environmental Impact Assessment) Association in Hamm and by comparing environmental impact assessment procedures and the results achieved in various countries e.g. Brazil and Germany (Internationale Arbeitsgruppe Technik und Umwelt, 1994).

However, this instrument is imperfect as yet since it does not systematically include cross-border effects (not only in neighbouring countries but globally).

Some countries have developed comprehensive instruments, such as the National Environmental Plan, which includes the cross-border effects of imports and exports (flows of material) and is able to develop criteria for a sustainability policy.

Even on a European level, people are thinking about a European sustainability strategy. Such a strategy has been drafted (EEB, 2000) and was later on adopted by the European Commission.

6.3 Project for a viable planet – consumers

In view of the unequal balance of power between companies/governments and the social groups affected, the very unevenly distributed information, the absence of opportunities for communication and the lack of transparency and participation, the voices of consumers and insurance companies are of extreme importance (Hoffmann, Ott & Scherhorn, 1997) [17]. However, their consistent inclusion will require intensive consideration of meaningful information, real transparency and practical participation in democratic processes. What should be done?

7. SUGGESTIONS ON HOW TO ACT

Only a few suggestions will be given here, with reference to the situations described above:

7.1 Participatory research – preparing information

Research activities should be undertaken with the people affected in a participatory manner since this will provide an opportunity to discuss the results and cooperate in the preparation of strategies by the actors [18]. In any case, research results should no longer be kept secret from employee organisations. Regulations are needed to ensure that employees and all interested parties have access to data on living and working conditions.

7.2 Training – transparency of the projects

The results of analysis and research into the way companies operate should be used to formulate strategies to protect the working and living conditions of employees and residents. Employees and residents need training in order to understand their working and living situations and so that they are able to tackle monitoring and help formulate regulations.

7.3 Strengthening organisations – democratic participation in social planning dialogues

Training can promote participation in social planning dialogues. Training, transparency and democratic procedures are pre-conditions for the kind of capacity building that can promote participation and self-determination.

7.4 Participation in social monitoring

Social monitoring of emissions and waste disposal should be done by commissions on which companies, states, workers and neighbourhood organisations have equal representation. This will empower these stakeholders to actively monitor their living conditions and, if necessary, request remedies for grievances. This is in their own interests, but it also works in the interests of other stakeholders, including those wishing to control the cross-border impact of company operations – i.e. the disposal of harmful chemicals in the oceans and air pollution.

7.5 Social Participation

By acquiring information for everyone and therefore achieving transparency of on-site conditions, everyone is given the opportunity to take part in the democratic processes: to vote, to be elected, to investigate, to plan and last but not least, to safeguard information and transparency.

7.6 Institutional incorporation of product responsibility

International human rights and environmental organisations have already drawn our attention to the serious shortcomings along the product line. However, these social and ecological problems will continue to exist and their global effects will increase, unless manufacturers, employees and consumers create institutions that will ensure they maintain standards of responsibility.

8. CONCLUDING REMARKS – PROSPECTS

We can conclude by saying that development theories that deal with social and economic aspects but which ignore environmental issues were misleading. However, adding an ecological dimension to the socio-cultural and economic dimensions can produce a coherent theory of sustainable development. Metalworking in countries that contain the raw material has caused irreversible damage to the rainforest and has resulted in new forms of dependency, even though the development of a national processing industry was initially considered to represent progress.

If we want to achieve sustainable development without creating new forms of dependency and preserve our future, all three dimensions must always be transparent:

- The ecological dimension of the project – in particular in rainforest countries – must be transparent. Forests in different parts of the world, and even within the same region, are different. They have different water storage or carbon dioxide absorption capacities. The climate-regulating function of a forest cannot simply be compensated for by forests planted at a later date. Human beings have been cultivating forests for centuries and forests are vital to the sustenance of livelihoods. A forest that tolerates the many and diverse minor interventions of man provides a livelihood. Replanting does not mean that it will continue to provide such a livelihood. The forest, as a reservoir of biodiversity for mankind, cannot be reproduced.
- The economic dimension must be coherent. The right to development must be observed, as was pointed out at the World Environmental Conferences in Rio and Johannesburg. Regional, small-scale producers must be able to put their plans into effect and take part in all the planning decisions. This means that environmental impact assessments in rainforest countries must examine alternatives, especially those that are more sustainable and economic in the long term. In the local and global interests, they have to internalise costs that have been externalised up till now.
- The social dimension must be transparent. Projects should be aware of all social groups and people in the project areas and keep them informed. They should be informed about project plans and be included in all the decision-making and implementation processes. The introduction of social impact assessments, such as those used in the USA, Canada and Australia[19], could fulfil these information and communication requirements.

We have seen how the bauxite and hydroelectric energy potential of the rainforests attracts the bauxite-energy-aluminium product line like a magnet, not only in Latin America, but also in Africa, Asia and Australia. There are plans to use large areas of fragile rainforests to expand aluminium production. The Deutsche Bank estimates that aluminium production outside the US will increase by 3.74 million tonnes per year between 2002 and 2005 (Reuters Company, 2002).

Such growth is incompatible with the three dimensions of sustainability. We must unequivocally point out that the rights of the inhabitants of affected regions must be respected and – in the interests of their, and our own lives – insist on preserving the earth's atmosphere[20]. Both of these concepts are not compatible with the "business as usual" attitude typical of the beginning of the third millennium, and that is why political decisions are required. The interests of all those involved, including the companies, governments and international organisations as well as the regional populations and future generations, – must be balanced on a lasting basis. In Rio, the indigenous organisations requested an international environmental court of justice. In the run-up to Johannesburg, there was talk of establishing an international sustainability council to safeguard international interests at local production sites and deal with appeals from groups who considered their interests were being harmed by production. Until we have this kind of international authority, best practice should be sought, including the transparency of all three dimensions on site and proper communication with affected population groups.

Political discussion should allow society to value the metal for what it represents and to use it only for those products where there is no substitute.

- Future generations in the rainforest countries will consider it their right to use their resources independently and continuously and to preserve the forests and their biodiversity for the world.
- Returning to the beginning of this work, we agree with Amartya Sen that we can only act in the interests of future generations if we acknowledge that the elimination of poverty and enslavement is a prerequisite for development.

NOTES

[1] Between 1985 and 1998, primary aluminium imports increased by 76%, whilst the relative share of imports from rainforest countries rose from 5.3% to 12.6%

[2] Interview by Klaus-Michael Schaal with Dipl.-Ing. Dietrich Engelhart, technical project leader of the A2 range, on the use of aluminium in the production of large-scale series, in: ACE Lenkrad 15.4.2000; cf. also the comments on this topic by Gerhard Berz: Die Politik muss handeln, Der Chef-Meteorologe der Münchener Rück über die steigenden Kosten der Umweltkatastrophen und die engstirnige Liebe zum Auto, in: Die Woche 13.10.2000.

[3] See studies by WHO, IPAI, National Institute of Occupational Health, Norway (summarized in tables 19-4 to 19-6). This stage has been analysed more than preceding stages. See also, section 3.

[4] See World Bank: Environmental Assessment Sourcebook, Vol III, Guidelines for Environmental Assessment of Energy and Industry Projects, Environment Department, World Bank, Technical Paper 154, Washington 1991. In the north of Brazil, in the Amazon area, chemicals were used to clear land. This had a serious impact on human and animal health and on livelihoods.

[5] Like chlorofluorocarbons and CO_2. Norway cf. tables 19-3 to 19-5. This stage has been the one worked on the most up to now cf. section 3.

[6] Cf. the use of these methods in Rainer Grießhammer et al: Entwicklung eines Verfahrens zur ökologischen Bewertung und zum Vergleich verschiedener Wasch- und Reinigungsmittel.

[7] PLAs may be conducted for services as well as material products. In the interests of simplicity, we always refer to product line analyses below, but we mean both types of goods.

[8] Transnational corporations.

[9] In order to examine the effects of aluminium production on health, I would like to take a brief look at three publications on this subject that have appeared within the past twenty five years.

[10] The draft was drawn up by scientists from the Fraunhofer Institute in Hannover, Germany and by a scientist from the "Institute of Terrestrial Ecology", Monks Wood, England. It contains a comprehensive appendix which lists studies on the issues mentioned. The occupational medicine section is relatively brief.

[11] In particular, union conferences on occupational health and safety should be mentioned here. Standardisation organisations also study the issue. For example, a conference of the International Standardisation Organisation (ISO) on occupational health and safety took place in 1996, although it did not specialise in aluminium. Interestingly enough, trade unions, companies, governments and insurance companies all took part in the debates.

[12] Descendants of African slaves who escaped from the plantations.

[13] Christopher Avery quoted at the Evangelische Akademie Mülheim, Ruhr.

[14] The Christian churches' major relief organisation.

[15] (www.ilolex.ilo.chi1567/egi-lex/convde.pl?query=C169&query0=169)

[16] (www.dams.org)

[17] Also the votes of citizens, whose taxes are invested in high risk investments in major energy projects, which are protected by state risk-bearing credit.

[18] Cf. Concept of the Öko-Institut: Cooperation of participants on the basis of product line analyses.

[19] In Australia, there is also a social impact assessment law.

[20] Like at the "Climate Justice Summit" in New Delhi at the end of October 2002 (www.CorpWatchIndia.org), this concerns a new definition of climate change from the perspective of human rights and environmental justice.

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Chapter 20

THE OK TEDI PAGES

Ecological and Social Impact of Large Mining Projects on a Developing Country

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1. INTRODUCTION

"Norddeutsche Affinerie" (NA) in Hamburg, Germany, is the leading copper-smelter in Europe, which is the largest market for copper in the world. NA does not own mines but buys ore concentrate from mines abroad. Since the beginning of copper mining at Ok Tedi, NA has been an important customer, at present receiving approximately 20% of the Ok Tedi Mine's production. In relation to NA's primary production, this means a 10% share.

Two decades ago NA was severely criticised for polluting Hamburg and the river Elbe with toxic metals and arsenic (Umweltschutzgruppe, 1985). NA had to refurbish its utilities and now applies better cleaning techniques. The dominant environmental damage today will occur at mines like Ok Tedi. This, however, is detrimental for NA's public relations strategy, which promotes copper as a clean and sustainable product.

At the shareholder's meeting in April 2000, the environmentalist group "Rettet die Elbe" = "Save the Elbe" (StE), which had bought one share, proposed:

> "NA will take an initiative for the closure of the Ok Tedi Mine. For the relief of social consequences of mine closure, NA will make a deposit of 1% of its profits."

NA's board and the large shareholders rejected the proposal. But after an intense discussion, when other shareholders supported StE's position, NA's supervisory board offered to enter into a dialogue with environmental organisations, mine owners and the government of Papua New Guinea (PNG). NA sent a delegation to PNG, that was formed by the member of the executive board, Dr. Michael Landau, the Environmental Manager Dr Hans-Joachim Velten and the head of the workers

A. von Gleich et al.(eds.), Sustainable Metals Management, 483-515.

council Mr Hans Grundmann. They were accompanied by Dr Klaus Baumgardt, member of StE, Dr Klaus Schilder and Dr Volker Boege, both members of the "German Pacific Network". From November 6, 2000, to November 8, they visited the Ok Tedi Mine as guests of Ok Tedi Mining Limited (OTML). In the days following, at Port Moresby, meetings were held with Secretary Mr Kuma Aua, PNG Department of Mining, and representatives of BHP, OTML and the World Bank. A round-table talk at the National Research Institute with environmental organisations followed. On November 9, the delegation reported its findings to the press at Port Moresby. NA delegates left PNG, while Dr Schilder and the author continued their investigations for several days at Port Moresby and the Mineral Policy Institute in Sydney, Australia.

2. A HISTORY OF NEW GUINEA AND MINING

To understand what it meant to the people, their culture and the state of PNG, to introduce big mining projects like Ok Tedi Mine to the country, history and mining on New Guinea are briefly described.

2.1 Man's Immigration to New Guinea

Boldest estimates say immigration from the Asian continent and the Indonesian islands started 80,000 years ago, more cautious archaeologists assume 50,000 years. The immigrants had to cross the sea because even at the maximum of glaciation, which means the lowest sea level, there was no land bridge to the Australian plate. The ancient Papuans were bold seafarers, long before their European relatives dared to cross the Mediterranean Sea to reach the Aegean islands. At the National Museum at Port Moresby they take some pride of that fact.

The first immigrants and those who followed adapted their way of life to the New Guinean environment. Some built sophisticated boats and navigated around the Pacific islands as traders. Others had to struggle for survival in rough and hardly accessible mountains, which did not allow attaining a high technical level. Split into small tribes and isolated from each other by the nature of the country, the people developed many different cultures and languages. Obviously, no tribe emerged as a dominant power, to form a large nation.

2000 years ago, the people who called themselves the "Min", began to move into the area around the Star Mountains and Hindenburg Range and settled on both sides of the divide in the valleys of the upper Sepik River watershed to the north, and the upper Fly River (Ok Tedi, Fly, and Strickland) to the south. The highest elevations and most remote places were reached 200 years ago. The different tribes changed their location or were forced out by neighbours and some were even extinguished by war, such that the pattern of the population was shifted permanently. Their languages have a common root but developed until they are quite distinct today. Their myths and regulations for daily life refer to their ancestress Afek, who lived 300–400 years ago. Though She was a woman, it is the men who are privileged in Min society.

Since the mountainous terrain is very difficult to walk, a Min almost never left an area of a distance of 40 km from his village. Rivers are too wild to travel by boat, like the inhabitants of the lowlands. Nevertheless, there always has been trade and other relations (e.g., warfare) even across the divide.

Villages had a size of about a dozen families. People lived on gardening, pig husbandry, gathering, and hunting. Because of the tropical climate, nutrients are readily washed out of the soil. The gardens, or a complete village, had to be relocated after some time. Therefore, and because suitable places to settle are scarce in the mountains, population density was very low. The maximum is 3 inhab/km^2, when the basic food is taro, the traditional staple crop. The introduction of the sweet potato from South America 300 years ago allowed a nutritional base on higher elevations than taro and an increase of population. This took place in only some of the Min clans. The difficulties in sustaining life at all did not allow the Min to accumulate riches. Cult houses (fig.20-1) are the summit of "luxury".

2.2 Contact to Europeans

When explorers from Europe, USA and Australia started to move into the interior of New Guinea 100 years ago – the early Spanish, Dutch, and English discoverers only knew the coastline – they met people running naked, talking strangely, living in small groups and bearing stone adzes (in contrast to axes, which have the blade parallel to the shaft, the adze blade stands perpendicular). To this situation, they attached the label "Stone Age" (Heinrich Harrer, 1963). Probably

Figure 20-1. "The Telefolip cult house is the tallest man-made structure in the Min territories. It is always rebuilt on exactly the same spot, its last restructure (the 13th) was carried out in 1977. Telefolip is to the Min as the inner sanctuary of the Vatican to Christians." Photo and text by Schuurkamp (Schuurkamp, 1995).

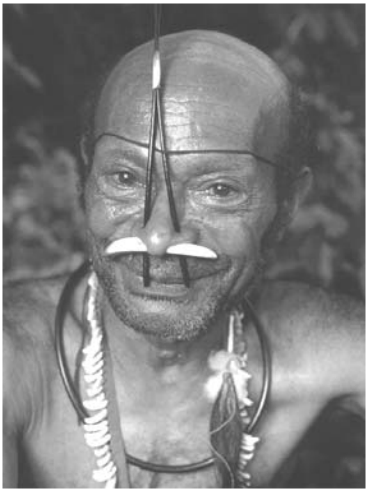

Figure 20-2. This elder of the Faiwol Min is wearing a traditional head decoration, a pig's tusk through his nose and two cassowary quills pierced through his nostrils. He added the new fashion of rubber O-rings around the neck – O-rings were introduced for machinery at the mine and dissipated to even remote villages. Photo by G. Schuurkamp (Schuurkamp, 1995).

some people on New Guinea lived in a way much more similar to the Stone Age than people in a civilisation with electricity and cities. But this does not make them living fossils.

What New Guineans had to learn, to meet the challenge of a changing world, were the abstract and scientific explanations of their world, the separation of material from spiritual meanings. For example, Kina or Dollar is just an abstract currency but a cowry shell is something that had lived and is traded for things connected to life and death. Land is not simply a solid state of earth, to build houses on, do farming, or dig for minerals. In the myths of the Min, the spirits of the dead still live on earth and not in some remote heaven. On their way to their last residence, they cross Ok Tedi at Moyansil (near Tabubil), and pass Mount Fubilan, where their great ancestress Afek had buried her adze ("fubi"). This is the reason, why Min living north of the great divide around Telefolmin, who are not affected by mining materially, nevertheless are paid compensation by OTML.

In general, the traditional cosmos is distinguished from the modern world and people know well when to apply which. However, technical civilisation spreads in leaps and bounds, so people adopted it to different extents and at different paces (fig. 20-2). Thus, conflicts arise between groups of the population, down to families, split into elders and children. The Min around the Ok Tedi Mine were no different from the rest of PNG but they had least time – less than one generation.

2.3 Independence of the State

When the state of NG gained independence from Australian rule in 1975, it faced serious problems,

- to join a diverse collection of tribes, some of which had led grim wars against each other, to a nation
- to acquire the skills to administrate a country
- to bargain with global companies and bankers and not be cheated
- to guide the cultural change that would inevitably come.

Compared to other developing countries, PNG managed the transition quite well – except for the Bougainville civil war. Though cabinets were sacked frequently, all were elected according to the constitution. PNG developed a language of its own, the Tok Pisin, formerly despised as Pidgin English by their colonial masters. Now all are wantoks (wantok = one talk, of ones own tribe). Tribes and villages remained stable social units that still provide care for the elderly and for children. The landowner system means that the land belongs to the people who traditionally live upon it. Only 3% of the area of PNG is state property and directly available for infrastructure projects or mining enterprises. All in all, the landowner system is more a stabilising factor than an obstacle to development. In America or Australia, indigenous people are frequently denied land rights. In PNG, even the least developed Min kept their land. This is strong backing to preserve their culture.

2.4 Mineral Resources and Mining

New Guinea is located on the northern fringe of the Australian continental plate. Where this collides with the Pacific bottom plate, the central mountain spine is folded upwards. The Pacific plate is pressed beneath the Australian. Thus, ore deposits were formed and still do, on New Guinea.

The Bronze Age, the Iron Age, the idea of metals at all, did not reach the Australian continent and the Pacific islands, until they were introduced by European discoverers and colonists. The idea of mining, however, must have been quite familiar to Papuans. Stones suitable for tools are not simply picked from the ground. Harrer (Harrer, 1963) describes the method of recovering proper stones at a quarry by the Dani people. The Dani live west of the Star Mountains, in Harrer's time a Dutch colony. A rock was heated at its weak point by fire, for several days, if necessary. It was then shock-cooled with water, such that inner tensions split it into pieces of convenient size to be shaped to adze blades, knives, or arrow heads. Before gunpowder blasting was introduced 400 years ago, the same method was applied in European mining.

Under German colonial rule, geologists ventured far upstream on the Sepik River in search of minerals. Two world wars interrupted such activities of German and other parties, except for some gold washing in the 1930s. When the Japanese attacked New Guinea, defence was by the UK and USA, which already had in mind to protect this treasure chamber. In the Cold War that followed, it was looked upon as a strategic reserve.

Panguna Mine on Bougainville was the first large mining operation after the war. Rio Tinto, the big international mining company, did wrong whatever could be done wrong. They did not pay compensation to local landowners. The workforce was hired from abroad, a colonial practice that always raised serious conflicts. The project had been generously permitted by the Australian colonial administration. The tremendous amount of waste that is always connected to copper mining was dumped into a river and the sea without treatment, which terminated gardening (the traditional method of agriculture on New Guinea) and fisheries in the affected area. Unrest among Bougainvilleans grew to a civil war, which led to the closure of the mine in 1989. The Hamburgian NA was one of the customers for Panguna ore but they found a substitute just in time: Ok Tedi.

The copper and gold deposit of Mount Fubilan on the Upper Ok Tedi was discovered by Kennecott, a US company. However, Kennecott withdrew its claim when negotiations with the independent government of PNG, which was determined to do a better bargain than the colonial administration, failed. Broken Hill Proprietary (BHP) from Australia and its consorts took over and founded Ok Tedi Mining Limited (OTML), because they estimated the ore reserves three times higher than Kennecott had recognised and the gold price went up at that time. BHP avoided many of the mistakes made on Bougainville but environmental damage turned out the same, though the PNG government had imposed on OTML the building of a dam south of the mine, to retain the tailings.

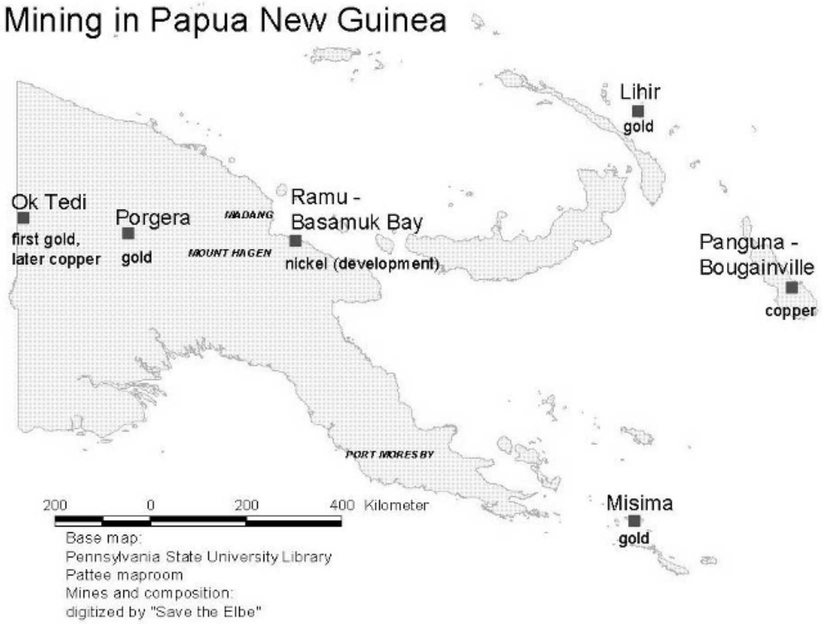

Figure 20-3. Important mining operations in Papua New Guinea; base map from (PSU), mining sites added by the author.

Ok Tedi was the reason to establish a Mining Act (Ok Tedi Agreement). It was the first exercise in environmental legislation for PNG, which was once regarded as a cornerstone of economic development and it is the first regular model of how to close a mine after exploitation. Anything that happens at Ok Tedi will set a precedent for other mining projects. If OTML is forced to dispose of tailings on land safely, every company will have to do it. The term “rehabilitation” will be defined in the mine closure plan for Ok Tedi mine. Other countries, where mines operate under tropical conditions, will look at PNG.

3. OK TEDI MINE

To develop the site, the mining town of Tabubil was built (see fig. 20-9). The area of the town is one of the “leases” to OTML, which means that it is formally private ground. The town depends on the mine – energy supply, drinking water, wastewater treatment, traffic connections. It is inhabited by 10,000 people.

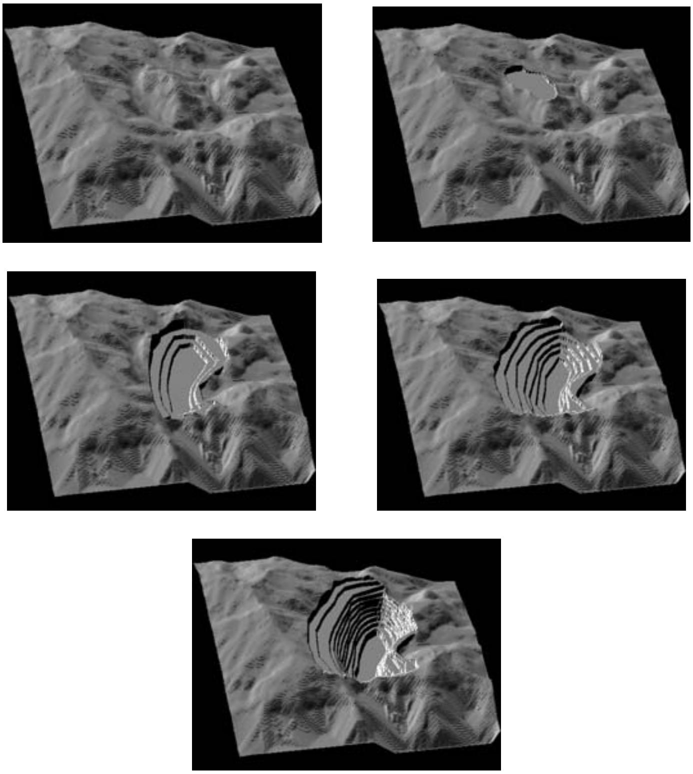

Figure 20-4. (From left to right and from top to bottom): 1973, Mt. Fubilan peak 2095 m above sea level. / 1984, Removal of the gold cap / 1990 Beginning of copper mining / 2000 Bottom mark at 1700 m above sea level / 2010 Final depth: 1300 m above sea level

OTML started production in 1984. When the cap of Mt. Fubilan, which contained gold, had been removed between 1984 and 1988, full-scale copper ore concentrate production started in 1989. The ore deposit will be exhausted by the year 2010 and the mine will be closed. There are no ore deposits to continue mining in the Ok Tedi valley.

The series of 3-D-views displays the development of the pit (fig. 20-4). Height contours were digitised from the topographic map 1:100,000, purchased from PNG National Mapping Bureau. A digital elevation model (DEM) was derived, using the geographical information system (GIS) "Idrisi". The pit was roughly outlined and successively subtracted from the DEM. The mountain is blasted step by step. Dead rock is removed (fig. 20-5, 20-6). Rock containing copper is coarsely broken and conveyed to the mill (fig. 20-7, 20-8).

Figure 20-5. Dead rock and ore is removed by giant trucks, which haul 150 tons in a load.

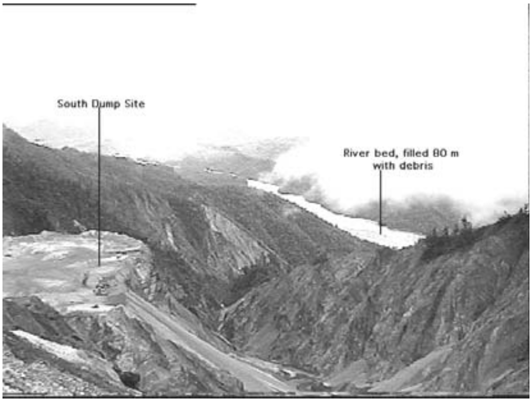

Figure 20-6. 120,000 tons a day of debris is shoveled across the edge into the valleys of Sulphide Creek/Ok Mabiong to the north or into Ok Mani to the south. Because of heavy

rainfall, the creeks and rivers are powerful enough to transport even coarse material downstream. Ok Mani in the background is already filled up to 80 metres with debris from the south dump!

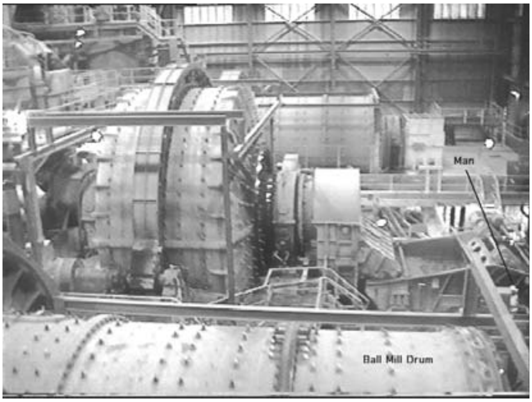

Figure 20-7. Ore is pulverised in huge rotating mill drums.

On a normal day of production, 85,000 tons of ore enter the mill (fig. 20-7). Depending on the type of ore, yields range from 50% up to 85% of copper-content. By flotation (fig. 20-8), 2000 tons of ore concentrate are gained, that contain 600 tons of copper. 83,000 tons of residue, called the "tailings", are discharged into Ok Mani and thus to Ok Tedi and Fly River. The tailings include a residual 120 tons of copper. Besides the mere physical impact, contamination of the environment may occur by mobilisation of copper, making it bioavailable

The copper ore concentrate is pumped through a small pipe for 130 km to the river port at Kiunga on the Fly River, where it is dried and loaded on river barges. Because of its high water discharge, the Fly River is a convenient waterway. Each barge carries 2,500 tons to the mouth of the Fly River to a silo vessel. From this depot, seagoing vessels take the load overseas.

Figure 20-8. The flotation hall. Flotation means, the slurry of milled ore and water is foamed with air. Bubbles are adsorbed to ore particles so that they rise from the slurry. To enhance efficiency, chemicals are added, mainly lime.

4. OK TEDI ENVIRONMENT

4.1 Geography of the River System

The Star Mountains and the Hindenburg Range, with elevations above 3,000 m, divide the waters of the Sepik to the north, and the Fly River system to the south (fig. 20-9). The Fly River and its most important tributaries Strickland River and Ok Tedi, form a watershed of 100,000 km^2. The Fly has a length of 1,100 km. With rainfalls some of the highest in the world – up to 14 m/year – the relatively short rivers are fed with enormous quantities of water. After a short course in the mountainous area through V-shaped valleys and narrow gorges, the rivers enter the lowlands. From the junction of the Ok Tedi and Fly, the river descends only 20 m to sea level. It meanders in wide bows, forming sediment walls on the banks and at the mouths of smaller tributaries, there are large swamp areas and shallow lakes behind the bank walls. Approaching the sea, it opens to a wide funnel with many islands in between. Because of the high tidal range and a sudden drop of riverbed level to the sea floor, a tidal bore develops regularly at the mouth of the Fly. Precipitation at the estuary still exceeds 2 m/year.

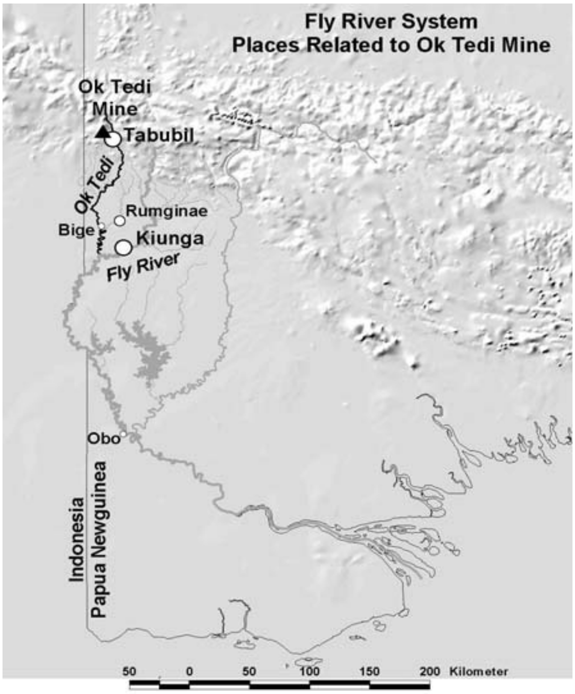

Figure 20-9. Digital Elevation Model cut from USGS DEM of the world (USGS); coastline and places[4]; river lines digitised and map composed by the author.

According to the landscape, vegetation ranges from highland rainforest, lowland rainforest, swamp plains, savanna, to mangroves. New Guinea is famous for its bird- and insect life (fig. 20-10). As the Fly River catchment is sparsely inhabited, wildlife is undisturbed in large areas, even by New Guinean standards.

The Fly River system hosts the most diversified stock of freshwater fish in the Australasian region. Hettler (Hettler, 1995) quotes an investigation by Roberts in 1978, that found 105 freshwater fish species , compared to only 57 in the Sepik. Numerous molluscs, crayfish and shrimp, amphibians and reptiles, among them giant salt water crocodiles, live in the Fly.

Figure 20-10. Moths are attracted by the floodlights of the mine, where work continues day and night.

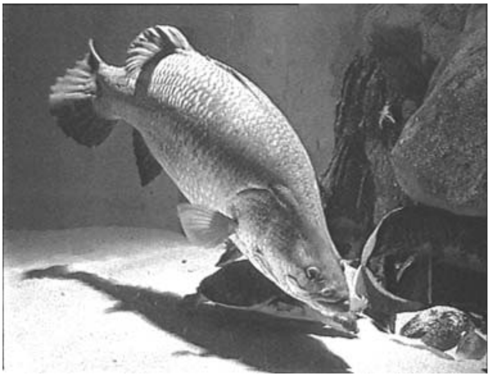

Figure 20-11. Barry the Barramundi (Lates Calcarifer) at Sydney Aquarium (picture from SA video).

The Fly River is a core habitat of Barramundi (fig. 20-11), which may grow to 1.5 m and 60 kg here. Barramundi spawn in the coastal waters and migrate upstream to feed and grow. Besides black bass and freshwater prawn, it is the preferred target of commercial fisheries. Barramundi is raised in aquaculture at many sites around the Chinese Sea but wild barramundi is priced higher.

Due to variable hydrologic conditions – the river level at Kiunga may change 15 m within a day – most species are opportunistic and adapted to natural disasters. The impact of the mine, however, adds a new threat to life in the river.

4.2 Pressure on the River

In Chile, where the largest copper mines in the world are operated, waste is just set aside and will remain in a desert climate for a long time. On New Guinea, the situation is more difficult. Tropical rainfall may wash away any disposals, if not confined by a dam or in a depository that is built and maintained like a building. The government of PNG imposed the building of a tailings reservoir and OTML started the construction of a dam south of the mine. However, a landslide damaged the foundations of the dam in 1984. Considering the impact of a sudden burst of the dam, caused by landslide or earthquake, the plan for a tailings dam was dropped without any alternative. The PNG government, overriding the advice of its technical staff (PNG, 1989), set levels of pollution that allowed OTML to discharge tailings without treatment.

On the upper Ok Tedi, coarse rock and sand aggraded the river bed. Ok Mani and Sulphide Creek, just below the dead rock dumpsite, are elevated 50 – 80 m. The Ok Tedi at Tabubil has a river bed elevated 10 – 20 m (fig. 20-12, compare to fig. 20-13).

Figure 20-12. Massive aggradations of the Ok Tedi river bed at Tabubil.

Figure 20-13. The Ok Tedi should look like the Kvirok river, which flows from Mt. Fubilan to the west and is not influenced by mining. Photo OTML.

Miners never miss an occasion to mention the landslides in the mountain areas, that may fill a river bed in an instant. However, the singular landslides must not be compared to the steady dumping of mine waste. River bed and floodplain are never given a break by the mine to recover. The soil and rock from a landslide is different in composition from mine waste. No comparable impacts of landslides at other rivers are observed, like aggradations of the Upper Ok Tedi in the course of 90 km, and a massive forest dieback in the floodplain for another 100 km of the Lower Ok Tedi.

Figure 20-14. Ok Tedi and dieback area at Bige.

Figure 20-15 The Fly River near Kiunga, upstream of its junction with Ok Tedi. The river and rainforest are visibly intact.

When the Ok Tedi enters the lowlands, it descends more smoothly and slower through its wide floodplain. Here the smaller grains of mine waste precipitate in such quantities that the river bed is filled to the rim. The water floods the plain completely anytime the discharge is slightly higher than normal. Sand walls trap the water in ponds and oxbows, such that it cannot retreat after a flood. Though the vegetation is used to temporary inundation, it cannot stand that much. The rain forest has died on the plain in an area exceeding 500 km^2 today (fig. 20-14, compare fig. 20-15). The Peer Review Group (PRP) expressed concern that the ongoing impact may increase the dieback area to more than 2000 km^2.

The fine fraction of waste, mainly the tailings, is transported down the whole Fly River to the Gulf of Papua. This problem is regarded as the most serious because it cannot be limited to a short stretch of the river and not to the main stream. Lagoons, side branches, swamps and tributaries in the flatlands of the Middle and Lower Fly are covered with thin layers of mining silt. This waste is fundamentally different from natural suspended matter. Its grains, fresh out of the mill, have sharp edges because they have not been weathered and polished, so they may hurt the gills of fish. Tailings are purely inorganic, without compounds from soil and organic detritus. Natural sediments were welcome to the gardeners along the river as a fertilizer. Because of the physical impact and unsuitable composition of mine waste, gardening along the dieback area has become impossible.

Copper is not completely extracted by flotation, so 120 tons/day of copper flow down the Ok Tedi along with the tailings. Copper is tightly bound to these lime particles as insoluble sulphide. However, if sulphides are exposed to air, they are converted to copper oxides and sulfuric acid is set free. Sulfuric acid leaching of mining waste deposits is a common phenomenon, which may release considerable loads of toxic metals into the environment. OTML claims that lime, the prevalent rock from the pit, will neutralise the acid, and copper oxide is still insoluble in water. This sounds plausible, if the tailings were disposed and kept under control, e.g., on the Bige dredge site. In the river system, however, many biological processes take place, which may lead to mobilisation of the copper and make it available to organisms. Some are very sensitive to copper, e.g., snails and prawns. Even undissolved copper oxide has a massive effect. Marine vessels are painted with copper oxide (as a substitute for organic tin compounds, which will be banned in some years), to prevent fouling by mussels and seaweed. The effects of an annual load of 30,000 tons of a toxic metal cannot be, by the present knowledge assessed as not dangerous.

Hettler (Hettler, 1995) concludes from his investigations of sediments in the Middle Fly River area:

> "Of all trace metals, ...copper is of highest ecological relevance because of its strong enrichment..., its high hydrochemical mobility and its ecotoxicity even at trace concentration.
>
> The areas of the inundation plain (of the Middle Fly)... play a central role for reproduction and feeding of fish. This part of the river ecosystem is most sensitive to changes in the ecological situation caused by the mining project.
>
> ... it may last for centuries, until the copper enriched layer is covered by an uncontaminated layer of sediment."

In 1998 OTML started the dredging operation at Bige, which is a village located just above the junction to the Fly River. A trench was cut into the river bed, 10 m deep, and 800 m long, where all particles that arrive from upstream of the size of sand are trapped,. When the trench is filled after two weeks, a dredger boat will suck out the sand, and the slurry is then pumped onto the land through thick pipes (fig. 20-16). There, it will pass through a settling pond. The water is deviated back to the river. The sand deposit is built up in terraces, which will rise in steps to 30 m above the ground.

In OTML's experience, the sand fraction is completely recovered from the Ok Tedi, which yields 18 million tons per year. It is not known how much of the sand is of natural origin. If all sand came from the mine – the assumption most favourable to OTML – 30% of the input from Mt. Fubilan would be removed from the river at Bige. Thirty per cent of mine input is coarse material, which fills the river bed upstream. Forty per cent of mine waste, essentially the fine tailings, passes the sediment trap. The Bige dredge deposit is only a solution for a minor quantity of the mine's waste and it will work only in the second half of the mine's lifetime. OTML did not offer any solution for 70% of the waste, which will continue to fill Ok Tedi and the Fly River for the next ten years.

OTML and its main shareholder BHP were accused in Australia by landowners on the Lower Ok Tedi and Middle Fly, to compensate the damage. In the out-of-court settlement in 1996, OTML promised to search for a solution for the tailings problem. Since tailings are probably the most serious threat, the precautionary principle requires them to start operations to dispose of the tailings safely, now. A study – revised and released in 2000 (Ok Tedi Mining Limited, 2000) – investigated the construction of a tailings pipeline from the mine to the Bige deposit. It says that a tailings-pipeline is feasible.

Figure 20-16. The sand deposit at Bige. The pipes are used to conduct the sand-water mixture from the river to the deposit. This is a very familiar sight to Hamburgians, since contaminated dredge from harbour basins and the shipping channel is disposed of using the same technique.

There are no major obstacles to building tailings into the sand deposit at Bige. However, the cost of US$ 130 million is scaring OTML. It seems OTML will carry out studies on the issue until it becomes obsolete in 2010. Another lawsuit by OTML's opponents of 1996 has been brought forth. Even the World Bank, which reviewed OTML's Mine Waste Management Plan (OTML, 1999) at the request of PNG government (World Bank Report, 2000), criticises the lack of options offered by OTML.

Riverbed aggradations by the coarse fraction of waste has not yet even been considered.

The dredging operation at Bige aims at a reduction of inundations of the floodplain by keeping the river bed open and allowing an easier drainage and retreat of water after flooding. To date, a significant recovery of vegetation has not been observed. The landowners, who were invited to the meeting at Bige, declared that nothing had changed so far, and gardening was still impossible. Monitoring data were not presented, e.g., an aerial photographic survey of the extent of the dieback area. The optimistic assumption of OTML, that he jungle would quickly reclaim its territory, was not proven, and the question remains open, as to what kind of jungle on what timescale will take its place.

Monitoring data on aquatic life were not presented, nor have they been published on the Internet. There are no fish stock statistics over the lifetime of the mine that might prove the magnitude of the impact or a recovery related to the dredge at Bige.

Insufficient monitoring (or publication of monitoring results) does not allow a quantitative assessment of impacts of the mine at present, nor of claims to be justified, nor of impacts in the coming ten years of mine operation. A mine closure plan that would make sense ecologically, has to be based on a quantitative description of damage, to calculate the amount of work, money and time to rehabilitate the environment. The monitoring parameters that indicate progress or failure have not been set. With respect to the environment outside the mining pit, the "Mine Closure Plan"(OTML, 12/2000) cannot actually be called a plan.

5. SOCIAL AND ECONOMIC DEVELOPMENT

5.1 Change of the Way of Life

The life of a Min was threatened by disease, war and accident, so life expectancy was just 30 years and infant mortality 30% before modern techniques, health care, pacification and transport facilities were introduced.

Many in the Ok Tedi valley saw the mine as the chance to close up to the standards of modern civilisation. The Min were boosted from a very poor standard of material living to wages and compensation payments considerably above PNG standards. This allowed them to afford new housing and the commodities of modern life. Tabubil's population rose from 500 to 10,000. Infant mortality is at 3% and life expectancy well above 50 years. Not all improvements, however, are merits of the mine, as OTML and its lobbyists, like Sir Ebia Olevale (whom we met at Port Moresby), like to claim. PNG made progress in other parts of the country without mining.

OTML preferably recruited and trained the working force from the region, i.e., Western Province. The management, however, is formed mainly by Australians. Landowners on the lease areas were compensated financially.

Women in general lost social status because they were not included in paid work like men. Men have gained more liberty, status and control of life than women, simply because they have money and command how to spend it. In the former society of subsistence, women were also inferior, but a man who did not comply with his chores was not much respected in his village community, which he could not escape.

Figure 20-17. Even a Min warrior in full arms and bilas (traditional dress) looks like a dwarf in front of a 190 t mining truck. OTML demonstrates the kind of progress it claims as its achievement. (picture taken in 1983 (OTML, 1983)).

5.2 Economical Balance

Tables 20-1 – 20-3 describe the production and financial flow of OTML from the start of production in 1985 until 2000, as compiled from business reports (OTML, 2000).

Table 20-1. production

Year	**85**	**86**	**87**	**88**	**89**	**90**	**91**	**92**	**93**	**94**	**95**	**96**	**97**	**98**	**99**	**00**	**Sum**
Gold bullion (tons)	16	19	11	6	0												**52**
Copper concentrate (1000tons)			107	1967	442	521	601	569	589	588	614	542	334	491	624	694	**6911**
Contained gold (tons)			7	12	16	14	11	11	12	15	15	13	8	13	12	17	**176**
Contained silver (tons)	6	6	11	20	30	27	26	24	28	30	28	27	16	26	33	45	**382**
Contained copper (1000 tons)			39	53	135	170	204	193	203	207	213	186	112	152	188	203	**2258**

In the first stage of mining, the rock cap containing gold was removed and the gold was leached with cyanide solution. This yielded "gold bullion" solid bars and some silver until 1989. The mine then changed to copper ore concentrate production. The metals – copper, silver and gold – are extracted at smelters like NA, Hamburg.

Table 20-2. National economy

Year	**85**	**86**	**87**	**88**	**89**	**90**	**91**	**92**	**93**	**94**	**95**	**96**	**97**	**98**	**99**	**00**	**Sum**
Exports (Kmill.)	172	205	274	285	350	521	443	420	381	536	882	606	378	701	805	1026	**7985**
Contribution to Total PNG Export %	17	18	22	26	31	38	26	24	16	20	3	18	12	19	16	18	
Goods &.Services (Kmill.)	n.a.	n.a.	n.a.	n.a.	125	151	172	156	131	87	220	124	176	321	463	319	**2446**
Proportion bought in PNG %	n.a.	n.a.	n.a.	n.a.	63	58	59	55	58	68	66	54	49	41	42	39	
Taxes/duties/fees (Kmill.)	6	11	25	13	14	50	39	26	23	24	24	63	62	52	92	113	**637**
Royalties paid to state of PNG (Kmill.)	2	3	3	4	5	6											**22**

Ok Tedi Mine contributes to the national economy by selling its products on the world market and buying domestic equipment and services. The part of the financial transactions that takes place on the national market improves state income and the income of the people. However, OTML does not provide the complete figures of profits and payments, e.g., to pay back bank loans abroad, nor do these figures give a picture of payments of the state of PNG for foreign debts, that were used to become a shareholder of the enterprise. The currency of PNG, the Kina, did not remain stable over the years. In the eighties, it was equivalent to the US dollar but since 1995 it dropped to one third at the end of 2000.

Table 20-3. Local economy

Year	**85**	**86**	**87**	**88**	**89**	**90**	**91**	**92**	**93**	**94**	**95**	**96**	**97**	**98**	**99**	**00**	**Sum**
Royalties to Provincial Gov. (Kmill.)							4	3	3	5	7	8	4	10	11	12	**68**
Royalties to Mining Lease L'owners (Kmill.)							2	1	1	2	3	3	2	4	5	8	**31**
Special Support Grant: Entitlement (Kmill.)						4	4	4	4	5	n.a.	n.a.	na.	n.a.	n.a.	n.a.	**21**
Special Support Grant: Amount paid (Kmill.)						3	5	4	4	1	n.a.	n.a.	n.a.	n.a.	n.a.	1	**18**
L'owner lease &compensation payments (Kmill.)	1	1	1	1	1	1	1	1	1	3	17	8	7	16	15	13	**85**
No. of OTML employees	1365	1777	2761	2468	2139	2016	1930	1875	1807	1928	1945	1993	1936	1761	1905	1965	
Proportion of PNG citizens(%)	81	79	76	79	86	87	67	88	88	90	90	90	90	91	92	92	
Lower Ok Tedi&FIy Riv, Develop. Trust (Kmill.)						3	3	3	3	3	3	3	4	4	4	8	**24**
Education&Training (Kmill.)	1	1	1	1	1	2	2	1	1	2	3	3	2	1	3	5	**20**
Landowner Business Development																	
Businesses fully or party owned by local l'owners				38	41	44	49	58	59	66	73	74	79	80	81	72	
Gross turnover of landowner businesses (Kmill)				22	29	33	51	56	64	68	73	73	80	81	73	114	**628**
Dividends paid by landowner businesses (Kmill)					0	1	1	2	5	5	5	5	1	1	1	2	**26**
No. of people employed by landowner businesses				621	571	774	1200	1260	1077	1141	1260	1400	1000	1050	1020	2300	

This covers the expenses of OTML and related landowner business to the Western Province (OTML-wages already included in table 20-2?).

In its lifetime, the mine exported gold and ore concentrate worth 8 billion Kina. It spent almost 1 billion Kina for taxes, royalties and local compensation. Goods and services bought in PNG amount to 1.2 billion. 80 million Kina in wages were paid to the miners in 2000 but it is not clear whether these are part of the "goods and services bought in PNG" (130 mill. Kina in 2000). A calculation in favour of OTML would add the turnover of landowner businesses (600 mill. Kina) to its contribution to PNG's economy. The business reports still leave a gap in the figures, which makes it difficult to assess what proportion of the mine's turnover remained in PNG and what was transferred abroad. The question raised by the Starnberg study (Starnberg Institute, 1991), as to how a developing country may benefit from a large-scale mining enterprise, cannot be answered as long as approximately 4 billion Kina remain unaccounted for.

5.3 Building a Local Economy

Services that normally are provided by state come from OTML. The company's health service takes care of all people in the region, many of the schools and education is sponsored by the mine, even police duties are executed by OTML's security staff, who were appointed reserve constables.

Business at Tabubil, Kiunga and the rest of the area along the supply line of the mine, emerged mainly as satellites to mining. With few exemptions, it cannot exist without the mine. OTML started programs that give incentives to save money and to invest it in a business. These businesses are prompted to grow food for the local supply, or cash crops, or to attract tourism.

Some approaches of OTML's rural and economic development program seem quite promising because they start at the experience and tradition of people. At Finalbin, a village close to the mine, improved breeding of pigs, poultry, rabbits and taro is tried out, to create a broader food base . Traditional gardening would not supply half the number of present inhabitants around Tabubil, which are expected to stay when the more mobile part of the workforce has left the valley after mine closure.

In contrast, at the Bige dredge deposit, the engineers try to persuade locals to plant cash crops like bananas and pineapples on the slopes of the deposit, to fix the slope. When asked, locals told us that this is not the proper way of gardening.

At Obo, at the junction of Strickland and the Fly River, the Obo Fishing Venture tries to draw benefit from the rich resource of fish, namely barramundi and prawns. Assisted by OTML (Ok Tedi Mining Limited, 2000), the cooperative was reformed in 1999 from the relicts of an earlier attempt. Barramundi and prawn are delicious treats – we tried it – but it is not clear and an objective study has yet to be done, as to whether fish stocks will allow a sustainable catch under the continuing impact of tailings!

The region has a great potential for eco-tourism. The landscape in the mountains is spectacular, birds, insects and other wildlife are abundant. Since many residents at Tabubil have built new houses, they may be used for bed & breakfast accommodation. In Europe and North America, many ornithologists spend considerable amounts of money to travel to bird-watching sites. There is, however, just one project at Kiunga, hosting 100 guests/year.

The first independent government saw mining projects as isolated places in the country, which would yield enough money to improve the lives of all citizens. Once the whole country was better developed, people from the mining areas would easily find another way of earning a living when mining finished. This concept did not achieve its goals. Ok Tedi mine suffered from technical difficulties and from the ups and downs of the world market, which cut the profits and payments to the state. Though the Western Province received more money from OTML and central government than other provinces, it was developed least. Many politicians and administrators seemed to have enriched themselves and their wantoks. Consequently, in the year 2000 the state government finally sacked the provincial government because of bad governance. Only around the mine, did wealth come to the people. After the closure of the mine, these people will slip into a society that is not, in general, progressing.

Mining cannot sustain locally. Once a mine is exhausted, mining will move, to wherever a new deposit will be discovered. Most Ok Tedi residents could not recognize that the golden (and copper) age would last for less than one generation of men. OTML did not prepare people for that from the start. A pronounced development strategy aiming beyond mine closure was started in 1998. On our visit, OTML gave the impression to be more a development agency than a mining company. This cannot disguise the fact that the prime objective for OTML's shareholders is profit and if there is not sufficient profit, there will be no funding of development projects. To achieve a sustainable economy and social structure, first of all sustainable funding is necessary. It has to be independent of shareholders, it has to be secured from bad governance and selfish landowners, it has to be laid out transparently and it has to be controlled by true and cooperating representatives from the affected region. The mine closure plan does not offer exact proposals on how to manage this crucial problem.

In 2002, BHP chose to exit the Ok Tedi mine by handing over its 52 percent equity of OTML to a newly established "PNG Sustainable Development Program Ltd.", based in Singapore. Of course, this happened with the consent of the PNG government. The actual value of the assets of the mine, or possible obligations remaining from loans, are not published by BHP, OTML or the government. The OTML-management, formerly appointed by BHP, remained in office and retains control of mining operations. The mining law was amended to allow the management to set environmental standards at their own will. Villagers in the Ok Tedi Region were urged to sign "Mine Continuation Agreements", which were declared valid if only one member of a village signed, with or without the consent of his neighbours. An Ok Tedi Development Foundation (OTDF) (OTML, 2001) was established, which will take over the OTML community activities. OTDF will be managed completely by OTML until 2007, it will be funded by the profits of the trust company in Singapore. The trust will build a reserve for the costs of mine closure. Leaving financial data obscure, it seems that BHP concluded its Ok Tedi engagement with the use ofhush-money for PNG government members and their wantoks. Under these conditions, the development of a viable post-mining-economy in the Western Province is at risk.

6. STAKEHOLDERS

In discussions on sustainability, the word "stakeholders" appears frequently. The use of the word suggests that conflicting parties have a legitimate reason for their actions. Here, the term will mean just "interested party", to avoid any judgement. To make profits from the destruction of environment is not legitimate, in the opinion of StE.

6.1 Mining Industry

A large investment is required to set up a mine. Even global companies seek consorts, to raise funds and to distribute the risk. "Ok Tedi Mining Limited" (OTML) was founded under the leadership of Broken Hill Proprietary (BHP) (Australia), which held a 30% share, Amoco Minerals (owned by Standard Oil Indiana) 30%, Metallgesellschaft, Degussa and the German State Agency "Entwicklungsgesellschaft" 20%, and the state of PNG 20%. US$ 1.4 billion were invested. Only US$ 300 million were contributed as genuine cash capital but US$ 1.1 billion was financed by bank loans. There is no statement of how much interest was paid ubtil the credit for the investment was paid off. The first preference dividend was paid in 1991. The figures from OTML's business reports show low profits and a gap in the balance that leaves a considerable part of their financial transactions in the dark, which raises the suspicion that the real profits were made outside PNG.

In 1993 ownership of OTML changed. BHP increased its share to 60%, Metallgesellschaft and Amoco quit the enterprise and a new shareholder appeared, Inmet (Canadian), which bought 20%. In the 1999, the state of PNG bought 8% from BHP and 2% from Inmet and so it is holding 30%.

Ok Tedi is a project by which the whole mining business is discredited, especially after the lawsuit in Melbourne in 1996, raised by landowners from the Lower Ok Tedi. Of greatest concern to the public was – this became evident in our press conference in Port Moresby – that BHP may sell OTML to a company from East Asia or similar, which would not be subject to political or economic pressure to act responsibly.

The costs of environmental protection and for social development was probably not the reason for paying no or only minor dividends. If there is an economic motive for BHP,to get rid of its shares, it could be the cost of rehabilitation after mine closure. This cost is not discussed in the mine closure plan but postponed for further studies.

Ok Tedi and many other projects in developing countries spoiled the reputation of the mining industry as a whole, which caused CEOs to worry:

> "Despite the industry's efforts, mining has fallen into increasing public disfavour. Many accept it grudgingly as a necessary evil. Others take as read the assertion that the industry is incompatible with sustainable development. There is a gap, which sometimes seems like a gulf, between the industry's self-perception and how others see it. Society's standards and priorities have shifted. Industry's behaviour must not only shift in line but must where possible try to

> anticipate future shifts. The current set of perceptions, if left unchecked, will have a direct effect on the fortunes of the industry. Moreover, they will drive legislation and distort markets in ways that will ultimately harm developing economies, and produce unintended environmental and social consequences." Sir Robert Wilson, Rio Tinto, Report on the Governors Meeting for the Mining and Metals Industry, 1 February 2000, Davos, Switzerland

In 1999, 27 global mining companies started a Global Mining Initiative (GMI), to find out how mining can be made "sustainable". GMI yielded a bulky description of problems (IIED, 2002) and a conference was held in Toronto in May 2002, appealing to all stakeholders to come together. It does not even aim at a "code of conduct", that would set minimum standards of environmental and social performance of mining. No independent control is implemented. GMI tries to "greenwash" the mining business and soothe shareholders but it will not prevent further "Ok Tedis".

6.2 State Government

When PNG had become an independent state in 1975, the government had no experience as to what it meant to permit a business like the Ok Tedi Mine. Considering Bougainville, which was permitted by the former Australian administration, the independent government, under Prime Minister Michael Somare, expected a larger share of benefits from mining. Of course they sought advice from the World Bank and development agencies of the rich countries, which warmly recommended the project. The terms of the partnership between state and companies were fixed in the Ok Tedi Agreement of 1976, which Sir Michael Somare called:

> "recognized around the world as possibly the best mining agreement between a developing nation and multinational corporations".

To buy its 20% share of OTML, the state of PNG had to borrow money (US$ 60 million) from foreign banks. The returns on the investment were too small to shake off the interest burden. To keep investors content and attract more of them, infrastructure like roads, airlines and telecommunications had to be developed and state debt increased more rapidly. The export/import balance was improved by OTML's sales but diminished for buying mine equipment abroad and paying interests to foreign banks.

Environmental experts were asked for advice too, but not listened to. The present state of Ok Tedi was foreseen, as can be read in the "Smoking Gun Files" (TSGF, 1989).

In 2000, after some ups and downs common to PNG policies, Somare became Mining Minister. When visiting Fiji, he warned Pacific Island governments that while mining may seem appealing as a lucrative path to development, there are serious costs that should make governments wary.

> "We have learnt a lesson and I am saying it loud and clear to the Pacific Island countries, to be careful of mining companies" Somare said in May 2000 in Fiji.(PNG, 2000)

When the Hamburg delegation met with Somare’s Secretary, Mr Kuma Aua, he opened his statement by saying that the Department of Mining was always very supportive to mining and OTML. Mr Aua is a member of the (supervisory) board of OTML.

6.3 Norddeutsche Affinerie

To secure a safe supply of copper ore concentrate, the Ok Tedi site was partly developed by Degussa and Metallgesellschaft, two major shareholders of NA at that time, assisted by the German state agency Deutsche Entwicklungsgesellschaft.

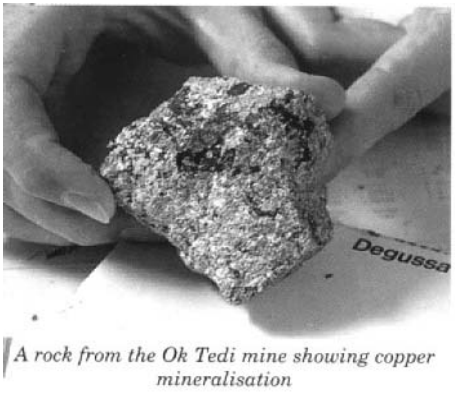

Figure 20-18. The name “Degussa” on the paper sheet indicates the business connection. Picture taken from a booklet published by the Department of Mining (DOMP, 1994).

Besides gold, which may be processed by Degussa, the only German company interested in copper ore was, and still is, NA. When Ok Tedi Mine started production of copper ore concentrate, it was marketed by Metallgesellschaft, which is the major shareholder of Degussa (fig. 20-18). The German companies sold their shares in 1993. NA does not hold mining shares, nor do mining companies own parts of NA, since NA was traded on the stock exchange in 1999.

In 1997, OTML and NA celebrated the deliverance of the first million tons of ore concentrate. This is a 20% share of OTML’s production up to that date, so NA is called the “largest single smelter customer” by OTML.

At the press conference in Port Moresby, which summarized the visit to PNG, NA was very cautious in admitting its responsibility. They promised to use their influence as a customer, that OTML may improve environmental care. However, they are not willing to apply pressure, to stop buying Ok Tedi ore. NA announced a contribution to a social project in the Ok Tedi area.

In an evaluation discussion between Save the Elbe, Pacific Network and NA’s board, NA did not change its position. NA offered to ask the Global Mining Initiative to include smelter companies (thus becoming a Global Metals Initiative) and locate one of their discussions and workshops in Hamburg. This attempt failed.

NA will not use economic pressure, namely to stop buying ore concentrate, to urge OTML to improve environmental protection. The crooked argument is that the ore would be sold to another company and smelted under worse conditions than at NA's. This calculation is not complete, however, because NA would buy ore elsewhere, which has not been processed cleanly so far. OTML was not impressed by just (sweet) talk. OTML expressed its concern that without NA as a reliable customer, ore concentrate would have to be sold less profitably and thus budgets for environmental protection and social development would be cut. It is a cheap argument used by both companies to justify the bad, because things could be even worse.

NA supported the health centre of the Evangelical Church at Rumginae with a donation of US$ 70,000 for a new school building and will keep in contact with the NA-company physician Dr Schultek. His help is of great value, but measured against the investment made by German companies and the accumulated value of the deal between OTML and NA, NA's compensation to the people at the Ok Tedi looks a bit cheap.

At a public lecture within the "Sustainable Metals" project at Hamburg, Dr Marnette warmly appreciated the idea of obtaining an eco-rating for his company. However, this is not possible, as long as NA contracts ore concentrate from Ok Tedi and similar mines.

6.4 Landowners

Landowners have a strong position in PNG. The villagers immediately neighbouring the mine negotiated considerable compensation payments. With the assistance of OTML, several landowners started small businesses, which are mostly contractors to the mine. There arose (and will fall?) 80 companies with 1000 jobs with the mine.

However, people downstream were neglected in the beginning and when damage to the Ok Tedi threatened them, the fighting began. Each group negotiated a different scheme, and how much it was compensated. The toughest struggle probably arose when the Aywin and Yonggom people (to the east, respectively west bank of Lower Ok Tedi) sued OTML in an Australian court in 1994 and settled the matter outside of court in 1996. Different from former agreements, OTML was committed to seek for a solution of the environmental problems, namely to build a tailings pipeline to a safe disposal site (Bige). Since OTML hesitated to build a pipeline, the following litigation has prepared.

Landowners do not act jointly throughout the region. If they did, OTML would really be in trouble. OTML distributes benefits in different ways, which are not transparent to the public. Thus, each landowner group may believe he is getting more than the rest, or suspect he is being cheated. Knowing, that there are just ten years left, for some the race is on to get a bonus.

6.5 Environmentalists

Environmental Protection is a constitutional obligation to the PNG people. But that is only in theory. Considering the difficulties, environmentalists are quite successful in maintaining public and political awareness in PNG.

More than in Germany, the promise of an investor to provide jobs will beat any ecologic objection. The strategy to win public agreement and political support is to claim environmental justice. Companies from developed countries should not be allowed to do things in PNG, that never would be permitted in their home country (fig.20-19).

OTML and government were not fair opponents towards environmentalists. Environmental information was scarce or one-sided, or released late. When the Starnberg Study was published, state representatives accused the Evangelical Church of discrediting the country and government. This is the usual fate of environmentalists. After the litigation in Australia, BHP urged government to create a law, forbidding PNG citizens from appealing to courts outside PNG. Recently, OTML has changed its information policy, many environmentalist groups have been hosted at Tabubil, to visit the mine. Many of OTML's studies are published on the Internet (but some of the more interesting papers were revealed by MPI). Whether this is a real change of mind or a clever public relations strategy will come clear in the course of discussions on the closure plan.

Gotcha, BHP.

LEAVING OUR ENVIRONMENT THE SAME WAY WE FOUND IT

BHP

Here is an advertisement that the BHP operators of the Ok Tedi mine run overseas.

This ad appeared in a magazine that people in developed countries would read....

Nice picture, BHP! Sweet words too!

But that's *not* how things look right now for *over 100 square kilometres* of forest below BHP's Ok Tedi mine. Those forests and river are not the same as BHP found it. In fact, they're dead.

Pictures are nice. Toktok is sweet.

But remember, BHP...

People in PNG don't just <u>read</u> about rivers...

They are our life.

Figure 20-19. This is a draft advertisement by environmentalists at Port Moresby, to be published in newspapers in PNG and Australia.

At Ok Tedi, the contracts were made and the damage cannot be made undone. To prevent further destruction by closing the mine will leave a bad situation. To continue for ten years without significant improvements in mine waste management would make things worse. The Mine Closure Plan in its present state will not change things for better. The only chance to improve something is to use the discussion of the Mine Closure Plan. The World Bank suggested that OTML and government should seek a scenario for an earlier ramp-down of mining and a ramp-up of rehabilitation. To environmentalists, all these options must be frustrating.

This is the position of the Environmental Law Centre PNG, NANGO, NGO Environmental Working Group, Pacific Heritage Foundation, Partners with Melanesia and Greenpeace Pacific on the closure of the Ok Tedi mine, August 1999:

1. River systems should not be used to dispose of mine waste

2. Environmental rehabilitation is very important for future generations. BHP should be prepared to post a bond [assessed by an independent expert] that will cover the cost of mine rehabilitation. All environmental damage should be cleaned up during the rehabilitation on the closure of the mine.

3. If mining at Ok Tedi continues BHP should:
    1. Deal with the overburden of the pit. It should not continue to be pushed into the Ok Tedi river.
    2. A new safe way should be found to deal with tailings, even if this means the mine should be smaller and new technology found to extract a greater metal content.
    3. BHP shareholders should bear the environmental cost of mine closure and should not be allowed to offload their environmental responsibilities onto the PNG taxpayer and the government of PNG.
4. If mining finishes early, BHP shareholders should carry any cost of social dislocation to the affected people of the Fly River by developing alternatives to ensure that those people have sustainable livelihoods in future. In any case, BHP should maintain its existing community, commercial, agricultural and infrastructural maintenance capacity until such time as local people can be considered to be self sustaining.

6.6 Church

New Guinea was a target of intensive Christian missions since it was taken as a colony. This mission, however, did not have the “confess or die”, character of the colonisation of Spanish America. Different churches had rather to compete for souls and convince them by additional benefits like health care and school education. In the Ok Tedi area, missions are the only institutions besides OTML that offer social services. In its closure plan, OTML considers the churches as stakeholders, which might take over facilities like health-centres and schools. Whether churches will welcome this, or regard it more as an additional burden, depends on the financial aid connected to the donation and the way OTML manages the transition.

Ok Tedi was recognized by the Evangelical Church as an example that church is responsible not only for the redemption of men but for the conservation of God’s creations. The issue was discussed broadly in Germany after the Starnberg Institute released its study on Ok Tedi, which was initiated by the Evangelical Mission Work. It was not related to production and consumption of copper in Germany but was mainly understood in the context of the development of third world countries.

In Germany, each church has a spiritual relation to copper because church bells are made of bronze. Many churches in Hamburg are roofed with copper sheeting. NA took the opportunity to improve its reputation, sponsoring the new copper roof of St. Peter’s, St. Jake’s, or fixing the bronze statue of St. Michael’s, all main evangelical churches. Therefore, the Evangelical Church is in a prominent but delicate position, in raising the question of clean copper from the consumer’s viewpoint.

6.7 Save the Elbe

"Save the Elbe" will not expand its activities to become "Save the Ok Tedi", nor will it give advice, or become a "stakeholder" in PNG. We introduced NA as a stakeholder to PNG. Our report on the trip to PNG may contribute to the discussion about the mine closure plan among PNG environmentalists. Still, the target of our work is NA, to make it a clean copper-smelter in Hamburg, from the mine to products to the recycling of products. Ok Tedi is but an example, showing that environmental problems within the copper production chain must not be exported to foreign countries.

7. CONCLUSION

It was demonstrated that well-prepared shareholder action will raise public awareness. The company's leaders could not ignore the problem. The tool of shareholder action was not developed in Germany, as it is in other countries, so our action may encourage others. NA may not claim to be sustainable and environmental friendly, but in contrast it has to be concerned that the bad image of mining may stain its image.

It is possible to open a discussion on a product like copper, where direct customers have no choice, in the same way as forest products. The Evangelical Church in Germany may raise the issue as an ethical question on public events like "Kirchentag" (their annual public convention).

The information gained on our travels were made available to environmentalists involved to the Ok Tedi issue. We will provide an up-to-date compilation of our own text, video-clips and pictures, mapping, Internet links, and documents of BHP, OTML, World Bank and MPI on CD-ROM and on WWW.

At present, we cannot assess whether the journey to PNG was a success or failure, since we are involved in a process that has not yet been completed. Since NA is susceptible to public pressure, this has to be applied, maintained for a long time and exercised by more stakeholders. Environmentalists, 3rd-world-groups, churches and ethical shareholders have to act coherently and take care that NA may not escape with either good-will declarations or alibi health projects. To allow NA be labelled "sustainable", requires a substantial economic change, namely not buying dirty ore from Ok Tedi, Batu Hijau (Indonesia), or elsewhere.

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A full report, including digital maps and video-clips, is available on CD-ROM (5 euros plus shipping costs)

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E-Mail: buero@rettet-die-elbe.de , Web: http://www.rettet-die-elbe.de

For information about Deutsches Pazifik Netzwerk see: http://www.pazifik-infostelle.de

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5

PRODUCT DESIGN AND USE

Chapter 21

METALS AND PLASTICS - COMPETITION OR SYNERGY?

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1. INTRODUCTION

Sustainability is a frequently used term, and often differently interpreted. The probably most popular definition is given in the report of the UN Commission under leadership of the Norwegian Prime Minister Gro Harlem Brundtland in 1987:

> "A sustainable development corresponds to the needs of the present-day generation without compromising the possibility of future generations to satisfy their own needs and to choose their own lifestyle"(Brundtland Report, 1987).

This definition does not describe the possibilities of a realisation of sustainable objectives but restricts itself on the desired effect of sustainable development. Since it is therefore only the generic description of objectives recognised as desirable, very different theories regarding measures and realisation are discussed among the most different interest groups.

Sustainability is an objective function to be worked towards to. Even if an unambiguous procedure for the manifold challenges arising from this target cannot be recognised yet, one can or should not wait, however, for a scientific, social or political consensus: already today sustainable actions are possible and necessary. Even now decisions are made daily and a well-directed decision orientated information procedure is already possible in most concrete cases.

This article sets realisation possibilities and consequences of material selection (here: metals and plastics) and their interconnected effects of products and processes over the entire life cycle (= from the mining of the resources over the manufacturing of pre-products and products, further over the utilisation to the recycling) into a particular light.

For the support of present or near future decisions of industrial questions the IKP, Department of Life-Cycle-Engineering of the University of Stuttgart, uses the method of "Life-Cycle-Engineering", which has been developed here since 1989.

A. von Gleich et al.(eds.), Sustainable Metals Management, 519-534.

In order to fulfil product sustainability from the view of Life-Cycle-Engineering, the evaluation aspects of a product regarding

1. technical feasibility,
2. ecological impacts, and
3. economic feasibility

must be necessarily included along the entire life cycle. Therefore Life-Cycle-Engineering is a further development of Life-Cycle-Analysis (LCA), which excludes the other two dimensions completely or largely. Already today this approach supports upcoming and sustainability-relevant decisions on the basis of quantitative statements and a transparent and comprehensible decision support (Eyerer, 1996). At present, this method is extended by the 4th dimension of "social effects" in order to allow another step towards the above definition of a comprehensive sustainability.

2. LIFE-CYCLE-ENGINEERING AS AN ASPECT OF SUSTAINABILITY

Aim of Life-Cycle-Engineering is the analysis and optimisation of processes, procedures, products and services under observation of the decision relevant quantities ecological profile, technical feasibility and economic sense of the measure (see also: http://www.ikpgabi.uni-stuttgart.de).

Based on technical and economic specifications, the ecological and economic effects of products, systems and services are analysed within Life-Cycle-Engineering along their entire life-cycle. Basis for the methodology of Life-Cycle-Engineering is an energy and material flow analysis for process chains, extended by economic parameters. In a subsequent evaluation step, different parameters can be measured and compared with each other. In Life-Cycle-Engineering complex structures are compressed to a few parameters.

Life-Cycle-Engineering therefore is known as an expansion of the procedure described in the standards of ISO 14040 ff. According to these standards Life-Cycle-Analysis includes establishing of goal and scope, the inventory, the impact assessment and the evaluation of the results.

Principle goal is the optimisation of the system (here: a product) regarding sustainability. If an approach was chosen which should completely avoid the environmental load from the production, one can assume that under present-day circumstances the production would have to be closed. This corresponds to a zero option leading to no product at all, which cannot be regarded as satisfactory if the product has a non-substitutable benefit (like food, mobility, living….).

If one assumes that a reduction of the environmental load from the production is a step towards sustainability, i.e. "only" the production is ecologically optimised, there still can nothing be said about shifting possible negative effects into other life phases of the product (example: decreasing environmental impacts of manufacturing an aluminium element - for example: a lighter, more thin-shelled one - can lead to higher environmental impacts in the use phase of the part since the life-span was shortened (unnoticed) and this element has to be exchanged frequently).

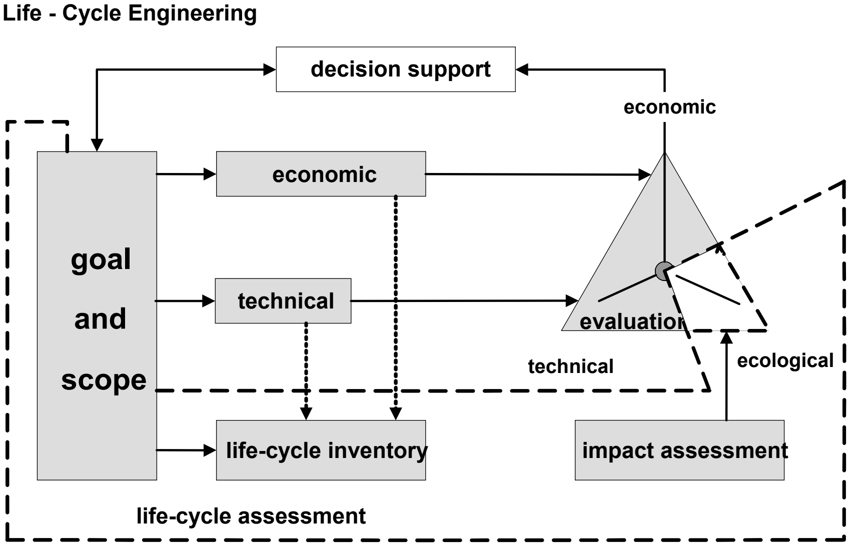

Figure 21-1. Life-Cycle-Assessment according to ISO 14040 ff as part of Life-Cycle-Engineering

Life-Cycle-Analysis was developed on the basis of such experiences. However, if the technical feasibility of the measures and the equivalence of the product alternatives in the multiplicity of their functions (specifications) are not part of the consideration, the measure will fail in practice.

If therefore the parameter "technology" is also taken into account (e.g. the process and the environmental engineer agree on the success of a measure), it can nevertheless fail since from an economic view point there might exist no chances for selling the ecologically and technically optimised product.

In the end, only an ecological product view, with explicit inclusion of the criterions "technical feasibility and equivalence" and "economic marketability" over the entire life cycle, can be considered a practicable approach towards sustainable products. With the optimisation of present-day products by Life-Cycle-Engineering one therefore speaks of an "optimal compromise". Since sustainability, as a paramount objective in optimising the present-day-situation, also has to handle manifold aspects, the approach of "optimal compromises" is probably the most effective approach in this case.

3. LIVE-CYCLE-ANALYSES BY MEANS OF LIFE-CYCLE-ENGINEERING

As described in chapter 2 the entire process chain with all relevant processes in the product life cycle is analysed. In this analysis the process chain is divided into meaningful and procedurally distinguishable sub-processes (example: sinter feed, blast furnace, steelworks, steel sticks, semi-finished-products street ...)

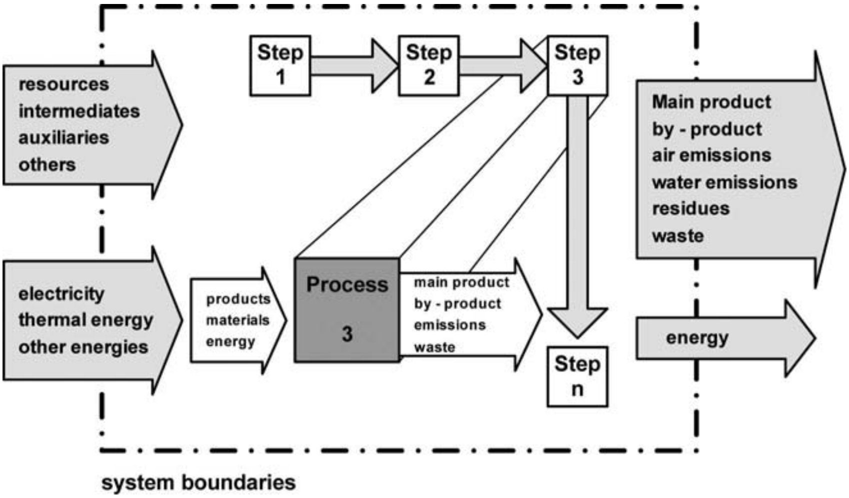

Figure 21-2. Division of the process network into sub processes

If the division into technically meaningful sub-processes was structured according to the product's life cycle, a closed picture of the process chain with all environmental and technically relevant masses and energy streams emerges. Using this structure the process network can be matched with economic data.

Parallel to the masses and energy streams, the costs for material, energy, work, machines, waste, and (potential) emissions, as well as the product and by-product value can thus be added.

Thus, the division of the life cycle into phases and steps is completed and all relevant inventory data is added, resulting in process networks that, on the inventory side, show numerous input and output items per each sub-process.

In a software (here: GaBi 4; see also: www.gabi-software.com) such process networks can become effectively visualised. Behind each process box stands another process network, leading back to the resource mining. The visualisation has found to be an important point in concrete projects and serves the following purposes: structural information presentation, transparency of the model, comparison of data (control), communication in the enterprise.

In the impact assessment the information from the inventory (consumption, emissions...) is then linked to ecological impact potentials.

The global warming potential (GWP), ozone depletion potential (ODP), summer smog potential (POCP), acidification potential (AP), eutrophication potential (EP), toxicity potentials (HTP, ETP), land use and resource consumption have become established and are used successfully. The inventory parameter "primary energy need" is usually included in the interpretation of the impact assessment.

This step is also to be understood as a compression or aggregation of at times some thousand single parameters into a manageable and interpretable number of effect potentials.

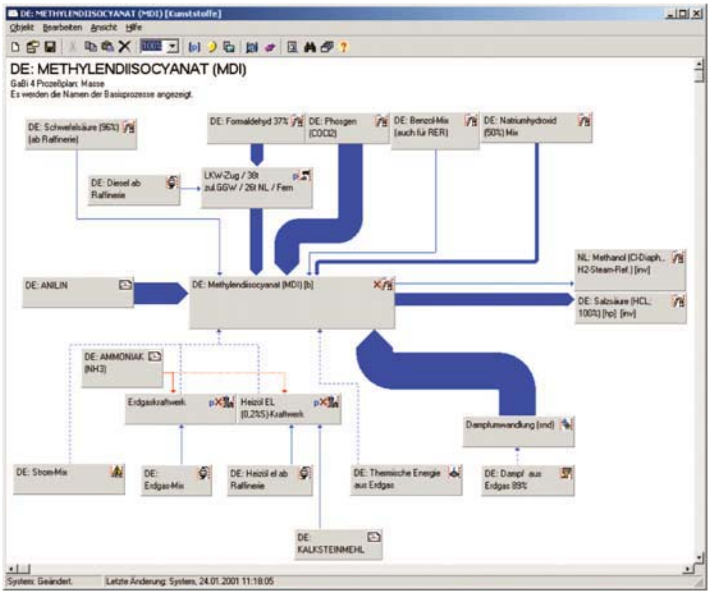

Figure 21-3. Visualisation of details of a plastics manufacturing process in the software GaBi 4 (Gabi, 2002)

The effect potentials are also sub-divided according to their geographical scope:

Global Criterions

Resource Consumption
Global warming (GWP)
Ozone depletion (ODP)

Regional criterions

Acidification (AP)
Toxicity (HTP, ETP)

Local criterions

Eutrophication (EP)
Land use
Summer smog (POCP)

This structure is meant for orientation only: according to substance and target medium overlaps are possible. The aggregation of the single parameters into environmental potentials is shown for the example of GWP.

According to the goal and scope of the assessment the results of the inventory and impact assessment lead to insights that can be taken as basis for decisions and measures.

The calculation of the main impacts and contributions from the inventory and/or the impact assessment is carried out next. It can be focused on individual processes, single life cycle stages, or the entire life cycle can be considered. This step also contains a check of the completeness of the impact assessment and the inventory and their agreement with the scope fixed in the goal and scope definition.

The evaluation of the results within the analysis represents the summary of the results according to a defined value system. This process is of inherent subjectivity since no universal value system is defined. Therefore maximum transparency and comprehensibility is also to be demanded for this evaluation (Eyerer, Reinhard, 2000).

4. EXAMPLES

On the basis of two examples it shall be clearly demonstrated in the following, how the above described method can be used for the analysis of different product concepts from metals or plastics. Are metals the "better" materials for the respective product or is it plastic? Which factors determine how much the sustainability of a material- (and hence product-) alternative can be realised?

4.1 Comparisons between plastics and metal at the example "air intake manifold"

The IKP balanced different air intake manifolds (Eyerer, 1996). Subsequently some results are presented.

Part of the scope were air intake manifolds from re-casted aluminium (different alloys) as well as such from polyamide 6.6 GF 35 because of which these variants are presented here. In the following the functions and technical specifications of components are presented.

Main function:

Supply of combustion air to a vehicle engine

Technical demands:

Mechanical: resistance to dynamic vibration (250 - 350 Hz, problematic, for example, with vibration weld)

Leakage: operation pressure 1bar, (vacuum), 5-10bar explosion pressure at misfiring

Thermal: temperature area (- 40°C to 120°C)

Chemical: resistant against oil, solvents, battery acid, refrigerant,
Optical: appealing but may not impair the mechanical demands

Material options:
PA 6.6 GF 35, PA 6 GF 30, cast aluminium

These technical specifications are transferred into information on used materials, masses, and manufacturing places (important for the assessment) in a close technical information exchange with the manufacturers.

For the use phase of the components, the fuel reduction equation combines the parameter “mass” with the parameter “fuel consumption”. A higher mass of the manifold therefore causes a higher fuel consumption due to a higher amount of transport mass in the use phase.

8-cylinders Otto engine:
Aluminium variant: Mass of air intake manifold: 8.2 kg
PA 6.6 variant: Mass of air intake manifold: 3.4 kg

4 cylinders diesel engine:
Aluminium variant: Mass of air intake manifold: 1.7 kg
PA 6.6 variant: Mass of air intake manifold: 1.2 kg

In order to be able to gain a product-specific assessment in the car manufacturing sector, the first step is the preparation of technical and economic specifications. Today both specifications mostly determine the selection of those materials and processes to be analysed in Life-Cycle-Engineering.

The second step then is the determination of boundary conditions and system boundaries (raw material supply, material manufacturing, processing, surface technology, utilisation phase, dismantling, recycling, waste disposal, energy supply, inventory data, energy content of raw materials, co-products, by-products, wastes etc.).

In the following the manufacturing procedure of the different air intake manifolds is summarised:

Aluminium air intake manifold

After the pre-processing the material stream leads to the recasting of the aluminium scrap metals under addition of salt and sub-sequent transport of the salt slag. Processing of the salt slag or its partial disposal with subsequent salt recycling is to be considered on a per-manufacturer basis. The alloying metals are added after the recasting. Per liquid transport the metal is brought from the recasting process to the car manufacturer where it is kept warm and where it can be further alloyed if necessary. For the smelting procedure a sand core is needed, the sand being bound with resins (phenol resin, isocyanat resin).

Impure aluminium scrap metals as well as swarf from the air intake manifold treatment are returned to the recasting plant.

After the utilisation the air intake manifold is shredded and thus returned to the recycling cycle. The primary energy need for the manufacturing of the air intake manifold is calculated to be approximately 326 MJ: approximately 35% for recasting, 45% for smelting and 20% for processing. The process chain is shown schematically in figure 21-4.

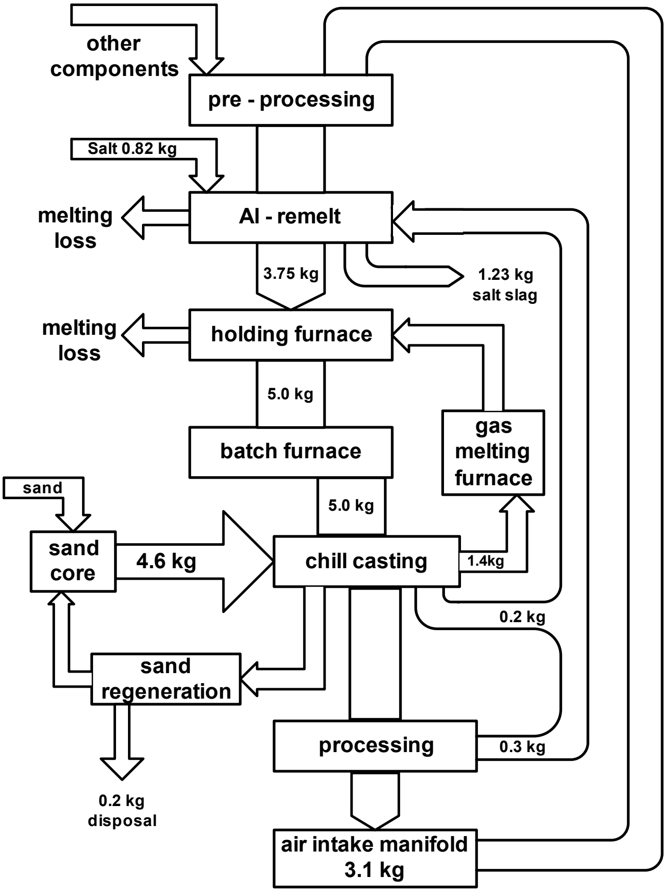

Figure 21-4. Material Flows of the aluminium air intake manifold manufacturing (Eyerer, 1996)

Polyamide air intake manifold

In the analysis of the supply situation for the polyamide 6.6 GF 35 of the air intake manifold in question, three manufacturing routes of three different raw material manufacturers had to be assessed. The most important basis materials for the polymerisation of PA 6.6 are adipic acid and hexamethylenediamine (HMDA). In principle, all three manufacturers produce adipic acid using the same process routes:

Steam cracker ⇒ benzene ⇒ cyclohexane ⇒ cyclohexanol ⇒ adipic acid

On the other hand there are three different routes for the HMDA:

Route 1:
Steam - crackers ⇒ butadiene
Natural gas ⇒ HCN ⇒ adiponitrile

Route 2:
Crude oil (Propylen) + natural gas ⇒ acrylonitrile ⇒ adiponitrile

Route 3:
Adipic acid + NH3 ⇒ adiponitrile

Route 3 has the highest adipic acid consumption: adipic acid is used as such and for producing adiponitrile.

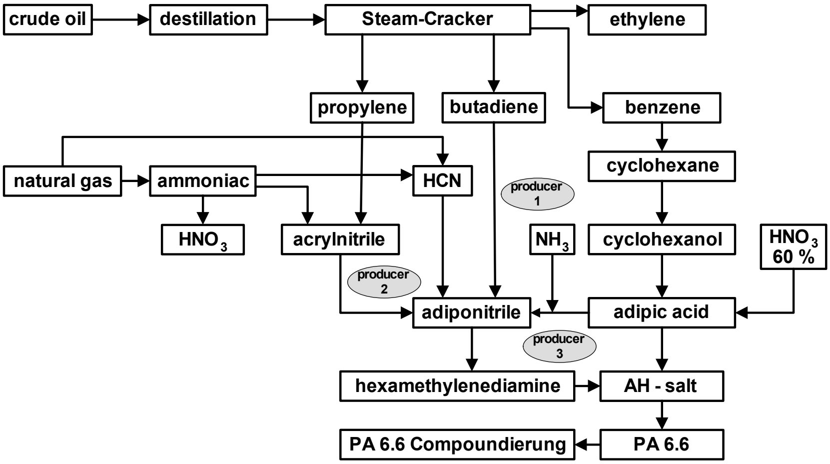

Figure 21-5. Manufacturing routes for PA 6.6 GF 35 (Eyerer, 1996)

In order to enable the inclusion of costs (economic component) into the consideration, the manufacturing costs (material - personnel - machine costs) have to be included in the analysis. The comparison consists of two plastic component manufacturing processes:

Table 21-1. Costs analysis in the manufacture for the example of PA 6.6 GF 35 component processes

	Manifold I	**Manifold II**
	6.6 GF 35	6 GF 30
Material costs	100 %	90 - 95 %
Energy costs	100 %	50 - 80 %
Personnel costs	100 %	65 - 90 %
Machine costs	100 %	70 - 90 %
Component costs	100 %	75 - 90 %
Example in Euro	12,00	10,00

Comparison of the variants

In the following some results of the different balances are presented: the energy consumption of the manufacturing and use phase of the air intake manifolds from aluminium and PA 6.6 GF 35 of a vehicle with 4 cylinders in comparison to a vehicle with 8 cylinders:

The energy consumption of the manufacturing and use phase in MJ are shown above the x-axis (driving distance in km).

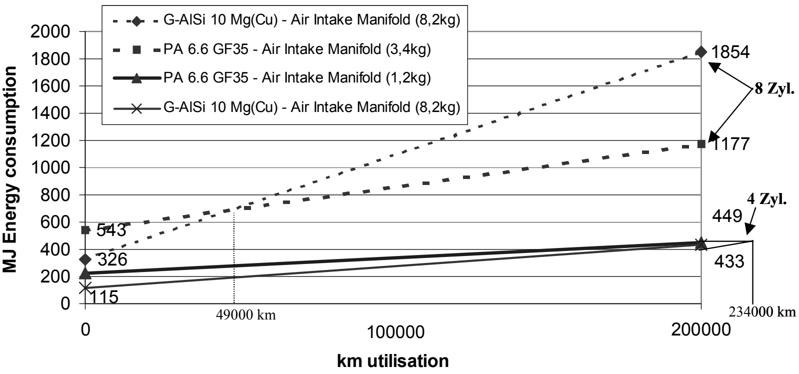

Figure 21-6. Energy need for the manufacturing and utilization of air intake manifolds from Al and PA 6.6 GF 35

For the case of the 8 cylinder vehicle (3.4 kg and 8.2 kg) the aluminium variant (diamond, dashed line) with 326 MJ manufacturing energy (start value at the left y-axis) shows less energy need in the manufacturing phase than the polyamide part (square, dashed line) with 543 MJ. However, this positive effect will be overcompensated in the use phase (dashed line) due to the higher weight of the aluminium variant. After the use phase the energy consumption for manufacturing and the fuel consumption add up to 1854 MJ for the aluminium variant and 1177 MJ for the PA variant (y-axis, top right).

In the case of the 4 cylinder vehicle (1.2 kg and 1.7 kg) a different picture emerges: the aluminium variant (triangle, solid line) with 115 MJ for manufacturing (y-axis, lower left) shows less energy demand in the manufacturing phase than the polyamide component (cross, solid line) with 200 MJ (y-axis, lower left). However, during the use phase the polyamide component does not succeed in converting the advantages of less weight into an energetic advantage after the utilisation (break-even is beyond the total life time driving distance of the car).

The details of the effects on the other environmental potentials should not be detailed here, (see: Eyerer, 1996).

Summarising this example it can be said:

- The plastic variants show higher energy need in manufacturing
- The aluminium variant (depending on the application) can have disadvantages in the use phase, i.e. the aluminium variant shows energetic disadvantages in the case of the 8 cylinder vehicle
- The recycling potential for Al is clearly better, which also leads to lower average expenditures in the manufacturing phase due to the use of secondary aluminium.
- Different technologies in manufacturing must be considered (polymer, polyamide routes, adipic acid, hexamethylenediamine, lost core / twin shell,... Al: anode type, cleaning step, recycling share ...), in order to be able to deduce the potentials of the material when using different manufacturing routes
- Polymer and Al-variant therefore show individual improvement potentials
- Generating general answers usually is not meaningful; depending on the system, the materials show different strengths!

4.2 Product development of the example “window frame”

Plastics and metals are not only used comparatively but also in combination allowing the use of synergies of the individual material strengths. The following example elaborates on this:

In the figures the metal component is shown darker (left: grey and black diagonally-striped, right: black) than the one made from plastic.

In the plastic construction, the PVC frame shows a low heat transfer coefficient. However, in addition the mechanical qualities of steel are required, lending the construction the necessary stability.

With the aluminium construction, the aluminium delivers the mechanical stability and the thermal insulation is given by insulation bridges made from polyamide 6.6.

This example is a classic one for the synergy of different materials like metals and plastic. The materials alone could not fulfil the complex demands, in synergy, however different construction variants are possible.

Consequently, the materials have different functions on the way towards sustainable products. Besides stability and durability as product qualities, the metals also guarantee good recyclability. The plastics provide a good thermal separation of cold outside air and warm interior, and thus reduce the heat energy demand.

If considering the ecological relevance of the constructions of Aluminium-PA 6.6 and PVC-steel (neglecting the use phase) the following picture emerges: (the size of the windows were both assumed to be 1.23m x 1.48m).

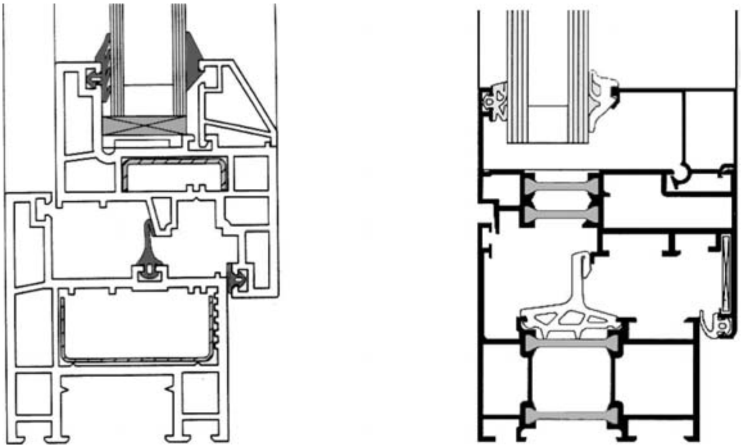

Figure 21-7. PVC-window with steel profile (left) and aluminium window with PA 6.6 insulation (right) (Baitz, Kreißig, 1997)

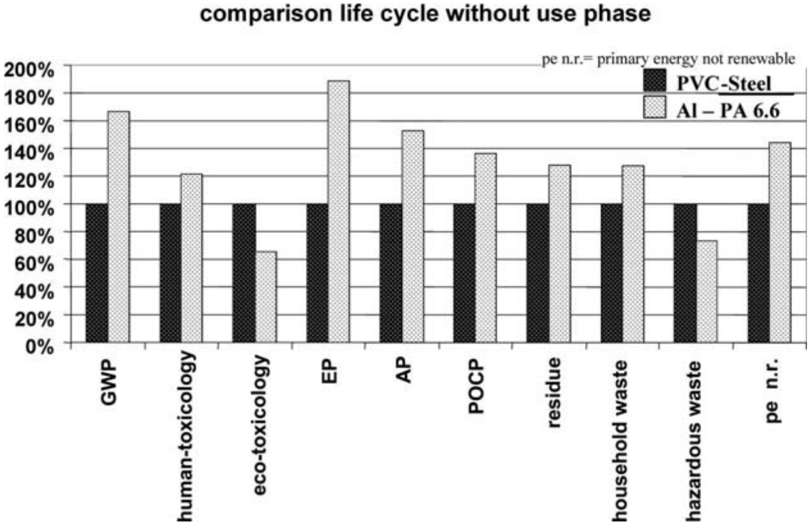

Figure 21-8. Comparison of the life cycle without the use phase, PVC-steel = 100%)

With the exception of the eco-toxicity and the amount of hazardous waste the aluminium-polyamide-construction performs less ecological over the entire manufacturing chain.

However, these differences level out if one includes the use phase and the recycling.

Table 21-2. Balance results of the aluminium window

aluminium-window 2000, 1,23m x 1,48m	aluminium profile	surface aluminium	polyamide profile	fitting composites	gaskets	insulation glass composites	assembly	transport	recycling
Global warming potential (GWP) [kg CO_2-equiv.]	153,5	12,2	48,8	8,5	8,3	52,4	7,3	2,1	-68,2
release of potentially toxic materials [kg crit. loaded body weight]	0,68	0,08	0,07	0,05	0,05	0,63	0,03	0,02	-0,31
potential damage to eco system [kg crit. loaded water]	4307	773	790	872	417	8214	296	128	-1988
eutrophication potentential [kg PO_4-equiv.]	0,028	0,004	0,034	0,002	0,002	0,035	0,001	0,003	-0,009
acidification potential [kg SO_2- equiv.]	0,406	0,045	0,047	0,026	0,027	0,295	0,014	0,018	-0,172
photo-oxidation potential [kg ethylene-equiv.]	0,028	0,003	0,018	0,001	0,012	0,016	0,001	0,003	-0,012
over-burden [kg]	408	56	19	32	25	24	34	0	-189
tailings [kg]	43	2	0	7	0	3	1	0	-22
houshold waste [kg]	3,03	0,33	0,40	0,14	0,22	0,53	0,14	0	2,67
hazardous waste [kg]	0,034	0,026	0,004	0,007	0,003	0,018	0	0	-0,013
nuclear waste [kg]	0,247	0,028	0,014	0,016	0,009	0,012	0,017	0	-0,116
non renewable prim. Energy [MJ]	2495	294	322	135	241	750	138	28	-1094
prim. energy from bio-fuels [MJ]	0	0	0	0	0	3	0	0	0
prim. energy from hydro power [MJ]	466	4	2	15	1	32	3	0	-232

The smaller frame of the aluminium variant increases solar gains through the bigger glass surface. This is mainly due to the better mechanical properties of the aluminium. Consequently, during the use phase, the aluminium variant (under the same conditions) requires less heating energy to compensate the heat losses since higher solar gains are achievable via the window surface. If one takes an east or west window with a given heat transfer of 1.8 W/ m2*K, and chooses the PVC-variant with 39% of the surface being the frame, a heat loss of approximately 25 kWh/m2 per heating period arises. The metal variant with a frame share of only 10% shows heat gains of approximately 20 kWh / m2 per heating period.

Table 21-2 and 21-3 show the results for a plastic and an aluminium window, respectively (Baitz, Kreißig, 1997). The complete report is available from http://www.window.de.

Table 21-3. Balance results of the PVC window

PVC-window 2000, 1,23m x 1,48m	PVC profile	steel profile zink coated	fittimg composite	gaskets	insulation glass composites	assembly	transport	recycling PVC	recycling metals
Global warming potential (GWP) [kg CO$_2$- equiv.]	43,1	28	10,1	4,6	48,2	10,8	2,2	1,2	-13,2
release of potentially toxic materials [kg crit. loaded body weight]	0,21	0,26	0,08	0,03	0,57	0,04	0,02	0	-0,13
potential damage to eco system [kg crit. loaded water]	15430	851	483	233	7547	428	134	-3728	-335
eutrophication potential [kg PO$_4$-equiv.]	0,01	0,004	0,003	0,001	0,032	0,003	0,003	-0,001	-0,002
acidification potential [kg SO$_2$- equiv.]	0,11	0,031	0,021	0,015	0,271	0,02	0,019	-0,007	-0,018
photooxidation potential [kg ethylene-equiv.]	0,026	0,002	0,001	0,006	0,015	0,005	0,003	-0,006	-0,001
overburden [kg]	145	39	26	14	22	35	0	42	-2
tailings [kg]	4	15	5	0	2	1	0	1	-7
houshold waste kg	0,89	1,09	0,29	0,12	0,49	0,34	0	3,22	-0,58
hazardous waste [kg]	0,079	0,003	0,031	0,002	0,017	0	0	-0,022	-0,002
nuclear waste [kg]	0,065	0,013	0,009	0,005	0,011	0,018	0	0,023	0,001
non renewable prim. Energy [MJ]	1036	282	116	135	689	166	30	-43	-111
prim. energy from bio-fuels [MJ]	0	0	0	0	2	0	0	0	0
prim. energy from hydro power [MJ]	7	6	3	1	30	2	0	2	-12

In order to be able to make reliable, quantitative and comprehensible statements on the optimisation potentials, detailed analyses are necessary even for such material-synergy-constructions as this one, in order to get a complete overview of the product life cycle and all influencing effects.

These examples show that the sustainability of products or construction from different materials with individual qualities can be optimised only in the context of the complete life cycle. It also becomes obvious that each material has individual strengths and weaknesses and the optimisation must target the construction level in order to identify the optimal synergy effects.

5. SYNOPSIS AND OUTLOOK

The most important key points arising from the topic of this article are summarised in the cornerstones:

1. Sustainability
2. Life cycle consideration and Life Cycle Engineering as well as
3. Metal and plastics in synergy or competition

The 5 main points are:

1. In most cases there is no wrong material
2. There are rather only sub optimal applications for materials
3. Technology, ecology and economics are to be taken into account. In the future, also social aspects will have to be considered (methods in development)
4. Life-cycle observations are essential in order to get a complete picture of the system and to avoid shifting problems into other life phases
5. Regarding ecological effects a number of different effects has to be included. Limitation to only one effect, for example CDE, leads to a shift towards other environmental problem fields (over-fertilisation, ozone layer depletion,..) (see figure 21-8 for example).

In order to move closer to the goal of sustainable products, procedures and services already today, the search for synergies and individual product optimisation is necessary instead of striving for a general material selection with only wholesale application-independent statements.

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Chapter 22

SUSTAINABILITY-OPTIMISED MATERIAL SELECTION AND PRODUCT DESIGN AT AUDI

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1. ENVIRONMENTAL COMPATIBILITY AS A HOLISTIC UNDERTAKING

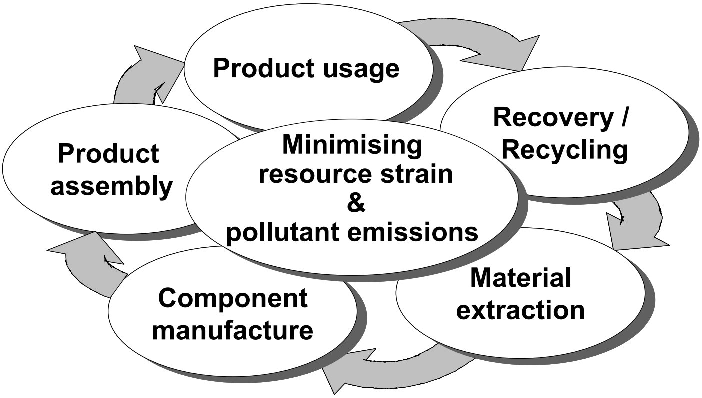


Figure 22-1. Improving environmental compatibility as a holistic undertaking

If a strategy to improve environmental compatibility is really to be effective, it has to meet holistic standards. By maximising efficient use of non-renewable resources and by minimising emissions of pollutants, the environmental effects have to be minimised for the entire life-cycle of the product, starting with material extraction and product manufacture, then product usage and finally to recycling for the next cycle – and/or disposal in as environmentally friendly a way as possible, cf. fig. 22-1.

A. von Gleich et al.(eds.), Sustainable Metals Management, 535-562.

1.1 Strategy of material usage for improved environmental compatibility

With the view of the objective of environmental optimisation in mind, entire product cycles of technical alternatives “from the begetting to the grave” are assessed at Audi. Utilisation of resources and also emissions into water, soil and air are analysed on the basis of material and energy flow inventories. In the case of environmental impact accounting for example, individual CO_2 emissions, nitrogen oxides, hydrocarbons and other substances are examined, and their detrimental effects – such as greenhouse effects – are summarised.

The efforts expended on such life cycle assessments are considerable. After gathering considerable experience from life cycle assessments on various issues, sufficient optimisation strategies with a specific direction in the field of automotive construction are however generally already produced from energy balances. Energy balances can be considered to be the symbol or the common denominator for pollutant emissions and resource strain. Undesirable emissions are still not at all approved, as legislative bodies generally examine these very closely. In comparison with life cycle assessment, energy balancing reduces the extent of analysis required for decisions with regard to products considerably.

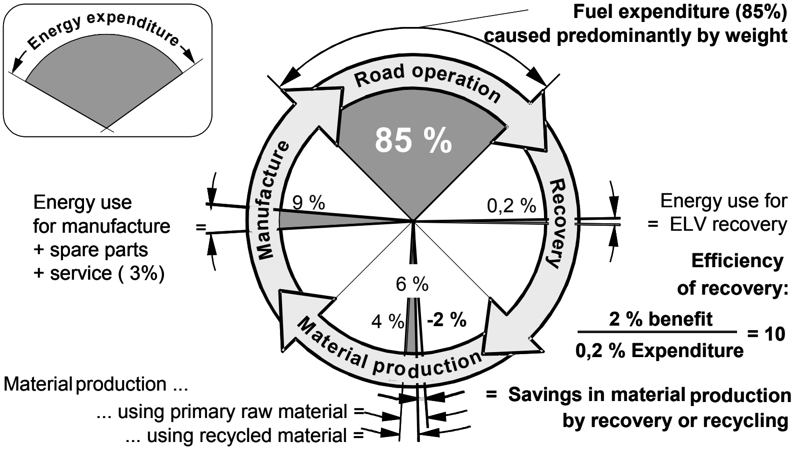


Figure 22-2. Holistic view on the basis of the energy balance of the life cycle of the Audi A3 over a driving distance of 200,000 km (Schäper as per IfE, Munich Technical University)

1.2 Potential for improved environmental compatibility

Figure 22-2 demonstrates the extent of the dark sectors as a measurement of energy consumption and the corresponding environmental burden in the various sectors of product life-cycle of a vehicle, such as the Audi A3. Some effects and correlations between driving mode, recovery and material production are illustrated in the following.

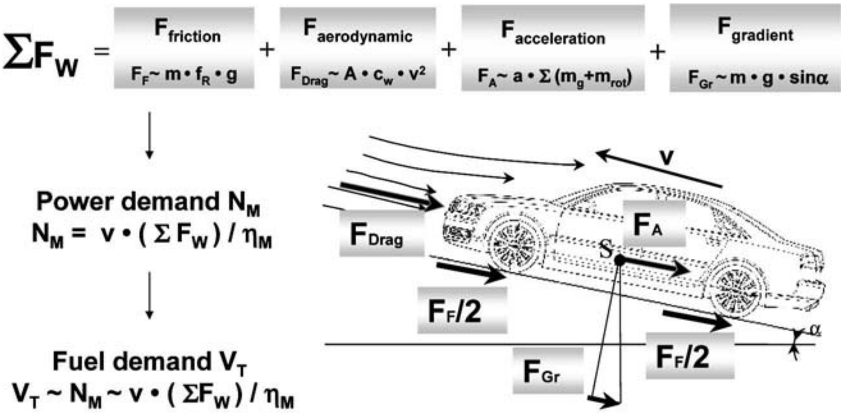
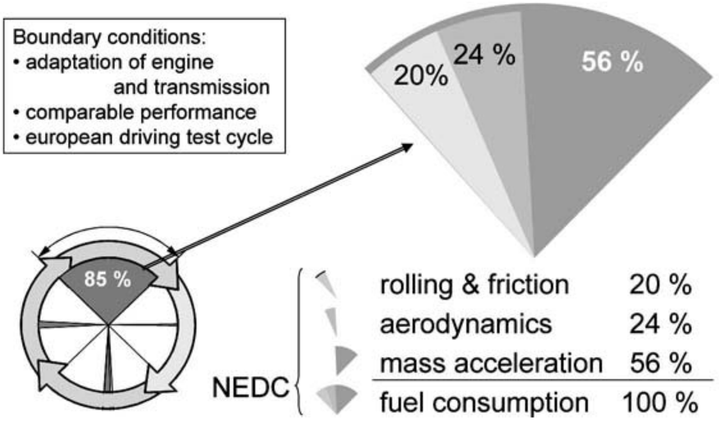


Figure 22-3. Influences on fuel consumption



A) Driving mode

The environmental burden caused by fuel consumption dominates the environmental assessment of the product-life cycle (cf. fig. 22-2). Improvements can be achieved by enhancing the efficiency of the drive system (η_M) and by reducing driving resistance (ΣF_W, cf. fig 22-3). Mass-related resistance accounts for more than half of all driving resistance, i.e. 56%. This ratio applies to the European driving cycle for vehicles, such as the Audi A3 (cf. fig. 22-4). Under driving conditions where acceleration ratios are more significant, consumption is correspondingly higher and their dependence on mass is even more marked. Analyses of the design margins demonstrate that the possibilities for influencing the vehicle mass are greater than, for example, in the case of aerodynamics or friction mechanics.

Alternative materials, design concepts and also functional theories are all part of the range of measures that can be taken in order to reduce mass and offer some opportunities that have not yet been explored.

B) Recovery

Recovery of end-of-life vehicles does represent a small, but useful contribution to improving environmental compatibility. Its level of effectiveness in particular is excellent: it only requires approx. 0.2% of the life cycle input. The bonus, calculated in terms of material production, is however 2%. The expenditure-benefit ratio is thus 10 (!) (cf. fig. 22-2). The illustration shows recovery practice in the near future, according to which organic materials are no longer disposed of in landfills, but rather are recovered for the purpose of energy utilisation. The question arises as to whether it is possible to further improve this excellent level of efficiency in recovery. Some have great expectations for mechanical recycling of plastics instead of energy utilisation.

One potential for mechanical recycling of plastics as compared with energy recovery does at least exist theoretically, because mechanical recycling already comprises the process-technological expense for plastics manufacturing for the second usage. Although the expenditure on mechanical recycling itself does detract from this advantage, it is nevertheless hoped that this is small and that the advantage will not thus be entirely used up. If we do not take into account the expenditure on logistics, separating, cleaning and also material losses, the theoretical advantage of recycling over energy recovery can be described using formula (1).

$$\frac{B_R}{NB_{eV}} = \frac{CE_{Hu} + (CED_{PSubstituted} - CED_R)}{CE_{Hu}} \qquad (1)$$

Formula (1) contains the following terms:

- B_R Benefit of recycling over landfill disposal
- B_{eV} Benefit of energy recovery over landfill disposal
- CED Cumulative primary energy demand
- $CED_{PSubstituted}$ Process-technological expenditure for that plastic which becomes substituted (!) with recycled material
- CED_R Expenditure for recycling process
- CE_{Hu} Net heating energy value

In the case of polypropylene formula (1) produces an advantage factor of 1.5 in favour of mechanical recycling – as an average in a range from 1.2 to 1.8 (Wagner 1997). The environmental advantage of mechanical recycling of plastics over energy recovery is thus not nearly so great as is frequently claimed. The EU Commission, in 1997 for example, in its explanatory memorandum for the compulsory recycling of plastics instead of energy recovery incorrectly assumed a factor of 10(!) (CEC 1997).

In actual fact, however, the environmental advantage of mechanical recycling of plastics without any market demand is frequently considerably lower than that environmental advantage obtained by energy recovery. This is because the minor advantage, which is even in theory only approx. 1.5-fold, is consumed by the unavoidable material losses in many process stages and also by the process-technological expenditures. Material losses are not taken into account at all in the theoretical assessment and the expenditures in the process may be considerably higher than is assumed in an ideal scenario. The advantage factor of 1.5 is thus easily reduced to less than 1 as a result, which means that energy recovery becomes more advantageous than mechanical recycling . Furthermore, feedstock recovery processes of organic materials offer both economic and ecological advantages as compared with mechanical recycling.

A major additional disadvantage is then noted if the recycled material is used in applications where it is used as a substitute for simpler materials, which can be produced with lower emissions and using fewer ecological resources. For the stated factor of 1.5 substitution of virgin PP by recycled PP materials is a prerequisite! Re-use in place of simpler materials, however, becomes very probable if the recycled material has to be produced without any market reference – and in some cases subsidised due to lack of demand. The EU Commission also predicted this scenario. However, surprisingly it did actually recommend downcycling in construction industry applications. Substitution of concrete by recycled plastic is one familiar example of this. From an ecological aspect, however, precisely these applications are not recommended, seeing as the cement for 5 to 10 concrete parts could be calcinated for the thermal energy content of one part recycled plastic material, thus saving expenditures on mechanical recycling. Substitution of wood or other bio mass based materials by recycled plastic materials would only be ecologically justifiable in certain special cases.

Market prices are created on the basis of supply and demand. If recycled materials are produced forcibly without any market reference and have to be subsidised, prices do not reflect the expenditures in ecological terms, which have to be invested in materials recovery. Low prices, which are created as a result of lack of demand and which are also kept artificially low as a result of subsidies, assist recycled materials in becoming economically viable in ranges of applications where simpler materials such as concrete or wood would have been adequate. Prescribed mechanical recycling quotas that do not have any market reference thus impede the otherwise desired internalisation of external environmental costs.

If mechanical recycling nevertheless becomes mandatory, in addition to the expenditure for meeting quotas, the expenditure for monitoring quotas also entail wastage, as they are not compensated for by any ecological advantage.

If a greater advantage than a factor of 1.5 in favour of mechanical recycling exists for other plastics, as is the case for technical thermoplastics such as polyamides, mechanical recycling should however not be imposed. For example, it is conceivable that mechanical recycling of polyamide parts in engine compartment, which were common in the mid 1990s, will become an economic winner. When these parts arrive at end of life vehicle dismantlers in a few years, the materials are also recovered without any prescribed quotas due to the high value of polyamide recycled materials. A prescribed quota would, however, upset the required equilibrium between supply and demand and would also stimulate downcycling in less exacting applications.

The expenditures which are ecologically relevant are also reflected in process costs. The ecological and economic objectives of recycling are thus closely interlinked. Unlike exacting quota requirements without any reference to the market, the following simple rule is thus fully compatible with the ecological objectives:

> *"In cases where mechanical recycling is successful in creating required products, mechanical recycling should also be implemented. In cases where it is not successful, at least the thermal value should be utilised."*

This simple principle applies especially under the sole viable prerequisite that the objective is sustainability and mechanical recycling is not considered to be a goal in itself. Exacting industrial systems engineering is also a prerequisite for energy recovery.

C) Comparison of lightweight construction and recycling

Even if the ideal design material permits both lightweight construction and material recovery, as is the case with aluminium, a conflict of aims may indeed exist between materials recoverability and lightweight construction, with the result that the correct priorities have to be questioned in some individual cases. The following rough estimation offers a point of reference to this end. Using the example of the Audi A3, a comparison is made of potential improvements that could be achieved, for the one part on the basis of mechanical recycling of the plastics and for the other part due to lightweight construction for the entire usage period. In the first instance the objective is the energy gain, which can be calculated by materials recycling of 15% of the plastics used in the Audi A3 instead of recovering the energy in these. In the second instance the objective is reduced consumption caused by the 15% reduction in weight, i.e. the advantage created by using an aluminium Space Frame instead of a conventional steel body in the European driving cycle (the percentages for plastics recycling and weight reduction are realistic values and by chance identical 15%).

According to figure 22-5, the potential for improving the environmental compatibility by mechanical recycling of plastics instead of energy recovery is only in the 1% range of that which is achievable by means of lightweight construction.

Even though the ecological potential of mechanical recycling of plastics is small, it should still be utilised and also complemented by "Design for Recycling". It is important to exploit opportunities for improvement. However, recycling does not have a priority over other recovery processes! Due to the interactions between the individual stages of the entire life cycle, care must rather be taken that exploitation of greater other potentials is not prevented by unjustified prioritising of recycling, which has very limited potential.

Under no circumstances may lightweight construction be impeded by the argument of insufficient materials recoverability, especially if other eco-friendly recovery alternatives are also available as an alterative to mechanical recycling or recycling in general.

A holistic approach thus produces the following simple basic rule:

> *"If automotive manufacturers can only choose between lightweight construction and mechanical recycling , then deciding in favour of lightweight construction is generally preferable from an ecological aspect."*

This simple principle also applies under the sole practical prerequisite that the objective is to optimise the life cycle audit and mechanical recycling does not become an end in itself.

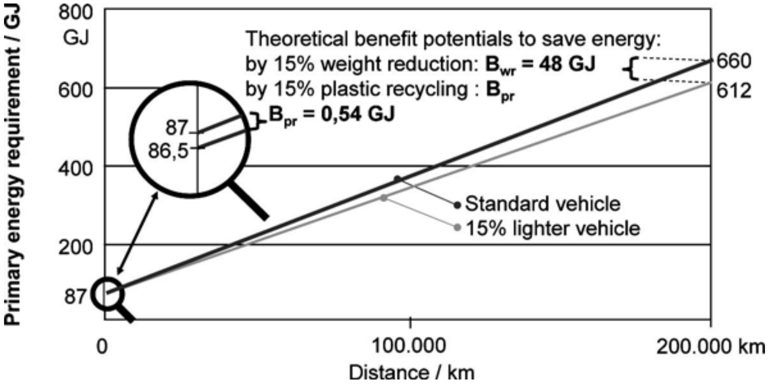


Figure 22-5. Cumulative energy demand (CED) for manufacture and use over 200.000km of the Audi A3 1.8T shows: the potential to save energy by weight reduction is nearly 100 times that of plastic recycling. Potential benefit relation B_{pr} / B_{wr} = 0,54 GJ / 48 GJ = 0,011!

2. LEGISLATION ON END-OF-LIFE VEHICLES

2.1 The European Directive on End-of-Life Vehicles and its implementation in Germany

European Directive 2000/53/EC on end-of-life vehicles (EP2000) has been in force since 21.10.2000. Its objective is to set out standardised minimum standards throughout Europe for environmentally sound treatment of end-of-life vehicles, while defining re-use of component parts and recycling as the main features of environmental compatibility. In order to impose recycling of non-metals, the Directive thus sets out quotas and limits energy recovery and landfill disposal, cf. fig. 22-6. The material ratio of the vehicle weight that is recovered or re-used must be increased to at least 85% by 2006 and to 95% by 2015. 80%, and later 85%, of this material must be recycled or re-used. Waste disposal is thus reduced to 15% of the vehicle's weight, and further reduced to 5% in the second stage. To ensure that the last holder is spared the cost consequences of end-of-life vehicle recovery, which is made more uneconomical by this provisions, at least a substantial proportion of the recovery deficits are charged to the vehicle manufacturer or the importer, respectively.

Implementation of the European Directive on end-of-life vehicles in Germany takes the form of the ordinance on end-of-life vehicles (BMU 2002).

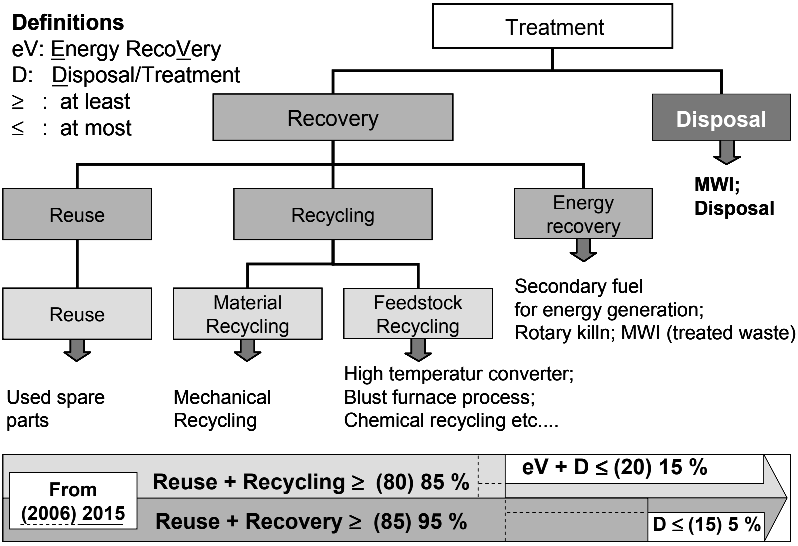


Figure 22-6. Quota requirements of the EU Directive on End-of-Life Vehicles

2.1.1 Obligations for vehicle manufacturers, importers and recovery management

The following obligations are placed on the manufacturer and/or the importer:

- securing of a comprehensive take back network for their own brand of end-of-life vehicles;
- take back of all vehicles as of 1.1.2007 at no charge for the last holder;
- design for waste reduction, recycling/recovery;
- obligation to provide information on:
  - pre-processing for dismantling, dismantling and re-use
  - development progress for waste reduction, recycling/recovery;
- quota achievability certificate within the scope of type approval;
- ban on the use of lead, hexavalent chrome, cadmium and mercury.

2.1.2 Recovery quotas

A) Requirements of end-of-life vehicle ordinance

The recovery chain economic operators are responsible for the material flows in the chain of recovery processes. The regulations governing this comply with three basic principles (BMU 2002), cf. fig. 22-7:

- Quota achievement is the responsibility of the entire recovery chain. Quota achievement and monitoring are thus not required in relation to specific vehicles and brands, but rather as a common feature for the different operators. Horizontal and vertical co-operation are thus possible.
- In accordance with the definition contained in the EU Directive, feedstock processes are also recognised as recycling processes.
- Metal recycling is an economic practice – because it is profitable. The average metal ratio is taken to be 70%. This also applies for individual cases where the metal contents may differ with the result that heavier vehicles do not receive preferential treatment and more environmentally sound designs are not placed at a disadvantage.

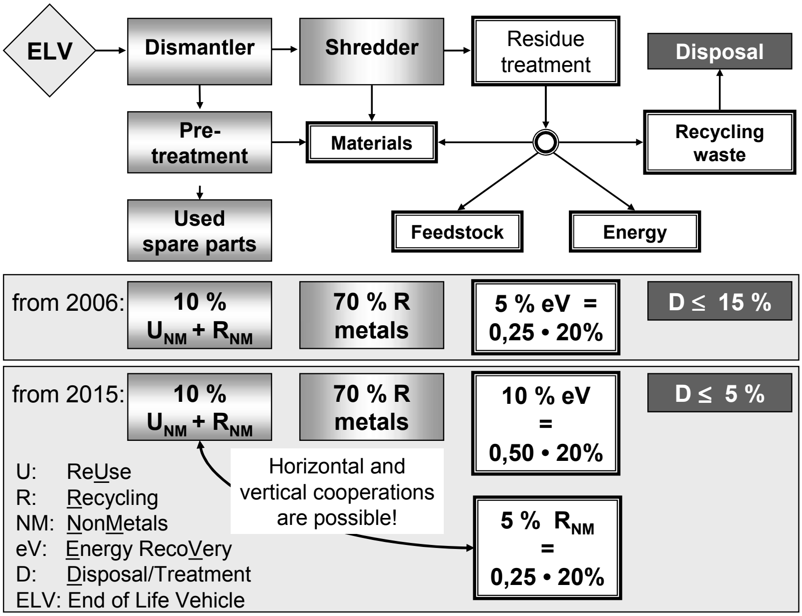


Figure 22-7. Quota achievement in accordance with German End-of-life Vehicle Ordinance

Consequently, only regulations governing the remaining divergences from the quotas contained in the EU Directive on end-of-life vehicles are required for recovery and recycling. In the course of dismantling 10% of the vehicle weight in the form of non-metal components should be removed and forwarded to recycling facilities or should be re-used. Dismantling 10% plus metal recycling 70% thus produce a recycling quota amounting to 80%, which will be compulsory as of 2006. Cf. fig. 22-6 for definitions of the different processes used as well as figs. 22-7 and 22-11 for information on material flows.

The remaining 5% still missing from the prescribed recovery quota as of 2006 as well as the missing percentages in quotas for recovery and recycling as of 2015 are to be achieved by processing shredder waste. As of 2015 half of the shredder waste will have to be recovered in the form of energy and one quarter in the form of recycling non metals. As far as non-metals are recycled over and above the required quotas by means of suitable post-shredding processes, an option exists to decrease the compulsory 10% dismantling quota for the dismantler. Inconsistently however, this important requirement does not apply to plate glass. Plate glass is to be removed as part of the dismantling process and collected by recycling systems, even if more suitable facilities exist after shredding.

B) Evaluation of quota requirements implemented in Germany from the car manufacturer's point of view

The Directive and the German End-of-life Vehicle Ordinance make it possible for material flows from the end-of-life vehicle recovery process to follow market trends. The current body of regulations thus distinguishes itself over other types discussed by a series of advantages, which include the following:

- development of optimum processes "from the begetting to the grave" is stimulated throughout the entire process chain;
- any ecological damage, especially by averting technical progress, is avoided; the reasons for this are as follows:
    - no (direct or) indirect penalisation of lightweight constructions, use of plastics, composites, bio mass based materials, recycled materials;
    - no compulsion to use unnecessarily complicated construction methods;
    - no compulsion to use a standard material, which would be unnecessarily costly in many cases;
    - unrestricted choice of material; furthermore the following principle can be followed: "every material in the correct place" including plastics, composites, bio mass based materials and recycled materials;
    - "every material in the correct place" also means: minimum ecological burden;
    - "every material in the correct place" also means: no temptation to waste ecological resources by recycling "on order", i.e. subsidised downcycling against market requirements.

The quota requirements contained in the End-of-life Vehicle Ordinance constitute a reasonable implementation of the EU Directive and avoid the conflict between recycling quotas and Kyoto objectives, which are entirely feasible in view of exaggerated prerequisites.

As the material flows used in recovery can largely follow market requirements, automotive manufacturers are not forced to make any additional financial provisions for lightweight construction and the use of plastics, especially composites and bio mass based materials (this correlation is explained at a later stage (cf. 2.2 B)). Ecologically practical concepts are thus not hampered, as set out by the explanatory memorandum contained in the EU Directive and as other drafts would have entailed for implementation.

But beside this rather positive evaluation from the car manufacturer's point of view one has to take in account the administrative problems of quota execution described below (cf. 2.2.C).

C) Quota achievability certificate as part of type approval

The quota achievability certificate becomes a part of the EU type approval Directive and is thus not subject to national implementation of the Directive on end-of-life vehicles. Standard ISO 22628 was developed for the quota achievability certificate together with a calculation diagram, which refers to the material quantities removed in the preparations for dismantling and, among others, also refers to the material composition of the vehicle.

Standard ISO 22628 represents a considerable achievement in comparison with other approaches discussed. The risk did exist that substantial limitations for lightweight construction designs would apply, especially for lightweight construction using plastics, composites and also bio mass based materials. The impeding mechanism is explained below (cf. 2.2 B). The ecological disadvantage achieved as a result of this would have exceeded the desired recycling advantage a hundred times over, cf. also fig. 22-5.

2.1.3 Effect of current recycling legislation on vehicle development

A) Promotion of recycling

In addition to the costs for his own component parts, the cost responsibility of the vehicle developer also extends to financial provisions in order to meet certain legal obligations. The developer can minimise provisions for "free" return of end-of-life vehicles by making his own design decisions, if he succeeds in making end-of-life vehicle recovery profitable throughout the entire chain between the end-of-life vehicle dismantler and waste disposal (cf. fig 22-11). Dismantlers are then interested in recovering vehicles and in purchasing vehicles from the last holder. The holder will thus not offer his vehicle for free return to the manufacturer's recovery point and the manufacturer is thus saved any additional expenses. Depending on the smaller risk the manufacturer can reduce his provisions, i.e. thus save costs.

There is an additional common interest of recovery operator and vehicle manufacturer, in terms of a profitable car recovery, due to the feedback of the economics of recovery on second hand car market prices. Higher second hand car market prices are a positive argument to buy new cars; cf. also fig. 22-8. This argument exists independent of legal quota provisions for re-use, recycling or recovery.

The developer is thus advised to keep the costs for the required action, e.g. draining of operating fluids, dismantling of window panes and large plastic components, as low as possible and to facilitate as much profit as possible from the recovery process. In favour of high recovery proceeds it is also recommended for the automotive manufacturer and his suppliers to stimulate demand for recycled materials and to have a preference for recycled materials over new materials, wherever these are functional and prices of recycled materials are competitive.

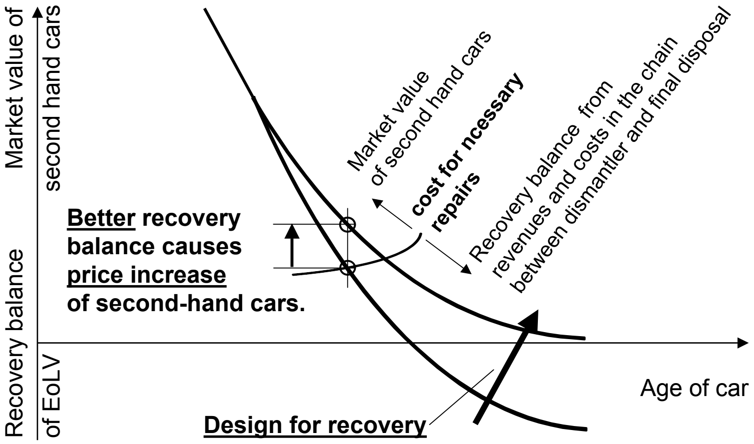


Figure 22-8. Congruency of car manufacturer's and ELV-dismantler's interest in the economic viability of ELV-recovery: market values of second hand cars are selling arguments for new cars – dependent on the economics of ELV-recovery

In this respect manufacturers have adopted the Design for Recycling as part of their corporate standards and they implement these standards in close contact with suppliers and the recycling industry. For Audi the following processes are used, for example:

- assessment of development alternatives also depending on their recyclability;
- boosting of recycling-compatible plastic fractions by means of
  - material labelling,
  - preference for materials and composites with improved recyclability,
  - elimination of materials that hamper recycling;
- application of know-how obtained from dismantling studies;
- preference for recycled materials over new materials even if costs are identical;
- lifting of universal bans on regenerated materials;
- use of recycled materials at a high level with regard to quantity and quality.

B) Duty to provide information on progress achieved

Automotive manufacturers and their development partners and sub-contractors also have to expend additional efforts on the duty to provide information concerning *progress in developments for waste reduction and recycling and/or recovery*. These efforts decrease, the higher the level of consistency is with which the required information is provided and documented right from the outset in the development process.

The legislative and administrative authorities are to set out details relating to the fulfilment of duties to provide information. As is the case with quotas, reasonable regulations are required in this area too. Concerning the limits and risks involved in quota monitoring please refer to Chapter 2.2.C*)* below.

2.2 Concerns about possible undesirable developments of recycling legislation

A) Risk of restrictive definitions of recycling and effectiveness

Equal status

- for recovery processes that require dismantling of components,
- with recovery processes that do not require dismantling of components.

This is a minimum prerequisite for an ecologically practical, sustainable solution for automotive recycling. This prerequisite is set out by the definition of the term *recycling* contained in Article 2 of the Directive on end-of-life vehicles (EP 2000). The key passage of the Directive states:

> *For the purposes of this Directive… 'recycling' means the reprocessing in a production process of the waste materials for the original purpose or for other purposes but excluding energy recovery….*

Feedstock processes are thus considered as recycling. They can be performed satisfactorily on the basis of shredder waste and therefore do not generally require dismantling of components.

An ideal, even better solution would even forego limitation of energy recovery – as was the case in the voluntary commitment that was applicable in Germany between 1998 and 2002 (FSV 1998). The reasons for this were as follows (Nürrenbach 2004; Schäper 1995 – 2004; Huisman 2003; Krinke 2003, Lirecar 2003; Jenseit 2003; TNO & TU Delft 2002; Brezet 1999; Wagner 1997):

- The frequently assumed ecological advantage of mechanical recycling as opposed to feedstock recycling or energy recovery does not generally exist, even theoretically
- The key advantage that can be achieved at all with shredder waste is achieved once it is no longer disposed of on landfill sites, but rather when the energy or feedstock recovery is utilised. This will be the case when the ordinance governing waste disposal comes into force as of 2004 in Austria or 2005 in Germany. On the other hand, prescribing more detailed recovery channels at most creates marginal additional advantages – if at all. In many instances the disadvantages outweigh the advantages.
- Energy recovery should be the appropriate form of recovery over the long term in many regions of Europe due to the lack of other alternatives and should create greater ecological advantages than mechanical recycling "on order" – which means mechanical recycling without corresponding market demand, subsidised by automotive manufacturers. However, made-to-measure treatment processes and correspondingly stringent plant engineering are a prerequisite for this.

- So, energy recovery is also not available for free at all. Pretreatment is a prerequisite for both methods of recovery, i.e. feedstock recycling and energy recovery. In these treatment processes, the expenditure is only slightly smaller – if at all – for the objective of energy recovery than it is for material recovery processes. Otherwise, the gate fee, as it is known, for material recovery processes will be lower than for the energy-related processes, maybe even proceeds can be obtained.
- Due to these arguments and because of the common interest of both the vehicle manufacturers and the recovery operators in a profitable ELV recovery (cf. fig. 22-8), opening of energy recovery does not signify the end of reuse, nor mechanical nor feedstock recycling, but the effort would be reduced and the administrative problems of quota execution described below would decrease (2.2.C) – in combination with better environmental performance.

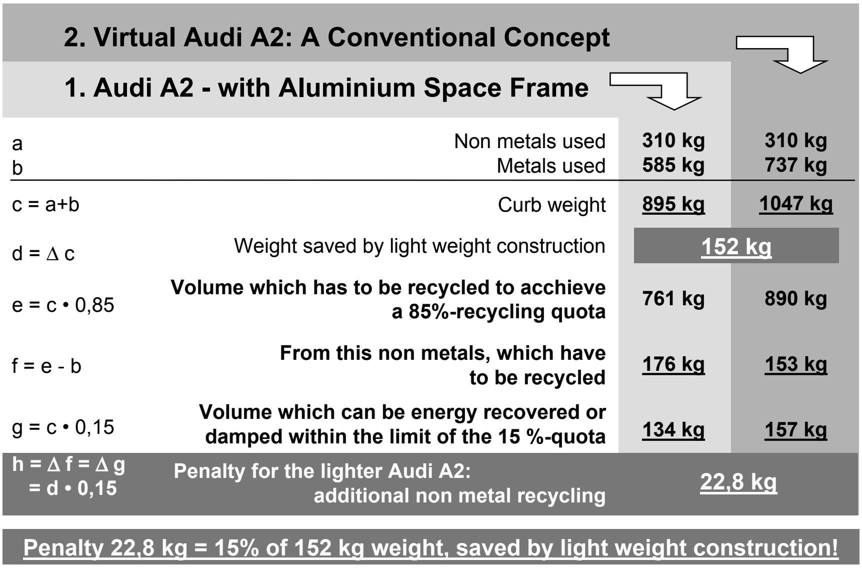
By 2005 a critical re-examination and, if necessary, correction of the quota requirements contained in Article 7 of the Directive on end-of-life vehicles are planned. This would provide the chance to place the different recovery processes on an equal footing, i.e. to eliminate the disadvantages of the unfounded hierarchy of recovery processes.

Some studies and some proposals presented by the EU Commission, however, do unfortunately demonstrate that the trend towards fatal prioritisation of mechanical recycling is continuing over and above other recovery methods. Instead of sensibly extending the margin for structural technical solutions for products and for free-market recovery processes by overcoming discrimination of energy recovery, the important recycling definition is planned to be restricted in favour of those recovery processes which require dismantling of component parts. It is occasionally suggested to provide the recovery processes with additional sub-quotas in accordance with the output/input relations. “Process efficiency” is another key word. These demands too can hardly create an advantage, as they ignore essential prerequisites for managing substance flows. Certainly, they would however multiply the efforts expended in many places, i.e. for process technology, logistics and monitoring (cf. chapter 2.2 C). By excluding common processes additional capacity bottlenecks would be created, to say nothing of the fact that the prescribed quotas would not be attainable at all. The quotas, e.g. 95% for recovery and 85% for recycling, were discussed and resolved against the background of the known processes and corresponding definitions. The quotas would naturally have to be adapted to new definitions and/or further sub-quotas – on the basis of corresponding large-scale tests and not on the basis of working hypotheses with questionable practical references. However, the spread of all data should principally be included in considerations and finally especially also in recycling regulations. Spread of data is unavoidable, cf. 2.2.C (Reuter 2004)!

Both measures – restrictive recycling definitions or introduction of process efficiencies – would have a similar unfortunate effect: car manufacturers would have to establish higher financial provisions. This would impede technical progress, which is certainly much more important, especially lightweight construction including the use of plastics, high-performance composites and bio mass based raw materials, as is shown within the chapter following.

B) Risks of weight-related quotas for mechanical recycling

It has been proven that efforts, which generally aim to give higher priority to mechanical recycling than to other forms of recovery, are not in keeping with a holistic approach. On the one hand, the ecological potential that is to be gained by mechanical recycling does not exist at all. Formula (1) shows an advantage factor, which is not equivalent to 10, as is frequently implied, but which is rather close to 1 (cf. Chapter 1.2 B). On the other hand, even if the advantage implied in mechanical recycling were actually to be achieved, it could not by far compensate for the disadvantageous effects of the increased weight, which occurs as a side-effect. This relation is explained in the following (Schäper 2004 – 1995; Lirecar 2003; Brezet 1999; Wagner 1997).



		1. Audi A2 - with Aluminium Space Frame	**2. Virtual Audi A2: A Conventional Concept**
a	Non metals used	**310 kg**	**310 kg**
b	Metals used	**585 kg**	**737 kg**
c = a+b	Curb weight	**895 kg**	**1047 kg**
d = Δ c	Weight saved by light weight construction	**152 kg**	
e = c • 0,85	**Volume which has to be recycled to acchieve a 85%-recycling quota**	**761 kg**	**890 kg**
f = e - b	**From this non metals, which have to be recycled**	**176 kg**	**153 kg**
g = c • 0,15	**Volume which can be energy recovered or damped within the limit of the 15 %-quota**	**134 kg**	**157 kg**
h = Δ f = Δ g = d • 0,15	**Penalty for the lighter Audi A2: additional non metal recycling**	**22,8 kg**	

Penalty 22,8 kg = 15% of 152 kg weight, saved by light weight construction!

Figure 22-9. Increased expenditures for non metal recycling as a “side-effect” on lightweight construction of 85% recycling quota. The example of the Audi A2

For two vehicle designs, i.e.:

- the Audi A2 with aluminium Space Frame body (vehicle No 1)
- and a virtual counterpart to the Audi A2 of conventional design, body weight × 1.66, otherwise identical (vehicle No 2),

the table contained in fig. 22-9 indicates the following:

a) the weights: metal ratio, non-metal ratio, total weight,
b) the quotas prescribed for the year 2015 by the Directive, i.e. at least 85% recycling and the maximum quota of 15% for the total comprising energy recovery plus disposal.

For the lighter vehicle (vehicle No 1) the 15% volume, which may be recovered in energy and/or disposed of, is reduced by 22.8 kg in proportion to the 152 kg lower overall weight as compared with conventional vehicles. 22.8 kg of non-metals thus become part of the 85% recycling quota and have to be recycled from lighter vehicles additionally over heavier vehicles.

If the quota specifications would be restricted to “mechanical recycling” instead of “recycling”, an additional compulsion to dismantle thus would be created. In accordance with the original explanatory memorandum of the EU Directive on end-of-life vehicles dated 1997 and some other more or less official initiatives, this restriction of the definition seems to be politically desired. The justifications for it are at the very least scientifically questionable; the consequences however give cause for concern. For additional 22.8 kg in the form of plastic components that have to be dismantled, in the dismantling curve we move far into the zone beyond 90 kg (cf. fig. 22-10), i.e. plastic component parts are dismantled in the 10 gram range. This is a costly process and is also counterproductive from an ecological aspect due to the considerable efforts expended for dismantling, separating, recycling and logistics.

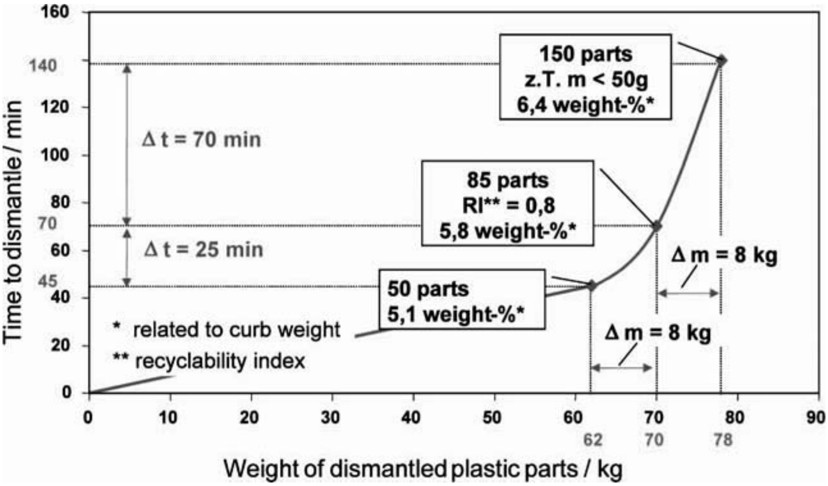


Figure 22-10. Dismantling of plastic components in end-of-life vehicles

Energy and feedstock recovery processes, which are performed after the shredding process, do however function without dismantling, thus avoiding such disadvantages. So the shredder waste can be prepared selectively for the intended recovery processes.

By introducing a compulsory quota for mechanical recycling, which in the case of plastics normally presupposes dismantling the component parts, it may prove to be extremely attractive for cost-conscious designers to replace non-metals by metals. Recycling of metals does not require any dismantling and is generally profitable. Metals thus reduce the manufacturer’s risk for free take back of end-of-life vehicles: the cost risk of meeting quotas decreases proportionally to the increase in metals weight.

Any comparison of competing design solutions in the product development process also entails cost considerations. As is the case for manufacturing and recourse costs, the developer is also responsible for provisions for the free take back of end-of-life vehicles. The combination of the obligation to bear costs and compulsory quotas for mechanical recycling thus for plastics would become at risk, in particular for high-performance fibre composites and for materials made from bio mass based raw materials.

Legislation thus could discriminate against technical progress, which represents the most important tool for managing the strategic mission of "minimising the overall burden", in favour of a comparatively ineffective recycling option. Strictly speaking, the combination of the *obligation to bear costs* with *compulsory quotas for mechanical recycling without market reference* in fact would produce the following questionable construction rule:

> *"If a volume is recyclable economically, it should be made as heavy as possible!"*

But actual legislation really opens the choice to fulfil recycling quota provisions by feedstock processes not needing component parts to be dismantled.

C) The limits and risks of quota monitoring

Vehicle manufacturers may be able to handle the recycling quota provisions which demand "recycling", not "mechanical recycling". The provisions are so flexible that the technical progress of vehicles construction is not impeded essentially. But car manufacturers are responsible only for quotas being fulfilled. They are not responsible for implementing and monitoring the quotas.

In contrast to the vehicle manufacturers, the economic operators and experts responsible for quota implementation and monitoring are prophesizing serious enforcement problems. The "Arbeitskreis Kfz-Recycling" (Motor Vehicle Recycling Taskforce) of the Lower-Saxony government commission "Environmental management and Closed loop economy " considers the current quotas unable to be monitored, and as a result of the problems it has experienced, it comes to the following visionary suggestion: *"In light of the problems that arise in connection with the targets from the perspective of comprehensive environmental protection as well as for the affected industry and the enforcement agencies..., the taskforce has worked out an alternative proposal for a pragmatic solution..., that does away with the differentiated recovery quotas. In its core, this proposal is based on the premise that in order to achieve the environmental objectives it is sufficient to ensure that the streams of recoverable waste/material in the required quality are fed into approved recovery channels that meet specific tough minimum requirements, analogously to a progressive approval process procedure, if necessary rounded out by just a few additional details. By combining waste- and process-specific requirements and making them homogenous throughout Europe, the enforcement problems can be solved without harming the environment and uniform competitive conditions can be established across Europe."* The taskforce for electro and electronics scrap recycling came to a very similar conclusion (Bertram 2003; Fricke 2003; NiSa AK16 2002)

Scientific findings as those from Delft University matches these experiences and conclusions: basing on a recycling experiment in Belgium with 1153 ELV the statistical spread within the chain of recovery processes between dismantling and reuse, and landfill, respectively, have been investigated. Findings and conclusions were as follows (Reuter 2004)

- Statistical spread within the recovery processes is so essential, that all older investigations about the item can be called irrelevant (spread until now has been neglected).
- Because monitoring respecting statistical spread cannot be achieved in the practice of recovery, monitoring results will be worthless.

Fig. 22-11 shows an impression of the complexity of material flows in recovery. The flows separate and intermingle at several points. Each actor in the recovery chain also operates using materials from non-automotive sources. The entire industry is also characterised by an extremely high level of flexibility, which enables it to follow optimally the market conditions of waste supply and the demand for recovery products and recovery waste, which frequently undergo dramatic changes. With regard to quota monitoring, it can be predicted that it might be entirely feasible to present different figures concerning the exact same process in a plausible way. The risks of abuse are correspondingly high.

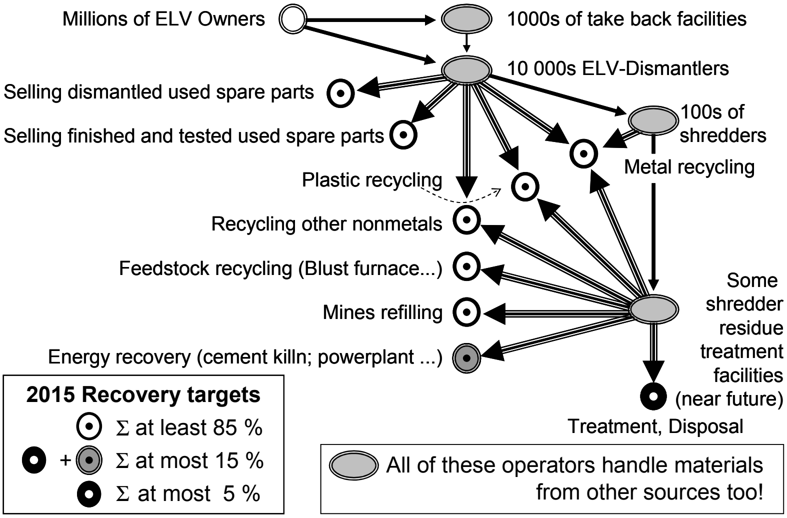


Figure 22-11. Substance flows in EU and end-of-life vehicle recovery

It must also be taken into account that the figures have to be established, collected and aggregated in many places. The values to be determined may not be just so accurate as a result of detection tolerances and also non-transparent or even unintentional errors, amongst other factors. Formula (2) describes in which bandwidth quota values Q may occur depending on the quota quantity Q_{target} and tolerance t of quantity detection – without taking into account exact statistical spread and probabilities. The reference quantity 100% applies to the weight of those vehicles for which a certificate of destruction has been issued.

$$Q = \frac{\{Q_{target} \cdot (1 \pm t)\}}{\{100 \cdot (1 \pm t)\}} \qquad (2).$$

Waste management experts state that tolerances of ± 5% both for the reference value and also for the quota values should not be unexpected.For *recovery as of 2006* and also for *recycling as of 2015* values amounting to 85% must be achieved. In accordance with formula (3), fig. 22-12 demonstrates the bandwidth for 85% quotas depending on the tolerance. Quota values Q_{85} can thus occur following a ±5% quantity detection tolerance between 77% and 94%!

$$Q_{85} = \frac{\{85 \cdot (1 \pm 0{,}05)\}}{\{100 \cdot (1 \pm 0{,}05)\}} \qquad 77\% \leq Q_{85} \leq 94\% \qquad (3).$$

More precise statements would require knowledge of statistical spread and probabilities. For the single process step this is achievable. But not for the complete chain of processes with its different technology variations and target products and separation and merging material flows, all that over the time schedule. So it was proven by the recycling experiment of TU Delft at the Comet Sambre shredder with 1153 ELV (Reuter 2004).

Administration responsible for quota implementation thus faces considerable problems as a result of this. For example, the status of penalties for “incorrect quota requirement” is not provable as it would be necessary.

D) Vision: legal framework in line with market requirements

So far, no serious counter-arguments were heard against all these arguments to make the existing Directive more flexible and attuned to the market as e.g. suggested in the visionary concept of the Lower-Saxony government commission. They suggest to replace the un-executable quota provisions by specifications and certificates related to equipment, processes and waste input qualities of the complete treatment chain. However, it is not sure at all that the EU Commission, Council and Parliament have the desire to follow this helpful suggestions.

Yet, the benefits of flexible regulations are obvious. Fears that the ecologically oriented recovery of end-of-life vehicles will be lost along the way are unfounded. Rather, there are many arguments in support of the idea that the actual objectives of waste management legislation can be achieved with more certainty, to a greater extent and also with less conflict if the regulations are more flexible. One must remember that their implementation would take place in countries with progressive approval systems. The EU waste disposal directive will have gone into effect and anyhow, there are up to several dozens of laws and regulations that accompany the stream of end-of-life vehicles and safeguard environmental protection and health protection (Schwald 2001).

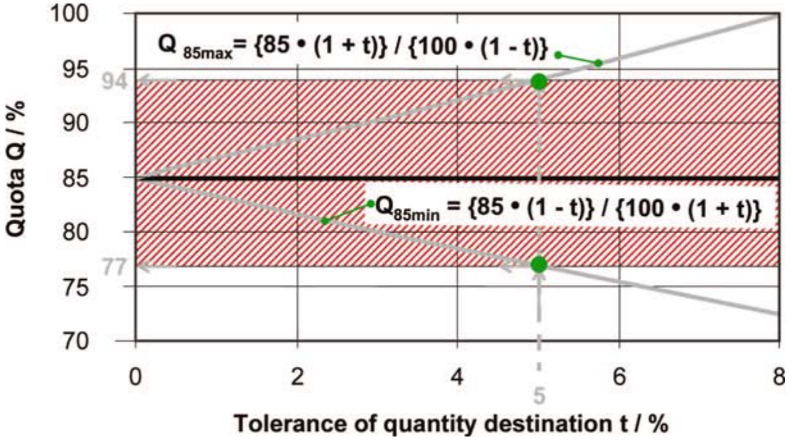


Figure 22-12. Values between 77 and 94% for the 85%-quota dependent on a +/- 5%-precision of quantity detection

The bureaucratic efforts required for proper enforcement would be reduced drastically. As of 2005 for Germany, the high costs of thermal treatment plus disposal will make recovery competitive. Waste will be disposed of only if justified. This eliminates the need for monitoring and control, so that the quotas and sub-quotas, which in spite of all efforts will be hard to determine, will become redundant. Moreover, with well-functioning processes, the respective quantities will become irrelevant as well and don't need to become controlled. Controlling could be replaced by data collection with small effort for statistical and planning purposes.

The underlying philosophy shows some parallels to the proven quality management systems, according to which quality is not achieved through checking, but rather through production processes. In analogy thereto, the entire chain of recovery processes would be gapless and characterized by the following features:

- certified partners in the entire recovery chain
- qualified recovery and disposal processes
- qualified material reception, with the supplier being responsible for his deliveries
- clear processes, requirements/conditions and responsibilities established by the process approval procedures and by contracts between operators
- consistent and comprehensible documentation by the process owners
- identification and elimination of shortcomings and causes thereof
- contractually agreed sanctions in case of violations.

Based on past experience, a system that follows proven quality management systems deserves more trust than the notoriously problematic quota systems, which rather reflect an outdated end-of-pipe way of thinking.

And the responsibility of the manufacturers would not be eliminated either, because in the event of an overall uneconomical recovery – which would be undesirable but not entirely unavoidable in light of tough standards for processes and materials – the manufacturer would still be required to enable the last owner to return his end-of-life vehicle free of charge for its environmentally sound treatment.

As a result, the car manufacturers and their suppliers would still continue to implement the rules of "Design for Environment" and "Design for Recycling" in the future. Moreover, the economic efficiency of the recovery chain would be improved leveling the playing-field. The expenditure for the obligatory activities of the dismantling facilities and the recovery of used spare parts and recycling-worthy plastic residues will be minimized. The information system for dismantlers IDIS will still continue to supply the necessary information.

Ultimately, the interests of the recovery chain's economic operators and the manufacturers are the same: high used vehicle prices, supported by a profitable end-of-life vehicle recovery, both constitute decisive arguments in the purchase of a new vehicle (cf. Fig 22-8)!

3. EXAMPLE OF MORE ENVIRONMENTALLY SOUND DESIGN: THE ALUMINIUM SPACE FRAME[1]

3.1 Combination of lightweight construction and recyclability in the aluminium space frame design

The energy balance of the Audi A2 over the distance covered also proves that lightweight construction has an ecological priority: Fig. 22-13 shows the cumulative energy used for manufacture and road operation for two vehicles, i.e. the Audi A2 with aluminium Space Frame body and a virtual counterpart of the Audi A2 of conventional design (body weight 1.66 times greater, otherwise identical). The statements contained in the figure are as follows:

- The greater efforts expended in manufacturing the Audi A2 aluminium body on the basis of primary aluminium is doubtless amortised in the first vehicle life.
- The amortisation range is approx. 55,000 km for the Audi A2 equipped with Otto engine. In the Audi A2 with TDI engine the aluminium body is amortised at approx. 85,000 km as compared with a conventional body – therefore likewise doubtless several times over the entire distance covered.

- The energy saved by aluminium recycling also cancels out the manufacturing disadvantage of aluminium-intensive vehicles compared to conventional vehicles.

The lightweight design of the Audi A2 is ecologically advantageous. The certificate of recyclability for vehicles with Space Frame structures and the eco-audit were not performed by Audi first of all on the Audi A2, but rather were already completed before the first Audi A8 was marketed in 1994. Equipped with a V6 engine, front-wheel drive and manual gears the unladen weight of the Audi A8 is 1530 kg. Metals account for 1115 kg, of which lead, copper and zinc account for 60 kg, ferrous materials 535 kg and aluminium 520 kg. 277 kg of the aluminium are used in the ASF body. Fig. 22-14 shows the sub-division into sheets, extruded profiles and castings.

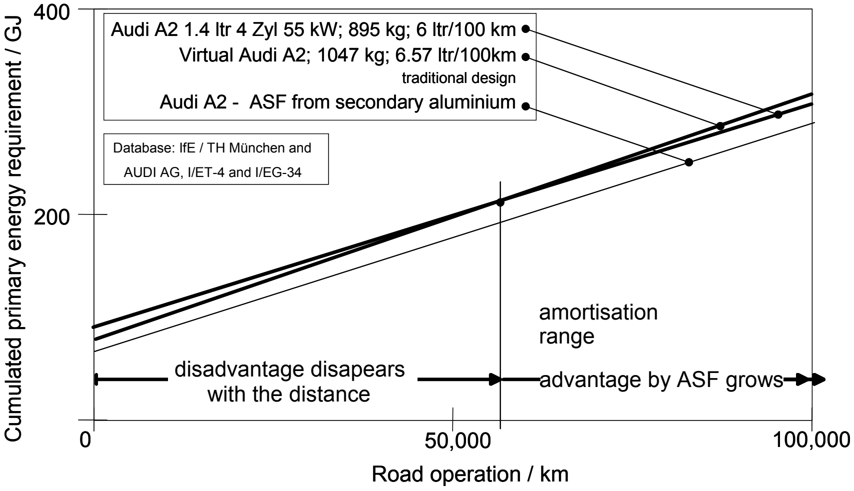


Figure 22-13. Primary energy use for manufacture and road operation of the Audi A2

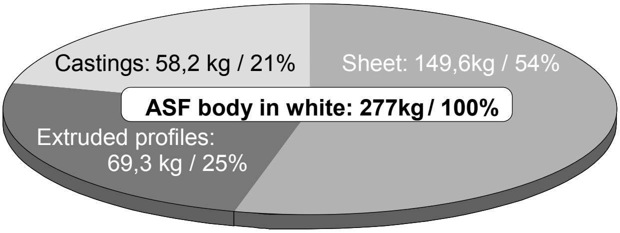


Figure 22-14. Aluminium fractions of the Audi A8 Space Frame body

3.2 Fuel economy due to lightweight construction and multiple amortisation of greater efforts expended on manufacturing in the course of vehicle life (Schäper 1996)

In conventional technology a counterpart to the Audi A8 should have 205 kg more in dry weight – equivalent to 13% – i.e. 1735 kg. In accordance with the *European driving cycle*, fuel consumption is approximately 1 l/100km less for the Audi A8 using Space Frame technology as a result of the weight saving. The audits show that despite the lower weight of the aluminium Space Frame body production initially causes higher emission burdens and requires greater energy usage than is the case for conventional bodies. In the course of the driving mode these disadvantages are however compensated for, significantly several times over throughout the life cycle. A graph of this is shown in fig. 22-14.

The audits show that despite the lower weight of the aluminium Space Frame body production initially causes higher emission burdens and requires greater energy usage than is the case for conventional bodies. On the road these disadvantages are however compensated for, significantly several times over throughout the life cycle. A graph of the energy balance is shown in fig. 22-13. Table 22-1 shows the distances for amortising (by lower fuel consumption) the higher ecological burden of the Al-intensive car body as compared to the steel car body. Depending on the quality of aluminium production, the amortisation sections are represented as bandwidths.

Only with regard to acidification no major advantage over conventional designs can be expected during the first life cycle, although a considerable advantage can be expected in terms of recycling. By using secondary aluminium, the disadvantages of manufacture as a whole are significantly reduced. For individual criteria, such as acidification, the manufacture of an aluminium Space Frame vehicle can even be better than a vehicle manufactured using primary steel.

Table 22-1. Distances for amortising (by lower fuel consumption) the higher ecological burden of producing the Al-intensive car body as compared to the steel car body (Eyerer 1995)

Type of environmental stress	Distance for amortisation ASF-/steel body [IKP Uni Stuttgart]	
	Primary Aluminium	Secondary Aluminium
Primary energy requirement	66,000 to 112,000 km	9,500 km
CO_2 emissions	14,000 to 62,000 km	< 0 km
NO_x emissions	100,000 to 210,000 km	21,000 km
Hydrocarbon emissions (NMVOC)	23,000 to 40,000 km	13,000 km
Greenhouse potential	15,000 to 75,000 km	< 0 km
Acidification potential	116,000 to 340,000 km	<< 0 km

3.3 **Recycling of the Audi A8** (Schäper 1995)

Recycling of the A8 is unproblematic in the existing infrastructure and using the usual vehicle recycling processes. Due to the fact that aluminium scrap obtains more than ten times the price of steel scrap, the A8 is logically more sought after by dismantlers and shredding enterprises than its conventional counterpart is. As is also the case with conventional vehicles, the various aluminium alloys are re-used for casting alloys after shredding. As casting alloys are produced from primary aluminium, if no scrap is available, recycling of the body scrap into casting alloys saves the equivalent quantity of primary aluminium – including related emissions and the energy to be used for this process.

Once Space Frame designs have become the standard in the automotive industry, it can be expected that more Space Frame scrap will accumulate than is required for the purposes of casting alloys. It will then be practical and necessary to separate the various alloy types used in the Space Frame body in order to recycle the extrusion profile and sheet alloys into wrought alloys and to recycle selectively the casting alloys back into casting alloys, cf. fig 22-14. This is possible using various processes before or after body shredding. The shredder alone cannot carry out separation up to now.

Before shredding, separation according to specific alloys can be carried out by "filleting". This principally entails separating the casting component parts from the body structure. (cf. fig. 22-15).

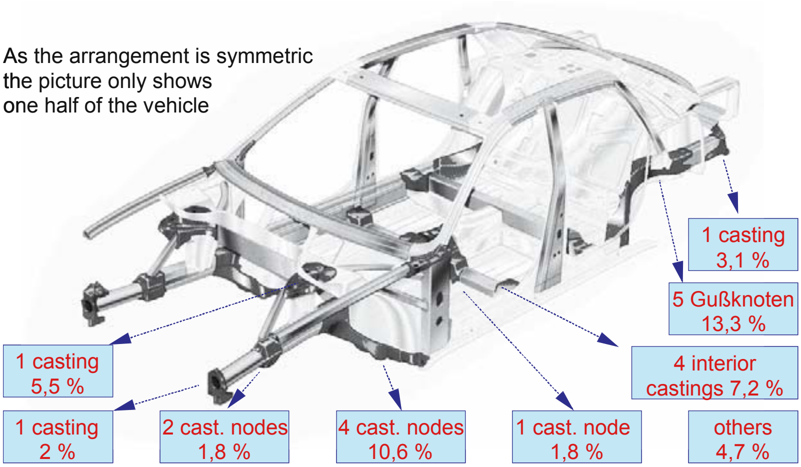


Figure 22-15. Distribution of cast component parts in the Space Frame structure

In case of complete "filleting" of the casting nodes, an addition of around 25% of new metals would be adequate in order to re-create a body sheet alloy from the mixture of wrought alloys. In spite of slight adherence of wrought alloys, the same component parts can be manufactured from the separated casting nodes without adding major quantities of new metals (around 3% – 5%).

If the aim is to reduce the efforts expended and thus the number of nodes to be removed, then an attractive result can still be obtained if one quarter of the nodes are left behind – effectively those that are more difficult to access: casting scrap can be used for the same component parts by admixing a small quantity of new metals and recirculation of wrought scrap requires the addition of approximately 40% new metal. The "filleting" processes would in fact comply with future processes of end-of-life vehicle recovery, (cf. fig. 22-16). The more interesting option, however, is continuous automatic separation of alloys after shredding. The tests prove that some processes which do not produce a complete separation are also entirely suitable.

For continuous automatic separating processes have to be used, which utilise other physical effects than those technologies installed so far in the shredder environment. The existing technologies essentially utilise differences of density, magnetic properties and electrical conductivity and do not work with regard to the aluminium alloys.

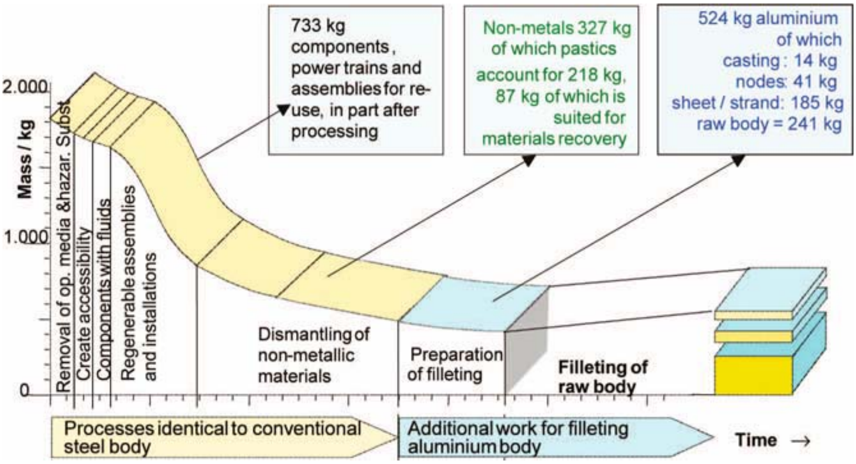


Figure 22-16. Time sequence for end-of-life vehicle dismantling and "filleting" of an Audi A8

There exist several promising processes for separating shredded aluminium scrap, e.g.the Hot Crush technology, or colour separation in accordance with etching treatments, or identification technologies using atom emission spectroscopy and also X-ray dual-beam detection. Combinations featuring automatic image processing could also be attractive. The effectiveness of the principles is demonstrated in the laboratory, in some cases also on pilot plants. However, a need for further development still exists.

As long as primary aluminium is still used for casting alloys, which will be the case for several decades due to the expanding market for casting applications, the separation of alloys used in vehicle bodies before and after shredding must also be rejected for ecological reasons. These efforts including the related emissions and the required energy should rather be saved by re-using the aluminium mix of castings and wrought alloys produced in the shredding process directly for casting alloys – instead of the primary aluminium that is otherwise used for this purpose.

3.4 The essence of lightweight construction using aluminium

Life cycle assessments prove the ecological compatibility of the ASF design: aluminium production does in fact entail higher environmental burdens than steel. These are more than recovered in driving mode or at the latest by means of the aluminium recycling process.

4. QUINTESSENCE

Hopefully, a more flexible, market-oriented concept will receive the necessary majorities in the competent political bodies, such that the environmentally superior car concepts may not be put at a disadvantage with the state of the art. The partly unclear correlations and arguments have so far, for the most part, been presented to the legislative bodies by the automotive industry. It is desirable that neutral parties, too, e.g. scientists, should become more involved in this area in order to improve acceptance of the prerequisites for technical progress. The more sustainable solutions, which are also required in the future, require more progressive technology!

NOTES

[1] Space Frame design: space framework made from a combination of sheet, closed extruded profiles and stiff cast nodes instead of pure sheet design; ASF stands for Audi Space Frame.

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Chapter 23

RECYCLING OF ELECTRONIC WASTE MATERIAL

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1. RECYCLING METHODS

If one compares the level of waste electrical and electronic appliances with other waste streams then this type of waste has a much lower importance with regard to quantity. With approx. 1.5 million tonnes this waste stream accounts for just a few percent of household rubbish. This type of waste gains significance with regard to its value and harmful substances content.

As ever our affluent society moves unconcerned towards the brink of disaster known as resource scarcity. If, for example, one considers the increase in metal consumption over the last 200 years it is clear that the point of exhaustion of some raw material sources, which includes non-ferrous metals, is not far off. And, among others, electrical and electronic products have a high value metal content. Value metals – that must be recovered from the large amount of impurities that constitute much of the metals.

The last sentence makes clear what the main focus of interest must be. On no account can recycling be undertaken at any price; the pros and cons of the different recycling methods must be balanced (see figure 23-1).

The reuse and recycling of products and their components must be of prime importance; so long as this is most advantageous to the environment with regard to the overall balance of the system (this must include what resources are consumed during the reuse and recycling of products and components). Only then can the reuse and recycling method be calculated that derives the highest possible level of material reuse.

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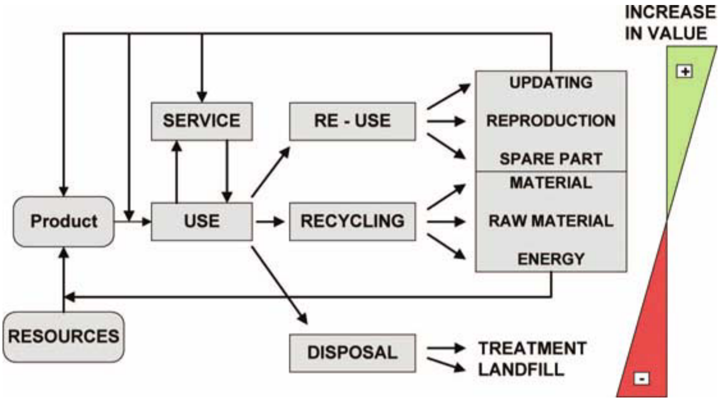

Figure 23-1. Increase of values through sustainability

By definition sustainability is the aim to meet the needs of the present generation without compromising the ability of future generations to meet their own environmental, economic and social needs. Thus the "most favourable" environmental case cannot be accorded the greatest importance, because serious conflicts of interest may arise with respect to economic and social needs. However, in the final analysis the environment gives us the "crash barrier" within which our society must operate.

If one assumes that no serious social disadvantages occur, it is preferable, with regard to minimising the entropy production of the recycling activities, to have narrow recycling cycles with long time horizons as long as this is not thwarted by the entropy production during the use phase. From an economic view such a strategic orientation is certainly the most advantageous as entropy production is always coupled with value loss.

Existing technological trends that support the development of a recycling economy can, however, run contrary to this aim. For example, miniaturisation can significantly save resources (see example) but inevitably renders the recovery of components for high value recycling more difficult.

2. ELECTRONICS AS A RAW MATERIALS SOURCE

Some non-ferrous metals are to a large extent already recoverable from material recycling. This trend will strengthen in future. An example:

> In 1999, some 305,000 tonnes of copper was recovered from primary raw materials in Germany, while some 391,000 tonnes was recovered from scrap metal and cupreous intermediate products. In addition, the recycling part of products manufactured from Cu and Cu-alloys in Germany in 1999 significantly exceeded 50%.

Non-ferrous metals have an especially strong presence in the electronics sector. Moreover, the material composition is subject to strong changes corresponding to technological developments.

Table 23-1. Occurrence of elements in electronic components [2]

Electrotechnical applications	***Elements***
Contact materials, conductors and conductor paths	*Be, Cr, Mn, Fe, Co, Ni, Cu, Zn, Rh, Pd, Ag, Pt, Au, Hg*
Solders	*Sn, Pb, Bi*
Dielectrics	*Ca, Sr, Ba, Ti, Mo, Ta*
Semi-conductors	*Si, Ge, P, Ga, As, Cd, In, Te*
Insulators	*B, Mg*
Foils	*Al*
Flame retardants	*P, Cl, Br, Sb*

It is a fact, however, that progressive miniaturisation results in a distribution that goes beyond the system boundaries of individual components whereby a clear material division via the separation of components (e.g. through the mechanical dismantling of printed circuit boards) is not possible (see figure 23-2).

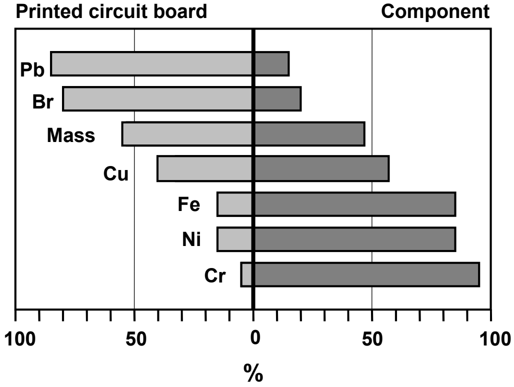

Figure 23-2. Distribution of the total amount of selected elements between printed circuit boards and components [3]

2.1 Precious metals

Precious metals have a wide application in the manufacture of electronic appliances. They serve as contact materials due to their high chemical stability and their good conducting properties. In essence they are gold, silver, platinum and palladium. Platinum group metals are used among other things in switching contacts (relays, switches) or as sensors to ascertain the electrical measurand as a function of the temperature. These metals are found in relatively large quantities in relay contacts (traditional forms of high current relays, switches such as network switches, micro-keys etc.), while reed relays (inert gas relays), in contrast, possess only thin contact layers (0.5 to 2.5 µm).

A particular importance is laid on the recovery of gold from electronic waste. This material is used extensively as a semi-finished product (wire-bond in chips, contact surfaces in relays etc) as well as in electroplating layers (contact strips on circuit boards, all types of connector plugs). Although the thickness is minimal (approx. 10 to 30 µm in wire bonds) its frequent application (up to 1g in personal computers) makes the recovery appear worthwhile. The amount of precious metals used in electronics, on a per appliance base, is declining.

This is due to the falling power consumption of modern switching circuits and the rising clock frequency (surface conduction). While the contact layer thickness in the '80s was in the region of 1 to 2.5 µm, in modern appliances today it is between 300 and 600 nm (gold wafer). Silver is used as a conducting material especially in hybrid technology (conducting paste) and in measuring and connection technology (BNC-boxes, other connection elements, high frequency conducting structures). It is also employed as a material in precision resistors and potentiometers. The recovery of precious metals can be carried out economically by dismantling companies using concentration techniques (dismantling specific components that contain precious metals). Separation plants then recover the precious metals by using material specific processes.

Appliances that have a high proportion of precious metals can be found in the following product groups:

- Data processing technology
- Personal computer technology
- Relay technology (BMSR, telecommunications technology, power technology),
- Radio technology (analogue, digital),
- Measurement technology
- Professional audio and video technology,
- Medical technical equipment, especially measuring and analysis equipment

The recovery of precious metals from shredder materials is problematic as the well-known dry-separation process lacks selectivity due to the high density plus, in this density regime, it is very energy intensive. It is, therefore, good sense to remove the components that contain precious metals at the same time as when the contaminants are eliminated.

2.2 Nonferrous heavy metals

Copper belongs to the most widespread materials used in the electric and electronic sector and is found in all mains-operated appliances as well as circuit boards and in components. Copper is used mainly as the conductor material in cables, wires, transformer windings, E-engines/generators and other electro-magnetic equipment as well as a construction material in the manufacture of deflectors, heat sinks, pipe materials and heat exchangers in refrigerators.

Copper recycling has become increasingly important as a result of the downturn in raw material reserves plus it can be easily used by copper mills to produce pure copper components. Pure copperplate or pipelines are removed during the manual dismantling of appliances and thus do not create additional costs.

Copper based composite materials and small components and hardware can be separated by mechanical processes (crushing, separating). Technically, copper recovery from cables can be ticked off as resolved. However, if this is achieved by employing cold-mechanical methods the residual insulation material remains problematic. There is still a need to develop effective methods to recover copper from printed circuit boards and micro equipment.

It should be noted that there is no decline in the use of copper in electrical technology and electronics. So, for example, modern electro motors offer considerable energy saving potential, but contain 25% to 100% more copper than traditional drive motors.

Aluminium is the most used construction material in electronics/electro-technology apart from copper. It can be applied in the form of pure aluminium as sheet metal or casting or in alloys. For the material recycling process, aluminium is interesting due to its value and its ability to be recycled.

The recovery of aluminium from used electrical appliances by dismantling is only worthwhile if the manual costs are reasonably offset by the yield. It is more efficient to recover components such as fasteners etc. by automated processes (shredding and sorting).

Appliances with large volume aluminium components can be found especially in data processing, large-copier technology and scientific measuring technology. In these appliances large volume constructional elements absorb vibrations:

- tape disk or magnetic disk drives
- high-speed printers,
- sorting machines
- precision measuring equipment

plus large savings are achieved by using cast aluminium frames:

- copiers,
- printers

and they also conduct heat (all types of cooling surfaces):

- power electronics,
- refrigerating plants.

The recovery of aluminium sheet mostly occurs during the dismantling of chassis or casing parts at the same time as contaminants are eliminated and does not incur additional costs. Alloy types should be kept separate to guarantee high grade recycling.

2.3 Dismantling

The treatment of electronic waste is orientated around its harmful substances content, reusable componentry and elements as well as the amount of recyclable valuable materials. (see figure 23-3). The current normal treatment methods and processes of electronic waste range from the stripping (manual dismantling) and crushing (shredding) of used appliances to the separation of valuable materials, which are passed-on to recycling companies, and residue products that must be sent for final disposal.

Moreover, in relation to the composition of the appliance and types of componentry the identification and elimination of harmful substances in each phase of the treatment is incorporated. In this respect manual dismantling is very important as it constitutes an essential prerequisite for componentry recycling.

The separation of valuable materials and the reduction of harmful substances that result from the dismantling of main components are carried out by dry-mechanical, wet-mechanical, chemical, thermal and thermal metallurgical processes. These processes are applied individually and in combination.

Where it is economically viable or environmentally unavoidable, electronic waste is pretreated during disassembly with respect to special contaminants, components and valuable materials. In connection with such pretreatment it is good policy to define appliance groups that have specific treatments in common.

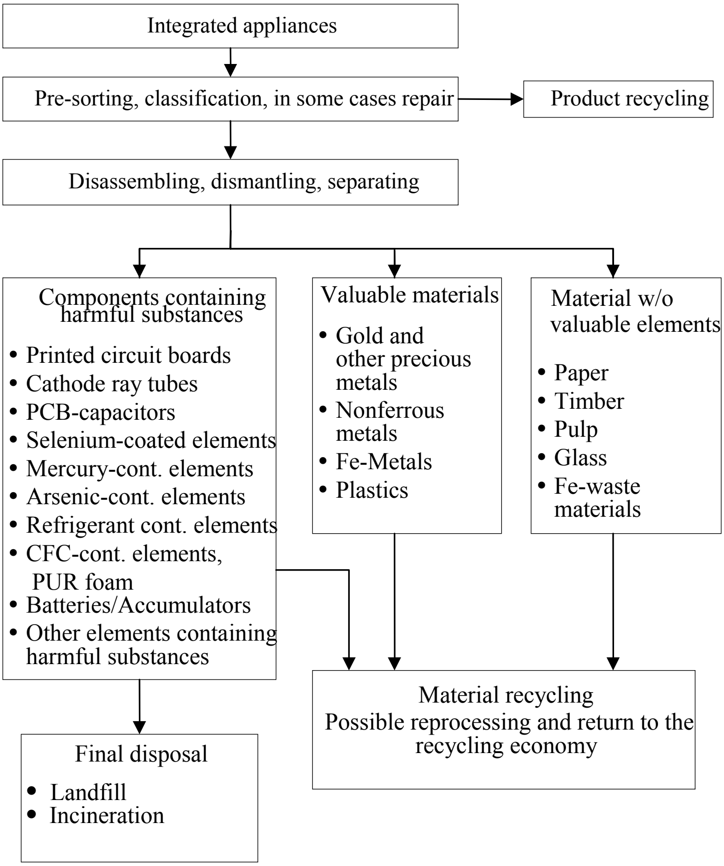

Figure 23-3. Appliance group specific treatment methods

Material group specific treatment methods must be integrated herein, since as a rule most electronic waste components contain harmful substances that impact their material processing.

Electronic waste components are seen as matter containing harmful substances if they contain environmentally relevant constituents and require special treatment or have to be disposed of as special waste. The specification is conducted according to componentry and elements that are described below. In addition the characteristic harmful substances and treatment methods are highlighted.

In essence, the relevant components are:

- printed circuit boards
- cathode ray tubes
- PCB capacitors
- Selenium-coated elements (printer drums, rectifiers),
- Mercury based elements (fluorescent lamps, switches),

- elements containing arsenic (luminous diodes),
- refrigerators (CFC-based internal coolants and insulating foam),
- batteries/accumulators and
- other elements that contain harmful substances.

A specification according to heavy metals or flameproof plastics has not appeared useful to date as these fall into a broad category.

Printed circuit boards with electronic component assembly, the so-called flat modules, form the central components of electronic appliances. Flat modules account for approximately 3% of total electronic waste. A rough estimate of the amount of circuit board waste in Germany is currently between 150,000 to 200,000 t/a and rising, if one also takes into account the electronics from the motor sector.

With the help of analytical-chemical examination methods (sample preparation in granulators and centrifugal mills, use of energy dispersion X-ray fluorescence analysis, atomic absorption spectroscopy etc) the composition of flat modules can be determined and the complex composition of the materials verified.

The most frequently used plastics in flat modules are phenolic resin and epoxy resin (glass fibre or paper laminated circuit board base materials and compounds). An entire range of thermoplastics (PA, PE, PI, PMMA, PP, PS, PC, PUR, PVC, ABS, etc.) are used as component jackets, plug casing or insulating materials. Thermo-gravimetric methods determine the proportion of plastics in circuit boards to be up to 20 – 30 wt%. The high level of plastics ("ignition loss") alone prohibits the disposal of this material in conventional landfill sites, according to waste disposal legislation, and as organic material requires careful and legally correct handling of emissions when such materials are used in conventional processes (copper mills). It is well known that a material mix of halogens (mainly from PVC and flame retardants) plastics and heavy metals has a high propensity to form dioxins and furans.

The recyclable used appliances are mainly disassembled with relatively high manual cost in the following major parts:

- casing (metal, plastics, composites)
- hazardous materials (accumulators, batteries, condensers, mercury relays, oils, fats),
- structural components for reuse,
- relays, transformers, motors
- cathode ray tubes,
- copier drums
- printed circuit boards,
- plugs and plug connections,
- cables.

The level of dismantling is determined by the selectiveness and impure materials tolerance of the down-stream crushing and separation processes and last but not least by economic factors.

To date, manual dismantling workshops are mostly individual operations equipped with simple tools (screwdrivers, extracting tools) and sometimes also rotary machines. Automated dismantling is still in its infancy. This is of course mainly blamed on the fact that there are almost no appliances on the market whose special design permits automated dismantling. The only exception to date is telephones, where there is a large number of similar old equipment.

The identification of certain components (e.g. those which contain harmful substances and those which are directly reusable) can be eased, where applicable, by component lists or instruction cards respectively. In this connection very old appliances or those manufactured outside of Germany present problems.

The separated appliance parts and main components are stored in suitable containers for further treatment.

2.4 Procedure for material separation

Reference, in particular, to the VDI Association of Engineers' regulation 2343, page 3 should be made for details and the technical procedure of the entire structure of the mechanical preparation of the electro(nic) components. Basically it can be established that a satisfactory treatment of electronic waste by mechanical means is only possible with a correspondingly high cost. Table 23-2 clarifies this. The table compares the degrees of disintegration of two different kinds of electronic waste compounds and the final disintegration of the assembled printed circuit board. The disintegration method comprises a three-phase technology, with crushing, grading, magnetic separation and nonferrous-sorting in each phase.

Table 23-2. Degree of disintegration when crushing solid components with shredders [1]

	Compound 1			Compound 2			Inserts		
	Total weight in %	Free ratio in %	Degree of liberation in %	Total weight in %	Free ratio in %	Degree of liberation in %	Total weight in %	Free ratio in %	Degree of liberation in %
Copper	22.9	21.3	93.0	4.4	2.8	63.6	0.4	0.2	50.0
Steels and Ferrite	55.5	52.9	95.3	51.4	47.8	92.9	41.7	41.7	100.0
misc. non-ferrous	4.6	4.1	89.1	30.8	29.6	96.1	36.1	19.2	53.2
residuals	17.0	16.3	95.9	13.4	12.3	91.8	21.8	14.8	67.9
	100.0	94.6	94.6	100.0	92.5	92.5	100.0	75.9	75.9

Source: P.Koch, R. Kasper: P.Koch, R.Kasper, Zerlege – und Aufbereitungstechnik für Elektroaltgeräte und Elektronikschrott, Mineral Processing, 1996, Volume 5

2.5 Crushing

Crushing is regarded as the preparatory stage for the further separation of the main components by manual dismantling and is realised by hammer mills and shredders. Cutting mills and granulators are particularly good for crushing elastic materials.

Components containing harmful substances are crushed in environmentally sealed plants with the aim of sparing landfill sites. It must be taken into account with regard to all crushing methods that all the material contained in the appliance to be fed into the machine will be spread equally over the crushed appliance as well as the equipment (contamination). So as to avoid this as far as possible, the dismantling of components containing harmful substances before crushing is indispensable.

Experience shows that the degree of the disintegration for electronic products with complex structures is just not satisfactory with two-phase procedures.

2.6 Sorting and grading

Dry-mechanical and wet-mechanical methods can be use for sorting (separating particle compounds in different groups of matter) and grading (separating matter into at least two size groups). They can be used together or combined with magnetic and electrostatic procedures.

The **dry-mechanical sorting and grading** is conducted after the crushing stage using vibrating screens and drum sieves as well as air separators. Sieves and screens separate particle compounds into two size groups. Air separators are particularly well suited for the separation of nonferrous metal compounds from nonferrous metal-plastics compounds.

Wet mechanical sorting and grading is primarily based on density differences to separate matter and is effected using float-sink methods (separation of plastics compounds and plastics-metal-compounds) and hydrocyclone methods (separation of plastics and nonferrous metal compounds).

Magnetic and **electrostatic separation procedures** are used to separate metals and non-metals. Magnetic tape or magnetic drums serve to segregate ferromagnetic metals (iron, cobalt, nickel).

Compounds of electrical conductors and non-conducting materials are segregated by eddy current separators, which are particularly suitable for separating out nonferrous metals (cooper, lead, tin, zinc etc.).

Electrostatic procedures (e.g. via a corona drum separator) use the different electrostatic chargeability and conducting ability of various materials and are particularly good at separating plastics with the same density from insulators and conductors as well as segregating metals.

For commercial production the relevant procedural steps are strung together in an operational process as highlighted in figure 23-4 as a typical example of existing plants.

A float-sink separation process using magnetic fluids is in development that is destined for the separation of high density non-magnetic material compounds. This procedure that does not require any separation energy and which operates with regenerable separation fluids comes with a low equipment and energy cost, such as for example air separation plants. The test also stretches to identifying PCB-capacitors.

Note should be taken of the high operating costs of dry-mechanical or wet-mechanical treatment methods. The electrical energy requirement is around 1 MWH per tonne and the wear on the crushing tools is naturally considerable.

In addition, the individual steps of the crushing and sorting create a vast amount of dust. Therefore, wide-ranging measures to de-dust by encapsulation, extraction, filtration and cyclones are necessary.

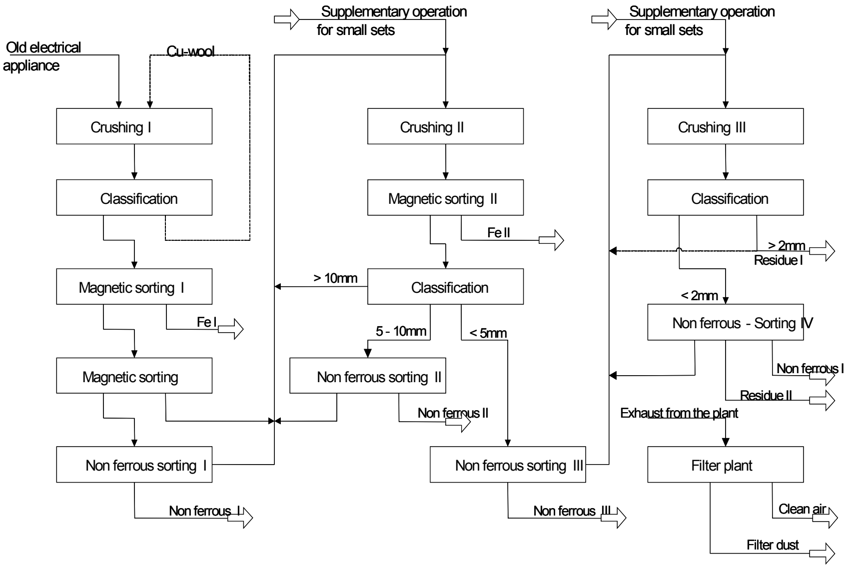

Figure 23-4. Main operational chart of the ECG separating plant in Goslar [1]

2.7 Chemical procedures

State-of-the-art wet-chemical procedures are used in combination with electrochemical procedures to recover metal, especially copper, nickel alloys, tin/lead-compounds and precious metals from mixed-metal granules. All non-metal components (plastics, glass fibre etc.) remain as non-recyclable materials.

2.8 Thermal procedures

Modern thermal processes such as a pre-stage to recycling raw materials and effectively eliminate harmful substances, as for example pyrolysis and hydrogenation, are in varying development stages with regard to electronic waste.

There are still no investigative results for the hydrogenation of plastics in electronic waste.

Chemical structural change is helpful to degrade harmful substances, such as halogen-organic compounds, and to counter the problems surrounding the variety of plastics found in electronic waste. Pyrolysis, i.e. thermal breakdown via the exclusion of atmospheric oxygen (figure 23-5), in suitable operating areas (T > 650 grade Celsius, Duration > 45 minutes) can achieve an extensive chemical uniformity (over 90% of all residual organic connections are reduced to aromatics [5]) and can also significantly ease the separation of metals and plastics. Experience on a commercial scale is already available with regard to the pyrolytic treatment of printed circuit board materials.

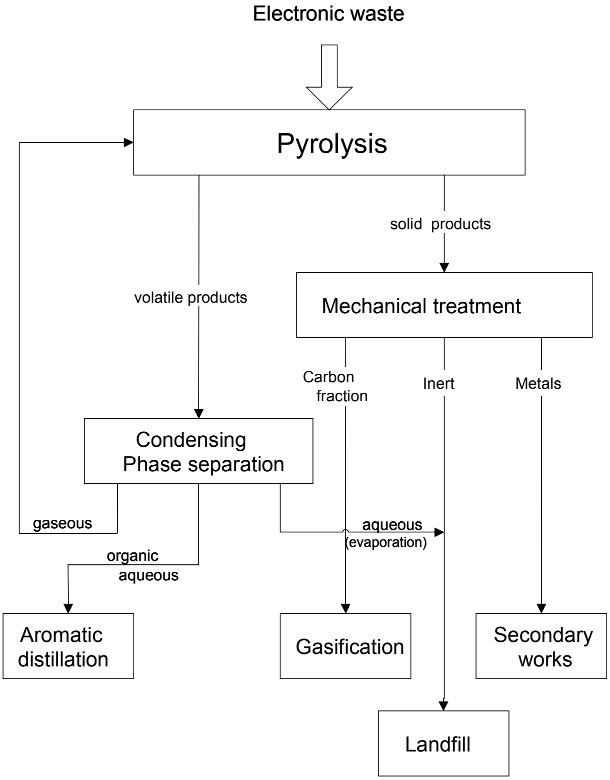

Figure 23-5. Material flow diagram for pyrolysis to degrade electronic waste

The transfer of this procedural principle to general electronic waste is currently being examined within the framework of a research project. As with all other thermal procedures, the complexity of secondary chemical reactions should be observed, as they result in the decomposition, modification and synthesis of compounds. Particular care must be paid to the recombination processes of halogen-organic compounds.

The incineration of electronic waste components (e.g. small appliances dumped in dustbins) is partially uncontrolled due to the incineration of household rubbish, which raises the proportion of harmful substances. Whereas a targeted disposal of non-recyclable components, which contain harmful substances, is carried out by special refuse incineration. This is not applicable for the recovery of metals contained in electronic waste. Attention should be paid in particular to the high industrial expenditure required by operators to achieve acceptable emissions retention in accordance with 17. Federal Clean Air Act (Bundesimissionsschutz-Verordnung – BimSchV).

Clearly cost-effective conditions are derived only from a drastic restriction of the exhaust stream to just meet the requirements. This occurs for example in the new development of the Velmede metal foundry. Here electronic waste is directly processed in a newly developed high temperature-melting furnace, i.e. without melting in a copper bath. The melting of the electronic waste, the incineration and the afterburning of the resulting gases is all effected in the melting furnace. Downstream waste gas cleaning fulfils the requirements of 17.BimSchV.

2.9 Industrial coupled processes

The above comments make clear that the main aim is to keep the waste gas stream as small as possible and to treat electronic waste in a special plant until such a point that a secure separation of harmful substances in the required bulk is guaranteed. After which available industrial processes can be implemented for the further treatment of metal compounds, in particular thermal-metallurgical procedures such as have been used for some time for metal compounds and metalliferous material. This includes the procedures of precious metal separating plants, steelworks and nonferrous metalworks.

The available combination of thermal chemical metal recovery through coupling the processes of copper smelting and the treatment of the "by-products" such as zinc oxide and precious metals through zinc refining and precious metal separating plants respectively is technologically mature and profitable (see figure 23-6).

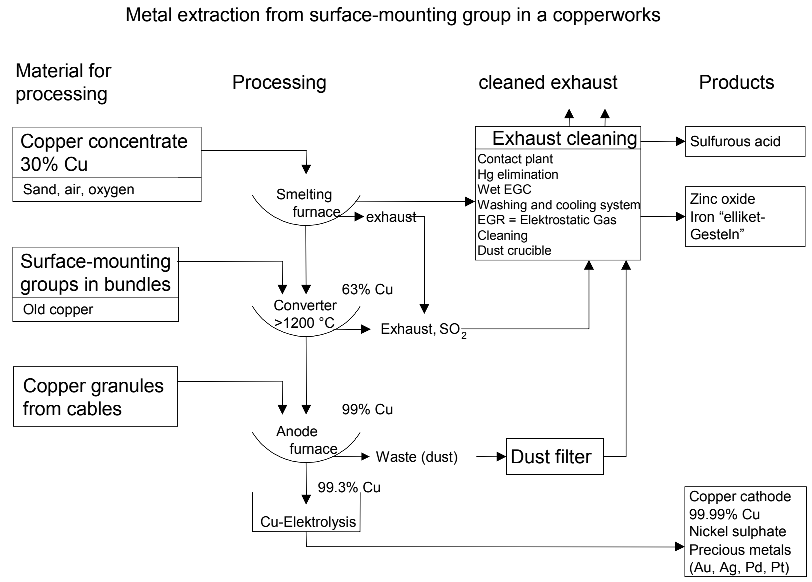

Figure 23-6. Metal recovery from flat modules in a copper smelter [4]

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Chapter 24

SUSTAINABLE DEVELOPMENT OF MICROELECTRONICS INDUSTRY
THE ROLE OF METALS IN FUTURE INTERCONNECTION TECHNOLOGIES

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1. LEVERAGE OF ELECTRONICS

The enormous potential of microelectronics technology and the importance of the microelectronics sector for nearly all leading industry segments according to the accumulated gross national product of Europe is illustrated in figure 24-1.

The microelectronics industry, with 55000 Jobs and a revenue of about $25 billion, supplies the leading industry segments like communications or the automotive industry and thus contributes to as much as 80,000,000 Jobs and part of the Gross National Product amounting to $4800 billion. Hence, we define the ratios of microelectronics via components, systems and revenue of leading industries to the GNP of Europe from 1:2:7:50:200 (Griese, 2001).

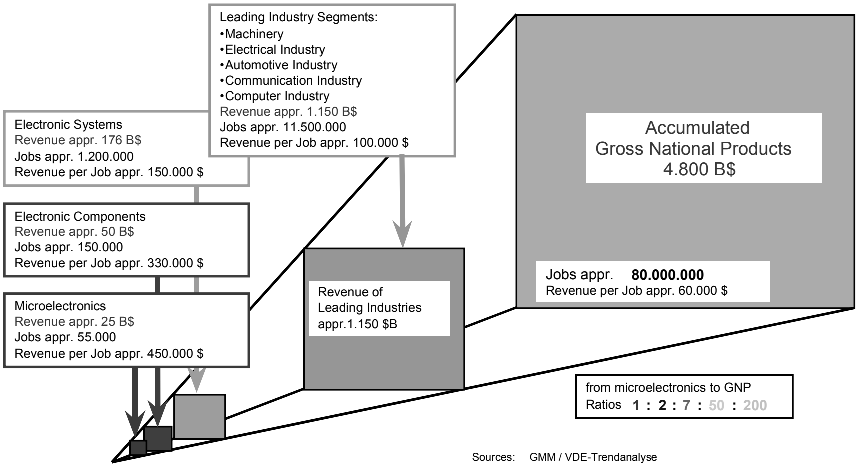
2. ENVIRONMENTAL IMPACT OF ELECTRONICS

The waste stream of electrical and electronic equipment (WEEE) is a complex mixture of materials and components. In combination with the constant development of new materials and chemicals having environmental effects, this leads to increasing problems at the end of the life of electronic products.

The rapid growth of WEEE is of concern. In 1998, 6 million tons of waste electrical and electronic equipment were generated in the European Union (4% of the municipal waste stream). The volume of WEEE is expected to increase by at least 3–5% per annum. This means that in five years 16–28% more WEEE will be

A. von Gleich et al.(eds.), Sustainable Metals Management, 577-592.

generated and in 12 years the amount will have doubled. The growth of WEEE is about three times higher than the growth of the average municipal waste within the EU (European Parliament, 2002).



Sources: GMM / VDE-Trendanalyse
ICE Mid-Term Status 1998
Statistisches Handbuch für den Maschinenbau 1997
Extrapolations

Figure 24-1. Leverage of microelectronics – direct contribution to revenues and Gross National Product.

2.1 Materials and Chemical Content

Only 3% of this waste is in the real sense electronics – mainly printed circuit boards (PCBs). PCBs can contain almost every chemical element from the periodic table in various compounds. Figure 24-2 gives some examples.

They contain not only inert materials like glass and ceramics but also highly toxic substances like special heavy metals, such as mercury, lead, cadmium or beryllium oxide. Some substances, like the flame retardant tetrabrome-bisphenol-A (TBBA), are probably not very toxic themselves but are predecessors of toxic reaction products formed during use or at the end-of-life.

Because of its hazardous content, electrical and electronic equipment causes major environmental problems at the end of life, if not properly treated. As more than 90% of WEEE is landfilled, incinerated or recovered without any pre-treatment, a large proportion of various pollutants found in the municipal waste stream in the developed countries comes from WEEE.

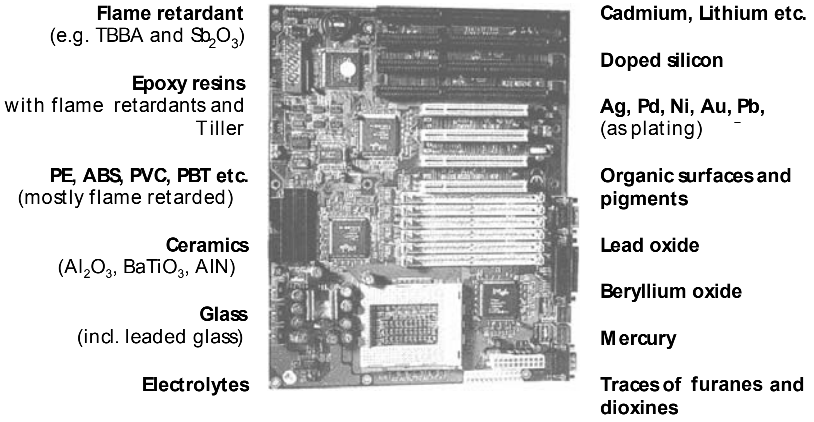


Figure 24-2. Material content of printed circuit boards.

2.2 Environmental Assessment

A number of methods exist for quantification of the environmental impact of electronic products (Graedel, 1995).

Some – like the Eco Indicator 95 mentioned later in this paper – are based on life cycle-oriented approaches and summarize various effects (like ozone depletion, acidification of surface water, etc.) during the phases of production, usage and disposal of a product to derive a single number that quantifies its impact. It is also possible to quantify all impacts during the product life by a common unit, e.g., as energy. Life cycle-oriented assessment is usually very time consuming and requires a lot of information, which is not easily accessible or sometimes even unknown.

The TPI (Toxic Potential Indicator) assessment method, also used later on in this paper, concentrates on material properties and material specific legal regulations like workplace threshold values. Impacts over different life phases can be assessed only indirectly but the assessment is fast and based on well-defined data (Middendorf, 2000; Nissen, 2001).

2.3 Miniaturization and Environment

In the development of electronic components and devices, increasing miniaturization is the basic tendency. The key technology in this field is the assembly and packaging technology. A major step was the transition from Through Hole Technology (THT) to Surface Mounting Technology (SMT), which allowed closer spacing of the miniaturized components.

To assess the environmental impact, material toxicity of the miniaturized products and energy demand during production must especially be regarded. The toxicity impact of the miniaturized components is small. Although highly integrated

ICs are expected to reach a share of 20% of the IC market, they will account only for 5% of the tonnage and only about 3% of the toxic potential of all ICs. The older generations of components will dominate the composition and amount of noxious substances because of their higher weight. Regarding raw material and energy flows, the miniaturized technologies have a higher impact (about 26%). This is caused by the higher content of silicon and precious metals (Nissen, 2001).

Generally speaking, we can suggest that boards with the same function unit become more environmentally friendly by miniaturization. However, shorter innovation cycles and an exponential growth of product numbers compensates the positive effect of miniaturization at least partly (this is sometimes referred as the rebound effect).

2.4 Regional Differences in Environmental Issues

In different regions of the world there are differences in aims and strategies for environmental protection in microelectronics (Pfahl, 2000).

The activities of US electronics companies are mostly driven by existing regulations and by cost reduction. Therefore, they are focused on the production process: replacing certain regulated materials, reducing energy consumption and the amount of material.

In Europe, regulations already announced as well as market forces lead to activities in design of products for the environment and life-cycle-assessment. This means that proactive actions play an important role in Europe.

In Japan, the influence of the government on the environmental behavior of electronics companies is still very high. In cooperation with nationally important companies, the long-term strategy is fixed and steps to get there are harmonized. Therefore, products for the global and domestic market are in focus. Lead-free soldering and halogen-free plastics have received much of their global dynamics from these activities.

Contrary to the US, the European Commission has announced three legal directives to reduce the environmental impact of electrical and electronic equipment. The draft has been divided in three parts:

- The first dealing with collection and handling of electronic waste.
- The second restricts the use of certain hazardous substances.
- The third is a directive on the design and manufacturing of electronics.

The most important part in our context is the second one. In article 4 of the proposed directive, substances like lead, chromium VI, mercury and cadmium but also certain materials like poly-biphenyl-bromine or poly-bromide-diphenyl-ether will be substituted from 1.1.2006 on (European Parliament, 2002).

3. EXAMPLES

The following two examples show specific environmental problems caused by the use of metals in microelectronics and the ways to deal with them.

3.1 Lead Containing Solder in Electronic Products and its Alternatives

There are world-wide efforts to substitute lead in electronic devices and there is an attempt in the EC to launch a directive referring to this (European Parliament, 2002). Japanese vendors such as Hitachi, Matsushita Electric and Toshiba have already announced the full implementation of lead-free soldering. Matsushita brought a portable MD player onto the market in October 1998, which adopts a Sn-Ag-Bi solder for the PCB assembly. The (planned) roadmap of the Japanese efforts to implement lead-free soldering is shown in table 24-1 (Suga, 2002).

Table 24-1. Time line towards lead-free electronics (Suga 2002)

Component		
-	Start development of full component supply with lead-free finishes	2001' end
-	Full supply available of components with lead-free terminals	2003' end
-	Full supply available of lead-free components	2004' end
Equipment		
-	Introduction of lead-free solders	2002 - 2003
-	Full adoption of lead-free solders in new products	2003' end
-	Full lead-free production for new and old products, with exception of legal exemptions	2005' end

3.1.1 Toxic Potential of Lead

Tin-lead solders are well known, used worldwide and easy to handle for small enterprises and so 80–90% of electronics are soldered by tin-lead. Boards as well as components are suitable for the temperatures required to melt this alloys.

Even though lead is only used in small amounts on PCBs, due to its toxicity it is one of the weak points in respect to the boards' environmental impact. The examination of a PCB example shows that only 7% of the material is SnPb but it contributes around 25% of the environmental impact of the PCB.

With simultaneous consideration of the strongly increased numbers of electronic products, that was one reason for world-wide efforts in research and development to substitute lead in electronic devices.

Figure 24-3 shows lead dissemination through water circulation. Discarded printed circuit boards come into contact with acid rain (acidified as the result of air pollution) and lead is dissolved and contaminates the groundwater. The polluted groundwater reaches the human body as drinking water. This leaching potential of lead is much higher than that of all other solder materials.

It has been known for more than a hundred years that lead affects the human nervous system and causes a range of serious problems. It is reported that the growth rate and intelligence of children that ingest lead are adversely affected. Low doses can accumulate. Lead is also known to be teratogenic and there is evidence that it is carcinogenic and mutagenic (Merian, 1991).

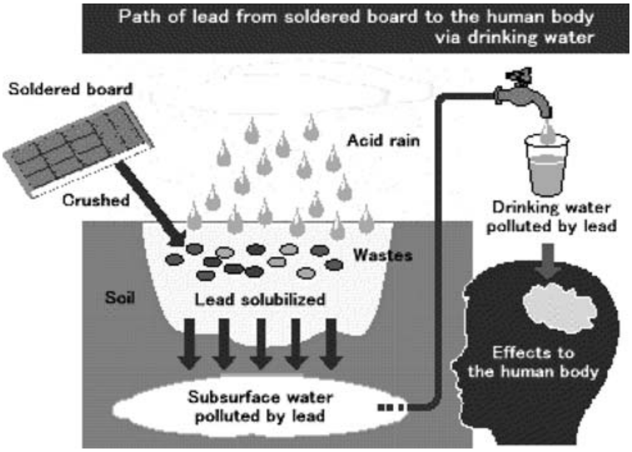


Figure 24-3. Leaching of lead from discarded printed circuit boards (Source: Panasonic).

3.1.2 Lead in Electronics: The Interconnection System

Most of the lead on PCBs is obtained in the interconnection system consisting of the surface finishes of the board and the component leads or terminals and of course, the solder itself.

Some components such as varistors, thermistors or multilayer capacitors contain smaller amounts of lead and there are no alternatives at present. Therefore, a transition to lead-free electronic devices has to aim at the most heavily used parts, which will be the solders and surfaces finishes, and replace them.

A soldered contact, for example a surface mounted “J-Lead” in figure 24-4, consists of the component contact area and its finish, the solder, conducting area of the board with finish and the intermetallic compounds between them. This whole interconnection system including the surfaces and the component terminals must be considered if the solder is to be replaced.

Thus, are there alternatives for lead containing solders: less toxic, commercially available, easily processable with the same equipment? Today we can say yes, but associated with a lot of problems. The main point is that there is no simple binary or ternary eutectic solder available that meets all the requirements at the same time.

In table 24-2 possible lead-free solders are listed in comparison to tin-lead. The melting temperatures differ a lot. Most of the activities are now directed towards tin-silver-copper, tin-silver and tin-copper. Tin-bismuth plays no important role until all lead is phased out of the solder partners, because it forms a lead alloy with a very low melting point, for example in contact with tin-lead coated component surfaces.

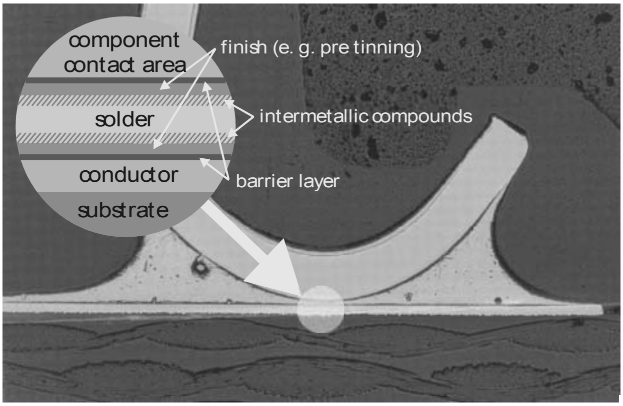


Figure 24-4. Electronic interconnection system.

Table 24-2. Lead free solders used by Japanese electronics industry (Suga, 2000)

Process		Alloys category	Recommended composition	Remarks
Wave		**Sn-3.5Ag**		Sn-Pb plating metals on components might cause fillet-lifting and damage to boards
		Sn-(2-4)Ag-(0.5-1)Cu	**Sn-3Ag-0.5Cu**	
		Sn-0.7Cu + Additives (Ag, Au, Ni, Ge, In)		
Reflow	Medium & high temp.	**Sn-3.5Ag**		Needs temperature control as Sn-Ag melts at high temp.
		Sn-(2-4)Ag-(0.5-1)Cu	**Sn-3Ag-0.5Cu**	
		Sn-(2-4)Ag-(1-6)Bi, including the ones with 1-2% of In		Incompatible with Sn-Pb plated components when it contains some amount of Bi.
		Sn-(8-9)Zn-(0-3)Bi	**Sn-8Zn-3Bi**	Handle carefully Sn-Zn in corrosive environment. Ni/Au finishes preferred for Cu electrode at high temp.
	Low temp.	Sn-(57-58)Bi	**Sn-57Bi-1Ag**	Incompatible with Sn-Pb plated components
Manual/Robot (Thread Solder)		**Sn-3.5Ag**		Incompatible with different solder alloys in reworking.
		Sn-(2-4)Ag-(0.5-1)Cu	**Sn-3Ag-0.5Cu**	
		Sn-0.7Cu + Additive (Ag, Au, Ni, Ge, In)		

3.1.3 Environmental Impact of Solders

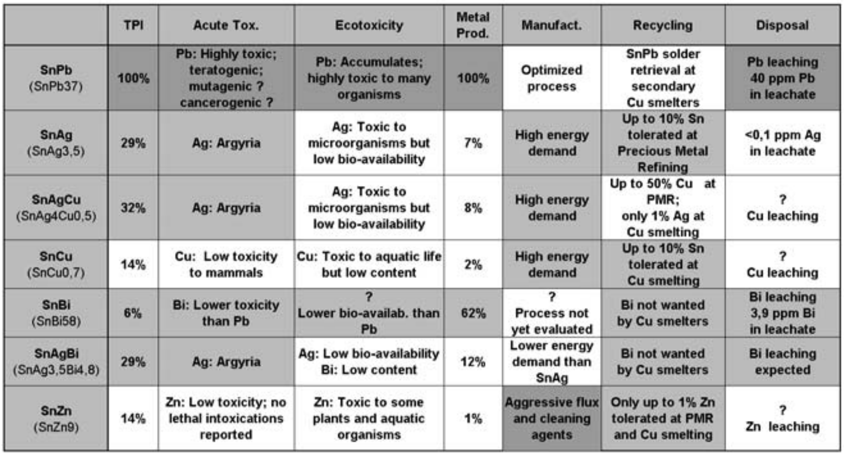
The implementation of a new lead-free interconnection technology should not lead to unwanted new environmental burdens. To prevent this, the environmental impact of possible substitutes has to be considered during the selection of a new technology. This is especially important because the choice of different solder alloys also has influence on the finishes of the printed circuit board and of the package leads, as described above. The environmental impact of the different manufacturing processes must be taken in account, too (Griese, 2000). The main question is: are the lead-free solders more environmental friendly in comparison to tin-lead? We will try an answer in the following paragraphs.

Table 24-3 shows different aspects of the environmental impact of interconnection systems in electronics that have been examined covering different phases of the life cycle. Results are summarized in table 24-4 and described below. The TPI (Toxic Potential Indicator), used here to give an overall rating, was developed at the Fraunhofer Institute for Reliability and Microintegration (IZM) as a fast screening method to evaluate the environmental impact of materials or products by their chemical contents (Middendorf, 2000). All lead-free solders have a better TPI rating than SnPb37. Even the use of the relatively poorly rated silver is favourable, because only a small quantity is used in the solder.

Table 24-3. Regarded categories of the environmental impact

Material Properties			
TPI screening	**Acute toxicity**	**Ecotoxicity**	
TPI Toxic Potential Indicator	Toxicological data	Toxicological data	
Calculated from legal threshold values	Direct effects	Toxic effects in ecosystems	
Life Cycle Impact			
Metal production	**Manufacturing**	**Material recycling**	**Disposal**
EcoIndicator 95	Energy demand, noxious auxiliary materials	Compatibility with copper and precious metal refining	TCLP Toxicity Characteristic Leaching Procedure of US-EPA
Impact of mining, transportation, refining of raw materials	Impact of the production process	Effect of material on recycling processes	Leaching behaviour during disposal

Table 24-4. Overview of the environmental impact of lead free solders compared to SnPb.



	TPI	Acute Tox.	Ecotoxicity	Metal Prod.	Manufact.	Recycling	Disposal
SnPb (SnPb37)	100%	Pb: Highly toxic; teratogenic; mutagenic ? cancerogenic ?	Pb: Accumulates; highly toxic to many organisms	100%	Optimized process	SnPb solder retrieval at secondary Cu smelters	Pb leaching 40 ppm Pb in leachate
SnAg (SnAg3,5)	29%	Ag: Argyria	Ag: Toxic to microorganisms but low bio-availability	7%	High energy demand	Up to 10% Sn tolerated at Precious Metal Refining	<0,1 ppm Ag in leachate
SnAgCu (SnAg4Cu0,5)	32%	Ag: Argyria	Ag: Toxic to microorganisms but low bio-availability	8%	High energy demand	Up to 50% Cu at PMR; only 1% Ag at Cu smelting	? Cu leaching
SnCu (SnCu0,7)	14%	Cu: Low toxicity to mammals	Cu: Toxic to aquatic life but low content	2%	High energy demand	Up to 10% Sn tolerated at Cu smelting	? Cu leaching
SnBi (SnBi58)	6%	Bi: Lower toxicity than Pb	? Lower bio-availab. than Pb	62%	? Process not yet evaluated	Bi not wanted by Cu smelters	Bi leaching 3,9 ppm Bi in leachate
SnAgBi (SnAg3,5Bi4,8)	29%	Ag: Argyria	Ag: Low bio-availability Bi: Low content	12%	Lower energy demand than SnAg	Bi not wanted by Cu smelters	Bi leaching expected
SnZn (SnZn9)	14%	Zn: Low toxicity; no lethal intoxications reported	Zn: Toxic to some plants and aquatic organisms	1%	Aggressive flux and cleaning agents	Only up to 1% Zn tolerated at PMR and Cu smelting	? Zn leaching

The direct effect on humans or mammals in general is summarized as ”acute toxicity. An effect in this category especially mentioned for silver is Argyria, a discoloration of the skin caused by the deposition of silver particles, usually with no other harmful effects.

„Ecotoxicity“ means the toxic effects on the environment, e.g., on certain groups of organisms (like plants or bacteria) or in certain compartments (water, soil, air). Compared to lead, all substitutes have advantages, especially tin/copper and tin/zinc solders have good properties (Merian, 1991).

The environmental impact of metal production was measured by the EcoIndicator95 method. The impact of ore mining, transportation and refining (energy consumption and emissions) are summarized to assess the metals. The lead-free solders have remarkably good ratings, only bismuth is rated relatively poorly because it is assumed to be produced mainly together with the noxious lead (Merian, 1991). Nevertheless, the rating of SnBi58 is better than SnPb37.

The manufacturing processes were coarsely rated according to the assumed energy demand and use of auxiliary materials (flux, cleaning agents, inert gases). It still has to be quantified more precisely. Of course, the higher melting temperatures of SnAg, SnAgCu and SnCu solders lead to higher energy demand. For SnZn, the flux and cleaning agents are an environmental minus.

The material recycling capability is (up to now) assessed as the compatibility of the solder components with copper refining and precious metal refining as pathways of electronic scrap recycling. According to the statements of copper smelters, especially the Bismuth rating is negative, because it contaminates the copper even in low concentrations.

To characterize the disposal performance of the solders, the US-American „Toxicity Characteristic Leaching Procedure“ TCLP1311 was carried out (Griese, 2000; Blackburn). Leaching behavior of SnPb solder is very poor compared to all alternatives. For copper, the leaching from the soldered joints is likely to be negligible compared to the copper PCB-layers. Zinc leaching has not been examined up to now.

At a glance, table 24-4 shows the potential for environmentally beneficial replacement of lead in the electronic interconnection systems but also indicates the need for in-depth studies to choose the appropriate solder.

3.1.4 Lead-Free Surface Finishes

- Up to now, the mainly used surface finish is SnPb Hot Air Solder Leveling (HASL). Alternative lead-free surface finishes are
- Chem. Ni/Au
- Chem. Ni/Pd/Au
- Chem. Sn
- Chem. Ag
- Organic solderability protectants (OSP)

The Ni/Pd/Au surface was not included in the following considerations because the market for palladium is very unstable and its costs are difficult to calculate.

For an average of 50% of the produced PCBs, the surface finishes have to change if the lead ban becomes reality. In Asia, where consumer electronics are produced, the low-cost HASL finishes with lead are applied more. The alternatives not only have to comply with technical/ technological requirements but should be more environmentally compatible than the conventional HASL SnPb layers.

In table 24-5 the different surface finishes are characterized by their layer thickness, the resulting masses of the several materials per square meter of PCB and their layer properties.

Table 24-5. Characterization of the lead-free finishes in comparison with the SnPb HASL layers

Surface finish	**Density (layer material) in g cm^{-3}**	**Layer thickness (µm) and mass* in mg cm^{-2}**	**Layer properties**
HASL SnPb37	Sn: 7.2 Pb: 11.3	25 / 54.7	Not bondable, multiple solderable, T-stress
Chem. Ni/Au	Ni: 8.9 Au: 19.3	5 /0.1 / 11.6	Bondable, multiple solderable, flat layers
Chem. Sn	7.2	1 / 1.8	Not bondable, multiple solderable, flat layers
Chem. Ag	10.5	0.1 / 0.3	Bondable, multiple solderable, flat layers
OSP	1 (est.)	<0.5 / 0.2	multiple soldering difficult, not bondable, flat layers

* Assumption: One quarter of the surface is metallized

All of the lead-free surfaces are very thin in comparison to the SnPb HASL layers and therefore the layer masses are very small.

Table 24-6 shows an overview on various aspects of the environmental impact of the different surface finishes along their whole life cycle: the screening assessment by means of the TPI, the assessment of the environmental impact in the raw material production by means of the energy consumption, the assessment of the environmental impact in the finish manufacturing by means of energy and water consumption and some short remarks about the environmental impact in the end-of-life phase.

The screening assessment by means of the TPI shows that the HASL and Ni/Au layers are relatively high (poorly rated) in comparison to the Sn-, Ag- and OSP layers. The reasons are the high toxicity and mass of lead in the HASL and Ni in Ni/Au layers.

For the environmental impact of the first life cycle phase – the raw material production – the energy consumption is considered. For the production of the precious metal Au a high energy demand is necessary. This means that the environmental impact for this process is very high.

Table 24-6. Environmental impact of lead-free surface finishes compared to HASL

Surface Finish	**TPI***	**E $_{RM}$****	**Manufacturing**				**End of Life**
			E in 10^6 J/m^2 non-c./ conv		**Water consumption** in l/m^2 non-c./ conv		
HASL SnPb37	51.7	9615	2.48	1.51	*50.5*	*40.3*	*Pb leaching*
Ni/Au	47.2	73312	5.08	-	*83.9*	-	*Ni-leaching* *Au-Recycling*
Chem. Sn	0.2	432	3.28	5.93	*73.7*	*35.6*	
Chem. Ag	1.1	907	-	3.26	-	*21.6*	
OSP	0.17	40 (est.)	1.42	0.83	*31.3*	*21.6*	*No Recycling*

*in 10^4 TPI/m^2 PCB, ** for raw materials, in 10^3J/m^2 PCB

(conv: conveyorized, non-c: non-conveyorized)

Environmental compatibility rating: Dark grey = very poor, grey = poor, white = good

For the assessment of the environmental impact of the manufacturing, the water and energy consumption have to be considered. These results were taken from the PWB Project Surface Finishes of the EPA in the USA [4]. There is a distinction between the non-conveyorized and the conveyorized process because of the large differences between them. For further examination of the environmental process impact, all the chemicals of the processes have to be included.

As shown in table 24-6, five surface finishing processes consume less water than the reference HASL, non-conveyorized process, including the conveyorized versions of the HASL, chem. Ag and Sn technologies, along with both versions of the OSP process. Two surface finishing processes consume more water than the reference process, the non-conveyorized version of chem. Sn and Ni/Au. The rate of water usage is primarily attributable to the number of rinse stages required by the processes. In general, the application of the conveyorized process is generally better than the non-conveyorized process, i.e., they consume less water.

Referring to the energy demand, table 24-6 shows that three of the process alternatives consumed less energy than the reference HASL, non-conveyorized process. Both the non-conveyorized and conveyorized versions of the OSP process, along with the conveyorized HASL process, consume significantly less energy than the reference process. The reductions were primarily attributable to the efficiency of these three processes and their short operating times. On the other hand, the long operating time in the case of the Ni/Au process is responsible for the relatively high energy consumption.

For a screening assessment of the environmental impact during the end-of-life phase, especially the disposal behavior of soldered PCBs, the leaching of the layer materials (only for metals) was examined by means of Toxicity Characteristic Leaching Procedure (TCLP). The results emphasize the well known solubility of Pb but also show a high Ni solubility.

Summarizing all facts of the surface finishes from an environmental point of view, the OSP finishes are rated best, whereas the NiAu finish should only be applied if required for technical reasons.

3.2 Environmentally-Friendly Gold Coating

The copper of the conducting paths on printed wiring boards has to be protected against contamination. In microelectronics, Au layers are gaining more and more importance as a universal surface finishing. These layers are deposited by an electroless chemical process on chemically coated nickel layers on the copper.

First an immersion gold layer with a thickness of less than 0.1 µm is generated in a charge exchange process. This thin gold layer has to be reinforced by a subsequent chemical reduction process for bondability reasons. The key components of such a coating bath are a complexing and a reducing agent. While the complexer keep the cations of gold in solution, they are reduced only at the active surface by the reducing agent and deposited there.

State of the art for this kind of gold coating is the application of baths containing cyanide as complexing agent and as free cyanide. But the highly toxic cyanide is potentially dangerous for health and the environment, if released during an accident. Therefore, its use requires high expenses for safety and environmental protection.

The administrative regulations based on the German water balance act (Wasserhaushaltsgesetz) as well as the professional association of the chemical industry in Germany, demand to replace cyanide by less harmful substances whenever it is possible.

Additionally, old bath solutions have to be detoxified before disposal, which can lead to high costs. Oxidation by sodium hypochlorite is widely used but this method also implies additional risks. In the bath, toxic chloro-organic compounds may be formed with organic substances, such as tensides and the AOX-threshold value has to be observed in this case.

Further weak points of the cyanide gold bath are its difficult handling, its low thermal stability and its nickel ion sensitivity. Finally, these baths are not well compatible with the masking process materials because of their alkalinity.

These are various reasons for developing a new bath and the corresponding coating technology with the aim of obtaining a technically, economically and ecologically optimized bath.

As a first step towards the substitution of cyanide, the literature on complex formation was surveyed to find compounds that form sufficiently stable complexes with Au (I)-cations. Further important properties were solubility in water and stability at temperatures up to 80° C.

The pre-selection led to a number of organic sulphur, phosphorous and nitrogen compounds. Already at this early state of development, the environmental impact of these compounds was assessed and compared to cyanide. For this, the Toxic Potential Indicator was investigated. The results are shown in table 24-7.

According to the results of the ecological assessment, 2,3-Dimercaptopropane-1-sulfonic acid and histidine are the preferable substances, but 2,3-Dimercaptopropane-1-sulfonic acid was rejected due to its high cost. In table 24-8 the detailed threshold values and classifications of cyanide and histidine are listed.

Table 24-7. Complexing agents and their environmental assessments

Compound	**TPI per mg**
Potassium Cyanide	67,5
Trimethylphosphine (TMP)	35,6
Mercaptosuccinic acid (MA)	33,5
2,3-Dimercaptopropane-1-sulfonic acid	1,6
Histidine	0,0

Table 24-8. Threshold values and classifications of cyanide and Histidin

Complexer	**MAK-value [ml m^{-3}]**	**Water pollution class**	**LD_{50} (or. rat) [mg kg^{-1}]**	***R-description acc. to German Hazardous Subst. Declaration***
Cyanide	5	3	5	Highly toxic in case of inhalation, contamination, swallowing
Histidine	-	0	> 15000	Maybe harmful in case of inhalation, contamination, swallowing

After selection of the complexer, the suitable environmentally-friendly reducing agent has to be determined. For some industrially used reducing agents, the TPI was also calculated (see table 24-9), but the selection of an appropriate reducing agent depends strongly on the complexer used. The combination must provide sufficient chemical stability of the solution.

Table 24-9 shows that thiosulfate and ascorbic acid have a good environmental compatibility and should be preferred. For the combination with histidine, thiosulfate was selected.

Before the gold-free worn out solution with the organic complexer can be disposed of, the organic load must be reduced, even if the constituents are not toxic. Otherwise, the self-cleaning capacity of natural waters could be exceeded. The limit is 600 mg·l^{-1} COD (chemical oxygen demand) for the plating industry in Germany.

Table 24-9. Reducing agents

Compound	**TPI per mg**
Hydrazine	77.9
Formaldehyde	20.4
Thiosulfate	0.0
Ascorbic acid	0.0

In general, biological degradation is preferable to chemical treatment of waste water with high concentrations of organic compounds. The constituents can be removed thereby without additional chemical agents. Microorganisms use the pollutants as a source of carbon and/or energy. The pollutants are metabolized to CO_2, water and biomass and thus eliminated from the water. The biodegradation of a cyanide-free plating bath solution could be shown as decrease of COD over time (Zuber, 2001).

The new cyanide-free bath for gold coating has excellent technical properties and the plating process is more environmentally compatible than the currently used bath. The substances are biodegradable and less toxic, the bath works at a lower operating temperature and the plating rate is higher.

Continued examinations are concentrated on the corresponding recycling process. The chemical principle of deplating, compared with plating, is shown in figure 24-5 together with typical carbon contents of the solution, which indicate its suitability for biodegradation after use.

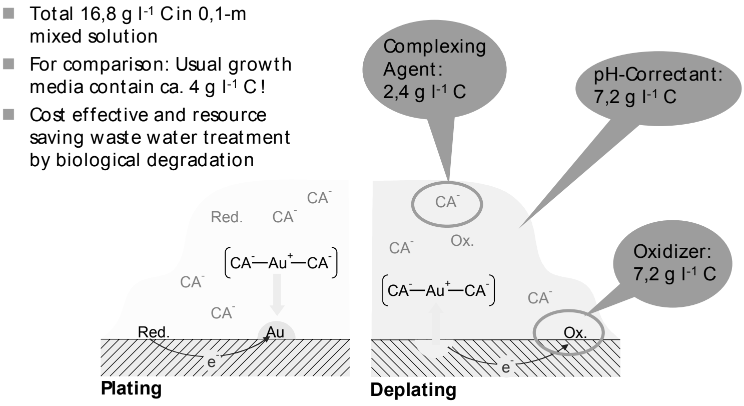


Figure 24-5. Biodegradable organic carbon content of gold plating and deplating solutions.

The aim is to make energy consuming, centralized gold smelting obsolete for the recycling of gold-containing electronic devices and to replace cyanide in the present recycling process. The recycling product (gold complex) can be used directly in the chemical industry, as shown in figure 24-6.

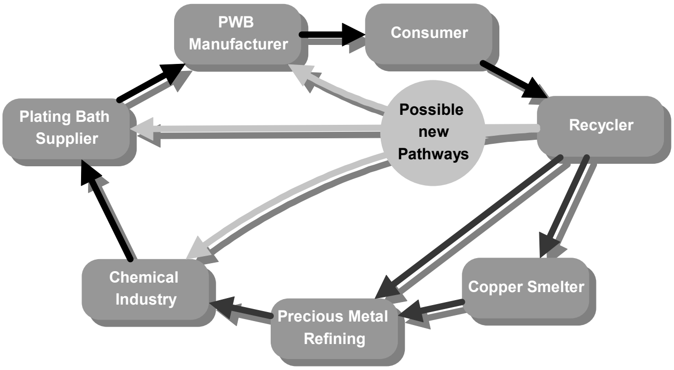


Figure 24-6. Industrial gold cycle.

Even more important than the described technological development was the successful cooperation of the involved technologists and practitioners with environmental scientists that led to this result. The inclusion of environmental assessment at an early stage of the process development besides technical and economical optimization, leads to process-integrated environmental protection and is profitable for the industry as well as for the environment.

4. SUMMARY

Electronic products contain numerous noxious substances, among them many metals, in components and boards. In general, the amount in a single electronic device is comparatively low in absolute numbers and even decreasing due to miniaturization.

However, the enormous growth of production numbers and the short innovation cycles compensate this positive tendency and lead to rising burdens for the environment by discarded products. Additionally, there is the significant impact of the complex production processes, such as raw material extraction or microchip production and others.

Therefore, there are efforts in many countries to evaluate and control the environmental impact of microelectronics. By careful optimization of microelectronic products and processes, as described in the two examples in this paper, the harmful impact on the environment can be minimized during the ongoing rapid development of production numbers and new technologies in microelectronics.

Facing the product numbers and growth rates forecasted for the developing countries by the ICT-Industry, all materials, especially toxic metals in electronic components, need to be closely examined. However, this examination should not primarily aim at legal regulations and the ban of materials, but on product responsibility and the environmental awareness of the producers.

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Chapter 25

THE ROLE OF METALS FOR DESIGNING PRODUCTS AND SOLUTIONS IN THE CONTEXT OF A SUSTAINABLE SOCIETY

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The beginning of the 21st Century will be shaped by at least three new issues:

- the implementation of new technologies resulting from scientific discovery in, e.g., life and material sciences and nano-technology, possibly leading to increased system complexity;
- societal developments that will increasingly impose the need for sustainability on policy makers especially in Europe and thus,for instance, force them to abandon subsidising unsustainable activities, such as road transport;
- the need to find solutions which are both sustainable and competitive in order to guarantee economic survival in a globalised world.

These three issues are interlinked. However, they mean that the old approaches of Taylorism and specialisation to solve problems will no longer work. Society thus faces the challenge of developing strategies that integrate all three factors of sustainable solutions, of ecologic, economic and social natures into a competitive economy. This means rethinking economic theory and the relevant public policies.

1. MARRYING TECHNOLOGY, COMPETITIVENESS AND SUSTAINABILITY

Technology

Technology driven by scientific discovery has always done things its own way. From the invention of the railways to dynamite to nuclear energy to the exploration of space, utopians have always promised us heaven and pessimists have predicted the coming of the Apocalypse.

A. von Gleich et al.(eds.), Sustainable Metals Management, 593-607.

In fact, both were right: the introduction of the railway did cause disasters, killing dozens of people (the prediction of the pessimists), yet they also constitute the safest means of mobility that we have on land (the prediction of the utopians).

History has also taught us that the best choices – according to best available knowledge – are made by the market, under condition that innovators reap the benefits of their success but also carry the costs of their failures. The difference between the past and the present is the complexity of the challenge involved. Whereas failures in the past ended in bankruptcy or even death of the individual risk taker (such as Louis Favre building the Gotthard railway tunnel and Ferdinand de Lesseps building the Suez Canal), modern risk takers need a third party to cover the costs of their failure. The disaster at Lockerbie has shown that modern corporations, in this case PanAm, will not survive a disaster without adequate risk management and insurance.

Shortly after World War II, insurance became a pre-condition for innovation and technological development, especially in 'hard sciences'. The consequence of this for policy makers should be to use the concept of insurability as the 'natural' borderline between the market economy and state regulation in order to achieve the highest competitiveness. A mandatory insurance cover, e.g., for environmental impairment liability and product liability, means an internalisation of the future costs of risk and thus a selection of technologies according to full cost principles, at no cost to the State. A 'command and control'-legislation, on the other hand, can lead to a falsification of the choice of technology and a liability of the State for mistakes.

Witness nuclear reactors: in autumn 1999, a German bank sold 5% of the shares of a Swiss nuclear power plant to a Swiss investor for 60 million euros – paid by the vendor of the shares to the buyer. The Swiss financial press commented on this by stating that we finally know the value of a nuclear power station in a liberalised market: minus 1.5 billion euros! If this is the case, we may not need to discuss the risk issues involved.

Functioning markets can thus be very efficient in evaluating technology. However, since they cannot deal as efficiently with ethical issues, there is still a key role for States in creating the optimal framework conditions for economic development within a societal vision. Sustainability could well be this societal vision for the coming 21st century.

Competitiveness

The OECD in Paris defines economic competitiveness as follows:

> *"The degree to which a nation can, under free and fair market conditions, produce goods and services which meet the test of international markets, while simultaneously maintaining and expanding the real incomes of its people over the long term".*

Competitiveness thus does not need to be in contradiction with choices of technology or the vision of sustainability. However, in a global world – and globalisation is the inevitable result of demolishing the Berlin Wall and the Iron Curtain – competitiveness means that the decisions on which new technologies should be developed should be based on sound economic judgement, as well as being integrated into the societal vision of sustainability.

Sustainability

The term '*Nachhaltigkeit*' (German for sustainability) is over two hundred years old, even if many people have only taken notice of it in the years following the UN Rio conference in 1992. In the meantime, the term has taken on a life of its own, often being shaped to fit the requirements of whoever needs a 'vision'. It may therefore be useful to recall the original definition coined by Prussian foresters:

> *'to live from the interests of a forest (such as construction timber, fire wood, animals and plants), while increasing the capital (such as trees, soil and water retention capacity)'.*

Two of the keys to sustainability are 'value' and 'responsibility'. For economic actors working in the context of sustainability, responsibility means 'performance responsibility' in a wide sense, encompassing economic but also ecological and social values.

A historical analysis of the development of sustainability allows one to analyse the past and look into the future, through the evolution of the five pillars of sustainability.

The first pillar at the origin of the green movement was the protection of nature, highlighted by people like Jean-Jacques Rousseau two hundred years ago. The protection of people's health then became a major issue about fifty years ago, fuelled by DDT and Seveso. Finally, the problem of huge material flows, codenamed resource productivity, became an issue in the late 1980s.

The future will increasingly be shaped by issues of cultural ecology and social ecology. Technology will have a major role to play in bringing the third pillar to fruition, in order to achieve higher resource productivity. The future economic competitiveness of Europe may thus well depend on choosing the best technology to achieve a quantum leap in resource productivity. Moreover, these will most certainly include life sciences, new materials and nano-technologies. Cultural factors, such as the quest for opportunities versus risk aversion, could become a major driver or handicap.

1.1 THE FIVE PILLARS OF SUSTAINABILITY

Sustainability is based on several pillars, each of which is essential for maintaining the natural eco-system on Earth in a state that enables human life. We cannot argue about priorities or speculate as to which of these pillars we can afford to lose first. In fact, we cannot take the risk of losing any one of them:

1. Nature Conservation,
   the global eco-support system for life on the planet (e.g., biodiversity, global commons), as well as the regional carrying capacity of nature with regard to populations and their lifestyle (e.g., drinking water, arable land); measured by for instance the ecologic footprint.
2. Health and Safety (a qualitative approach),
   or non-toxicity, combating dangers related to the health of people and animals, which are increasingly a result from man's own activities (e.g., DDT, mercury, thalidomide, hormones); measured in nano-grams.

These first two pillars are separated by a borderline from the third: the focus shifts from nature conservation to increased competitiveness!

3. Reduced Flows of Matter (a quantitative approach),
   the quest for higher resource productivity is necessary to prevent a potentially lethal change of the conditions of life on the planet (through a re-acidification of land, CO2 emissions in the air leading to a possible climate change; measured in mega-tonnes.

The first three pillars are separated by a second borderline from the last: a shift of focus from a sustainable economy to a sustainable society.

4. Social Ecology,
   encompasses the fabric of societal structures, including peace and human rights, dignity and democracy, employment and social integration, security and safety.
5. Cultural Ecology,
   includes education and knowledge, ethics and culture, risk management and thrill/ risk trade-off ratios, values of 'national heritage' at the level of the individual, the corporation and the state.

2. THE NEED FOR A CHANGE IN THE ECONOMIC OBJECTIVES

From a river economy to a lake economy

The present manufacturing or industrial economy has a linear structure and its success, both on a micro (corporate revenue) and a macro level (GDP), is measured as the monetary flow at the 'point of sale'. Its success thus depends on this flow (or throughput) of goods and resources, of both matter and energy – it might be called a **'river economy'** (fig. 25-1).

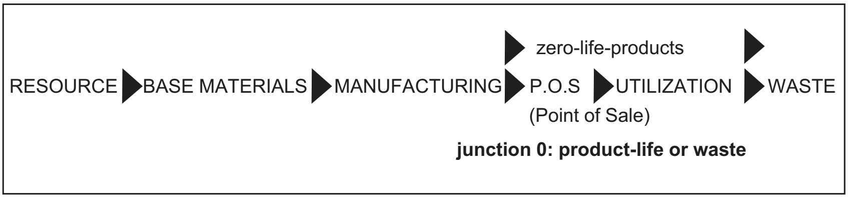

Figure 25-1. The linear structure of the industrial economy (or 'river' economy).. Source: *Stahel, Walter* and *Reday, Geneviève* (1976/1981)

The industrial economy has created wealth by transforming resources into goods. Resource flows, or throughput, was therefore a yardstick for success. As long as there was a scarcity of many goods, this approach was efficient. The bottleneck in the past was often access to a sufficient volume of raw materials, including metals.

Metals were therefore among the first resources to be recovered for re-use since ancient times, in order to avoid scarcity.

Things are different for goods. When the markets for certain goods reach saturation levels, marketing strategies such as annual fashion changes are necessary in order to enable manufacturers to continue to increase production. This has resulted in the transformation of many durable goods into disposable goods, which then helped to increase throughput and economic success on both a micro and macro level. However, this is the opposite of a sustainable economy.

The generalisation of the present per capita resource consumption (the 'ecological footprint') of industrialised countries on a world-wide level is not possible – it would either need another five planets the size of the Earth or lead to a collapse of the eco-system. In order to become sustainable, the economy of industrialised countries will have to operate at a much higher level of resource productivity, i.e., be able to produce a higher 'utilisation value' out of a greatly reduced resource throughput. Ways of doing this may be new 'resource-lean' technologies and a change from the linear 'river' economy into a 'loop economy' – a **'lake economy'** (fig. 25-2).

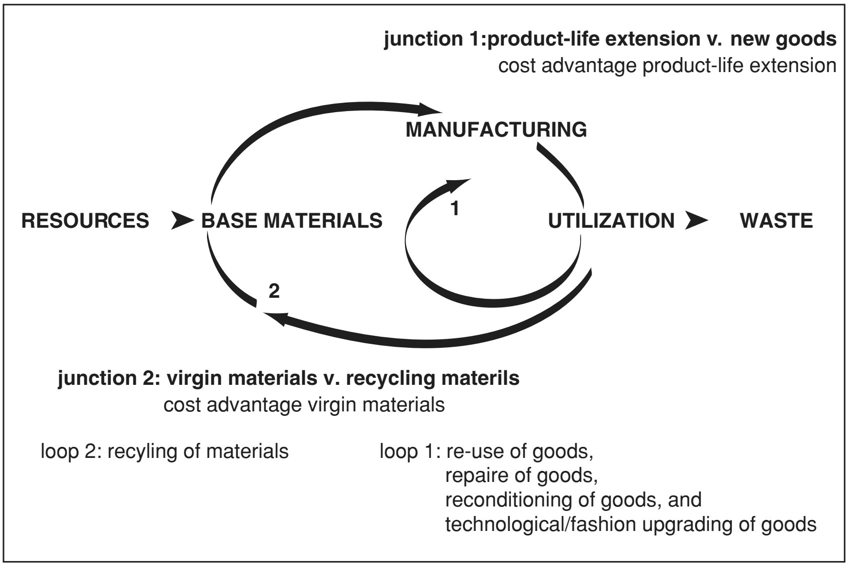

Figure 25-2. Closing the material loops: The loops of a self-replenishing, more sustainable service economy (or 'lake' economy), and the junctions between these loops and a linear economy.. Source: *Stahel, Walter* and *Reday, Geneviève* (1976/1981).

Achieving a higher resource productivity therefore means a departure from the theories of the industrial economy. Yet the fundamental changes that this borderline implies have not yet been widely accepted, neither by policy makers nor by economic actors:

- the new goal is to de-couple the economic success of both corporations and Nation-States from resource consumption and to create more wealth while consuming considerably less resources,
- the new drivers are money, technology and competitiveness, no longer the motivation to 'save the environment' (the first border line of the five pillars of sustainability),
- the main framework condition is a product responsibility 'from cradle back to cradle', through a series of loops and spirals – witness the single use camera – and an Extended Performance Responsibility for results – as is the case in IPM / ICM (integrated pest management and integrated crop management),
- the key tool is 'wild' innovation supported by free market safety-nets (such as insurance, *Berufsgenossenschaften*), instead of a 'command and control' approach dictated by laws and regulations (Stahel, 1997a),
- speed of action becomes as important as scientific correctness, as knowledge increasingly becomes private property,
- the reward is a first mover advantage leading to increased competitiveness, rather than a 'feeling of being green and good' leading to eco-awards.

On the supply side, the key actors in achieving higher resource productivity through more sustainable production are technology managers and innovators. The strategic priority for managers is to 'do the right thing'. 'Doing things right' (e.g., clean production, EMAS/ISO) is still important but it will not be sufficient to remain competitive in a global market.

What is the role of metals in a lake economy?

For the metals industry, the recycling of scrap has always been the norm, especially in times of high resource demand (such as wars). However, a rapidly increasing economy of scale in mining virgin ores, combined with a shift in mining activity to countries with low labour costs, have started to threaten the economics of the recycling of iron. Scrapping ships today is only profitable thanks to the few percentages of non-iron metals which each ship contains – the income from recycling the steel would not pay for scrapping![1] Progress in process technology, such as electric arc furnaces for steel recycling, have helped but cannot overcome the problem of low resource costs.

Yet there are also resource problems involved, mostly linked to the dissipation of metal ions. A use of metals for short-lived goods does not allow preservation of the initial stock of metal ions, as is shown in table 25-1. Even if drink containers are collected and recycled at an extremely high rate of 90% (as is the case in Switzerland), the total metal stock will be lost after a period of only 2 years. The only strategy to preserve the resource stock is thus the use of refillable drink containers, which are collected for cleaning and re-use.

Table 25-1. The impact of the Factor 'time' in a loop economy, using the example of Coca-Cola beverage cans in the USA

Cycle time is 3 weeks. Initial resource is virgin material			
Rate of recycling	50%	75%	90%
Share of recycling material in			
1. recycling	50%	75%	90%
2.	25%	56%	81%
3.	12,5%	42%	73%
4.	6,3%	32%	66%
5.	3,1%	24%	59%
6.	1,6%	17.8%	53%
7. (6 months)	negligible	13.3%	48%
8.		10%	43%
9.		7.5%	39%
10.		5.6%	35%
11.		4.2%	31%
12.		3.2%	28%
13.		2.4%	25%
14.		1.8%	23%
15.		1.3%	21%
16.		negligible	18.5%
17.			16.7%
18.			15%
19.			13.5%
20.			12.2%
21.			10.9%
22.			9.8%
23.			8.9%
24.			8%
25.			7.2%
26.			6.5%
27.			5.8%
comparison to re-use: re-useable glass bottle in Europe, 27 cycles			
28.			5.2%
29.			4.7%
30.			4.3%
31.			3.8%
32.			3.4%
34. (2years)			negligible

Source: The Product-Life Institute, Geneva.

There are many other ways of unsustainable dissipation or loss of metal ions to the environment, sometimes with subsequent potential effects on human health. Thin film coating technologies enable, among other uses, the application of gold layers on window glass to reduce the sunlight that enters a building. When the building is demolished, no-one bothers to recover the gold! Zinc is used in the production of vehicle tyres. Through normal tyre wear, the zinc powder ends up on the road surface and is washed into the environment with the next rainfall. Zinc is also used in galvanization as a ‘self-sacrificing’ protection of steel against corrosion. For the case of crash barriers along motorways, this means that over the years, a large part of this zinc will end up in the soil below the safety barriers.

The introduction of applications of nano-technologies onto the market during the first decade of the 3rd Millennium could highlight this problem and make it a major research issue in the years to come.

However, there is also dissipation of ions within the metal stock itself. Technological progress and the need for dematerialisation have led to an ever-increasing number of metal alloys that are used by industry. The use of lightweight steel for the automobile industry is one example of this. Present recycling technologies cannot separate all the different metals from each other at a reasonable cost, which means that the quality of the metals is degraded with each recycling. Some metals, which are recovered through electrolytic processes, such as copper and some aluminium alloys, may escape from this trap.

This means that ‘quality’ also has to be redefined in the context of a sustainable society. The notion of quality will have to integrate the issues of technical efficiency, liability and time in order to be meaningful in the context of sustainability (fig. 25-3).

The shift from a throughput or river economy to a lake economy in loops thus necessitates a review of all the boundaries and rules involved in production.

For instance, the first borderline cited in the five pillars of sustainability, from nature conservation to an increased competitiveness, implies changes in economic thinking. Economists have only just started to accept that ‘economy of scale’ goes hand in hand with a ‘dis-economy of risks’ (improvements lead to marginal savings but exponential increases in potential losses). Moreover, industrial ecology may lead to a technology lock-in and stranded investments and thus, to a loss of competitiveness. One example of this was the economy of the former GDR (East Germany), the demise of which was triggered by the disappearance of the Iron Curtain and thus the forced opening of their economies. Both the agriculture and the energy sector had been organised as perfect networks of industrial ecology, and they collapsed within a few years. Other examples include the possible collapse of centralised electricity production in countries that have privatised their state monopolies. A recent example of the risks involved in industrial ecology (my waste becomes your resource) is the animal feedstock produced from slaughterhouse waste, which probably led to the epidemic spread of BSE. Dead animals affected by the disease now have to be burnt – causing in Britain sometimes gigantic air pollution.

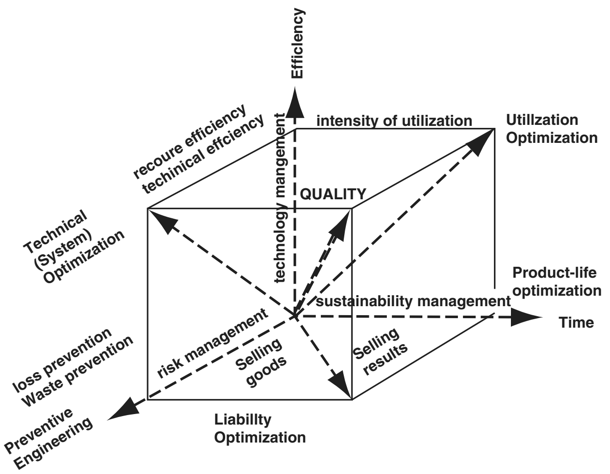

Figure 25-3. Quality defined as long-term system optimization.. Source: The Product-life Institute, Geneva, 1989.

The economy of performance-focused services

It has been calculated by the 'Factor-10 Club' that industrialised countries need to reduce their resource flows by a factor of 10, in order to enable the less developed countries to multiply their per capita resource input to a comparable level, while reducing world resource throughput to a sustainable level (Factor-10 Club, 1994)

A sustainable economy – what the WBCSD, World Business Council for Sustainable Development, calls the concept of 'sustainability through the market' – has to be frugal, creating wealth primarily from immaterial resources and existing material stocks (the 'lake economy'). Successful companies will manage existing assets by squeezing maximum performance out of stocks while minimising resource consumption. This will lead to a transformation of consumption goods into durable goods.

This objective cannot be achieved by dematerialised product design methods alone but also calls for changes in corporate strategy. The service economy uses the 'utilisation value' as its central notion of economic value and measures its success in terms of asset management, by revaluing the existing stocks of goods and by optimising their utilisation in the lake economy. This new focus thus allows the de-coupling of corporate success from resource throughput. However, 'maintaining wealth with less resource consumption' also means facing new risks in the emerging service economy, such as higher vulnerability in some areas. (Giarini/Stahel, 1989/93)

For pro-active entrepreneurs, there lies a considerable untapped economic potential ahead that can be harvested through technical and commercial innovation. The objective of 'wealth with less resource consumption' (Stahel, 1997) has been of little interest to the industrial (river) economy, as it would have led to "economic disaster" (as measured in resource throughput).

Companies that recognise and successfully develop the new opportunities will greatly increase their competitiveness: if customers pay an agreed amount per unit of service (and service equals performance translated into customer satisfaction), service providers have an economic incentive to reduce resource flows in order to increase profits. Their profits will increase twofold: procurement costs for materials and energy will go down and so will distribution and waste elimination costs. Examples for this are the Xerox life-cycle design programme for photocopiers, the retreading of tyres for cars, trucks and aircraft, rail grinding services. DuPont's voluntary programme to take back and depolymerise scrap nylon and all activities concerning the remanufacture of used goods lead to the same result. A number of major 'manufacturing' companies, such as General Electric and elevator 'manufacturers', already earn 75% of their revenue from services linked to the utilisation of their products and only 25% from manufacturing.

Among the key strategies to achieve this are prevention and precaution, sufficiency and efficiency:

- the use of immaterial resources such as knowledge to replace material resources such as coal and cement (DuPont strategy of selling painted body parts instead of paint to car makers and opening its loss prevention consulting services to other companies; Ciba's yield guarantee through integrated crop management),
- using 'dematerialised technologies', such as life sciences, instead of material-intensive technology, such as chemistry (life sciences can be regarded as chemistry at ambient temperature and pressure, whereas chemical processes use high temperatures and pressures),
- selling the performance demanded instead of the goods produced (introduces an economic incentive to sell sufficiency instead of efficiency based solutions).

These strategies can be clustered under the heading of the shift from manufacturing to a service economy and from selling products to selling the performance of products (PLI, 2000).

3. THE SHIFT FROM MANUFACTURING TO A SERVICE ECONOMY

The figures show that it is happening now[2]

The structure of national statistics does not allow observation of the shift from a manufacturing industry to a service economy. However, estimates can be made for key market segments.

The EU market for 'products sold as services' in 1998 is estimated at 758 billion euros, or 10% of GDP. Within this segment, selling the function of products (through, e.g., fleet management) accounts for 60% (equal to 6% of GDP); while remanufacturing services account for 40% (4% of GDP). The world market for electronic data services – selling the utilisation of computers instead of selling computers – is estimated at over 300 billion US$ per annum.

In comparison, manufacturing accounted for 17% of U.S. GDP in 1997 (for 20% in the EU), for 15% of total U.S. employment and 26% of corporate profits.

The shift from manufacturing to services has gone much further in the USA than in Germany and Japan, its main competitors. In the European remanufacturing sector, revenue today comes predominantly from the building and construction industry. In contrast, the USA has a well-developed market for the remanufacturing of components, estimated at 50 billion US$ per annum, 50% of which are in the field of remanufacturing of components for road vehicles[3].

The remanufacturing of components and goods made of metals increases the sustainability of the 'old' industrial economy. However, more sophisticated methods of repair and remanufacturing will demand specialised metals in small quantities, such as powders that are suitable for fusion bonding.

One of the key drivers to build an eco-efficient economy is scientific innovation and technology

After nature conservation, clean technologies and zero-waste (100% yield), the new objective in the move towards a more sustainable economy is substantially increased resource productivity; to design smart solutions that earn higher profits from each pound of material.

This goal cannot be achieved with linear improvements of existing manufacturing technologies. It calls for a change in strategy, bold innovation and a shift to new technologies based on modern science, including life sciences and material sciences.

Different scientific domains contribute to the shift from manufacturing to service in relation to strategy and product combinations.

A new way of corporate thinking

The prospects for companies that shift from manufacturing to services are bright. A strong first mover advantage is to be gained in the shift to services; a new way of thinking greatly facilitates the shift:

- strategy as a means of creating the future, rather than extrapolating it from the past,
- vertical integration from the plant to the customers, rather than from the suppliers to the plant,
- a performance-based asset management of the 'installed base' of goods, rather than cost reduction-based production management.

Three key issues have come to light: advantage through science, extended performance responsibility (EPeR), and job creation. However not all of these issues are open to all product groups.

A bright outlook – for innovators

The leading edge companies expect to double or quadruple their share of revenue from selling services instead of products by the year 2010. This implies changes in the structure and the rules of the game. These changes affect business managers as much as investors and bankers.

Fleet management (selling the function of goods) today gets its revenue predominantly from 'durable goods', i.e., from transport services (e.g., railways and airlines, computers); second is equipment leasing. The highest potential for future competitiveness and technological innovation, however, is in the fields of 'consumption goods' and 'catalytic goods' (such as engine oil or solvents, that could be re-refined instead of being eliminated as waste).

Existing research is focused on eco-designing durable goods and thus misses the most profitable areas, which also have the highest gains in eco-efficiency! An analysis needs to cover consumption goods, catalytic and durable goods, as well as prevention strategies.

Both waste prevention and loss prevention strategies constitute the ultimate sale of knowledge and performance instead of material goods. Some of these strategies were at the cradle of risk management, such as the switch from batch to flow processes after the Flixborough disaster in the 1950s. And Microsoft's Software Agreement (rent-a-software by the hour) will, if successful, do away with all the material support of software sales, upgrades and replacements – and give Microsoft an economic incentive to stop producing permanently new software, which is often (and has to be in a river economy) incompatible with older versions.

Remanufacturing includes a huge hidden sector of in-house remanufacturing by fleet managers. This sector develops highly innovative technologies but acts as a 'closed shop'. It includes the armed forces and major industrial corporations and could be larger than remanufacturing by independent firms. Statistically speaking, it is virgin territory.

The shift from manufacturing to a service economy also imposes new rules on economic actors: while retaining ownership is a successful strategy for durable goods, owning the distribution channels may be the only option for consumption goods. Hewlett-Packard announced a few years ago that it has stopped producing any material goods with the exception of black ink.

The shift is business driven

The main driver for shifting to a service economy is business itself: a change in the way we look at business opportunities

Many manufacturing industries are caught in a rat race of falling revenues from their products, increased competition and increasing production costs. The solutions to this problem have been cost cutting, re-engineering, a bigger economy of scale through globalisation; however, the present business focus is often still on improving manufacturing.

The solution proposed in this paper is a fundamental switch to selling the performance of goods instead of the goods themselves; a situation where shareholder value and income increase, while production costs decrease; where market capitalization increases even if production does not. The business focus is now on vertical integration to reach, win and satisfy the final customer. The strategies to achieve this differ mainly according to the type of product.

'Virtuous loops' push the service economy

Other factors driving the shift are hidden inside the new service economy itself:

- win-win synergies that only develop between companies selling services instead of goods, such as carpet leasing by Interface to facility managers; or 'rent-a-wash' (the sale of the function of washing by Electrolux and Merloni) combined with 'smart electricity meters' installed by utility companies,
- a first mover advantage inherent in services and some of the new technologies; this is counter-intuitive to managers in manufacturing with a history of disadvantages of prototype technology for first movers,
- changes in strategic thinking: 'closing the loops' through e.g., integrated product policy (IPP) for durable goods, means achieving the highest re-sale value from used goods and components, instead of aiming for the lowest recycling costs.
- structural change: the importance of manufacturing in the industrialised economies continues to decline. In the US economy of 1960, for instance, manufacturing accounted for 47% of corporate profits, 31% of jobs and 27% of GDP. By 1997, these figures had decreased to 26% of profits, 15% of jobs and 17% of GDP.
- Sectoral efficiency revolutions. In addition to 'doing things right', the name of the new game is 'doing the right thing'. The result can be quantum leaps in technological advantage and competitiveness. The key corporate strategy to take advantage of these business opportunities is selling performance, services or results, instead of goods. This in turn changes the distribution of risks and income throughout the economy.

Consumption and catalytic goods have a large potential to achieve a higher resource productivity through advances in life sciences and material sciences. Enzymes, for example, can replace chemical catalysts with increases in 'resource productivity' by a factor of 37'000[4]. This introduces a new dimension into the discussion on 'resource productivity'.

For durable goods, the main tools of the past were clean production processes and 'Eco-Design' efforts to dematerialise products. The new strategy complements these with commercial innovations aimed at more intensive and longer utilisation of goods. It includes preventive engineering and eco-efficient operation and maintenance of the goods.

Some obstacles obscure the change

The regional differences in the shift to a service economy are substantial. The shift from manufacturing to services and from selling goods to selling the performance of these goods, has gone much further in the USA than it has in Europe or Japan.

There are important cultural differences with regard to the nature of eco-efficiency. In Europe, the sustainability discussion has so far focused on the ecologic potential of eco-efficiency, i.e., on durable goods, as by far the biggest resource flows are caused by the construction sector and heavy industries. In the USA, the emphasis is on the potential increase of national competitiveness through sustainable technologies, such as life sciences. The social compatibility, the third factor of the sustainability triangle, has not yet received much attention. The job creation potential of remanufacturing, for instance, has been greatly neglected even in 'green' European countries, despite persistent high unemployment.

Present national statistics are insufficient to see what is happening. Their data are imprecise and falsified by new trends, such as outsourcing. If a company supplies both goods and services, its output, profit and jobs are allocated to the sector in which it is biggest – creating a potential for 'sudden landslides' in national accounts. Outsourcing 'falsifies' national accounts in other ways. If a manufacturer outsources its IT department, the department changes, statistically speaking, from manufacturing to services. Similarly, if an airline turns its maintenance department into an independent company, its jobs and activity change in the statistics from services to manufacturing.

4. CONCLUSIONS

The key to higher resource productivity – being the next challenge in the pursuit of sustainability – is radical innovation. Life sciences and material sciences have the highest technical potential to achieve a quantum leap towards higher resource productivity.

Technology is the key to increased competitiveness in combination with increased resource productivity. The highest potential might be hidden in consumption goods, such as energy, (agro)chemicals, food and water.

Dissipative goods, such as metals and chemicals, contain a big potential for higher resource productivity linked with emerging nano-technology applications and strategies of 'rent-a-molecule', as they have appeared in the USA after the introduction of the TRI legislation (Toxic Release Inventory).

The most successful strategies to reach a higher sustainability are sufficiency on the demand side and prevention strategies along with extended performance responsibility – which combines sustainable production and consumption in a single package – on the supply side. However, these strategies are only of interest to economic actors in the context of a service economy. Their implementation will thus depend on the rapid shift from manufacturing to a service economy.

Selling performance is a key strategy of the 'lake economy', which is at the centre of the shift from an industrial throughput (or river) economy to a new service or knowledge economy. Strategies to 'rent-a-molecule' have started to appear in the chemical industry and in ceramics, pioneered by companies such as Cookson Ltd, but are still very rare in the metal industry sector.

The dematerialisation of the economy is partly based on a shift to a knowledge economy. Speed and flexibility in finding the best solutions in a global context provide a substantial bonus for first movers. It is therefore crucial to develop and foster the use of free market safety nets that can deal with uncertainty in a faster and more flexible way than regulations and legislation.

Many of these innovative solutions contain a high inherent complexity. Framework conditions that internalise the risks associated with innovation and can deal efficiently with uncertainty could be instrumental in shortening the time to market of the new technologies involved.

NOTES

[1] 'Breaking into scrap', *South*, November 1985; quoted in: 'Hidden innovation', Walter R. Stahel, Science and Public Policy, August 1986.

[2] Multi-client study on the shift from manufacturing to a service economy, 1998 – 2010; the Product-life Institute Geneva, March 2000.

[3] http://remanufacturing.com

[4] Confidential information by Diversa Corp, on one of the products it sells. One gram of enzyme replaces 37 kilograms of a heavy-metal catalyst.

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