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Towards a Sustainable Copper Industry?

Trends in Resource Use, Environmental Impacts and Substitution in the Global Copper Industry

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Towards a Sustainable Copper Industry?

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1. Introduction

Copper is a metal which 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 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.[1] 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 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.[2]

Fig. 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.[3] 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.[4] Copper thus plays a key strategic role as an essential material in the infrastructure of power transmission and electronics.

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.[5]

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.[6] 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.[7] 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

1 Cf. Deutsches Kupferinstitut 1987: p. 2 and Metallgesellschaft AG (publisher) 1993: p. 16.

2 My own calculations using Metallgesellschaft AG/World Bureau of Metal Statistics (publisher) 1996: pp. 30–31.

3 Cf. Deutsches Kupferinstitut 1990: p. 3; Lyman/Black 1988: p. 1114 and Metallgesellschaft AG/World Bureau of Metal Statistics (publisher) 1997: p. 326.

4 Cf. Deutsches Kupferinstitut 1987: p. 13; Deutsches Kupferinstitut 1990: p. 3; Brodersen 1992: p. 1158–1159 and Lyman/Black 1988: p. 1114–1115.

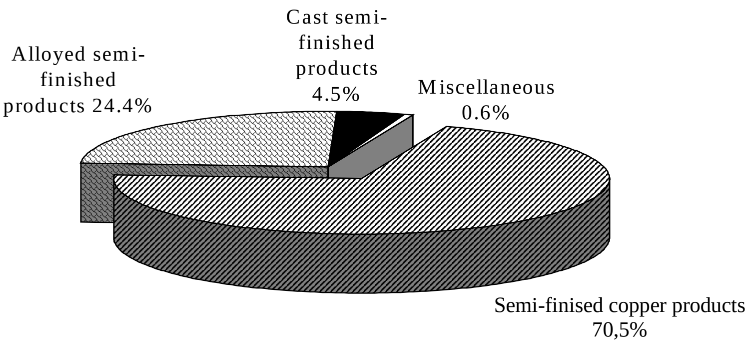
5 Cf. Deutsches Kupferinstitut 1987: pp. 13–15; Deutsches Kupferinstitut 1990: p. 4; Brodersen 1992: pp. 1158–1159; Lyman/Black 1988: pp. 1117–1118 and Oehler 1992.

6 Cf. Deutsches Kupferinstitut 1987: p. 15; Deutsches Kupferinstitut 1990: pp. 4–5; Arpaci/Vendura 1993: p. 341–342 and Schleicher et al. 1992.

7 Cf. Deutsches Kupferinstitut 1990: pp. 4–5 and for the importance of casting: Engels 1992.

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.

Fig. 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 (publisher) 1997: pp. 262, 325 and 340.

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 impairing the satisfaction of future generations' needs (WCED 1987: p. 43), the key management rules for a sustainable copper industry are as follows:[8]

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

8 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.

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.[9]

Copper is very important for the survival of 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 Impacts 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).

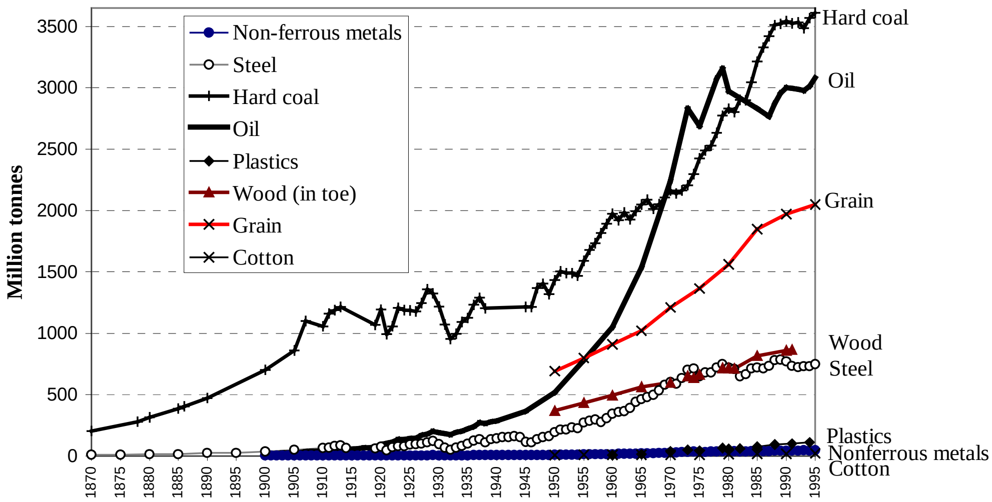
4.1 Development Trends in the Usage of Resources in the 20th Century

Figs. 2 and 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. 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 mostly 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 Fig. 2 shows,

9 For a discussion of sustainability and copper-exporting countries cf. Messner 1996.

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.[10]

Fig. 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. 2 and 3:

Data for iron and steel production and the production of refined non-ferrous metals taken from: Metallgesellschaft AG/World Bureau of Metal Statistics (publisher) 1996, Metallstatistik/Metal Statistics 1985–1995: pp. 60–65.
Production data on steel, iron and hard coal taken from: Wirtschaftsvereinigung Stahl (publisher) 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 (publisher) 1997, pp. 314–319.
Plastics data taken from: Glenz 1989: p. 1238 and anon. 1995: p. 1761.
Wood data taken from: Forest Products Society (publisher) 1994: p. 22 and Alexandros (publisher) 1995: pp. 206–230.
Data on grain and cotton taken from: FAO (publisher) 1969–1996, Production Yearbook.

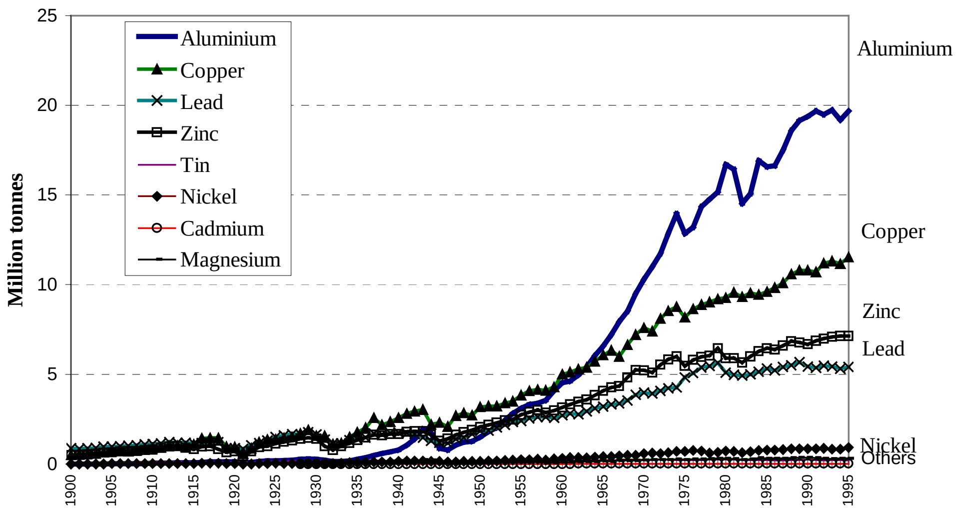
In fourth place in global mass resource usage comes grain, the first renewable resource in the list, of which in the mid-1990s about 2 billion tonnes were produced every year. It is followed by steel and timber production, both at about 800 million tonnes annually. The difference is that steel is only 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

10 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. (publisher) 1996: p. 29. The discrepancy between material and energy usage is shown in Fig. 2 using the different scales of the production of oil and plastics.

other half being used to generate energy (as firewood).[11] 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 Fig. 3, indicates they cannot be regarded as a significant *mass* resource.

Fig. 3: Global Production of Non-Ferrous Metals 1900–95 (million tonnes)



Source: Metallgesellschaft AG/World Bureau of Metal Statistics (publisher) 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 mass structural usage 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.

Figs. 2 and 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 the 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

11 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. 2 in terms of their energy content into tons of oil equivalent. 2.1 billion cubic metres of wood corresponds in energy terms to 520 million tonnes of oil. Cf. Alexandratos (publisher) 1995: pp. 215–220.

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.[12]

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.[13] *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 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 Environmental Implications of Copper Production and the Structural Transformation of the Global Copper Industry

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 copper's entire 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

12 For a detailed analysis of the stagnation in the global usage of resources cf. Messner 1999: pp. 413–433.

13 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.

copper content of the earth's crust is about 0.006%.[14] 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 West'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 Fig. 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

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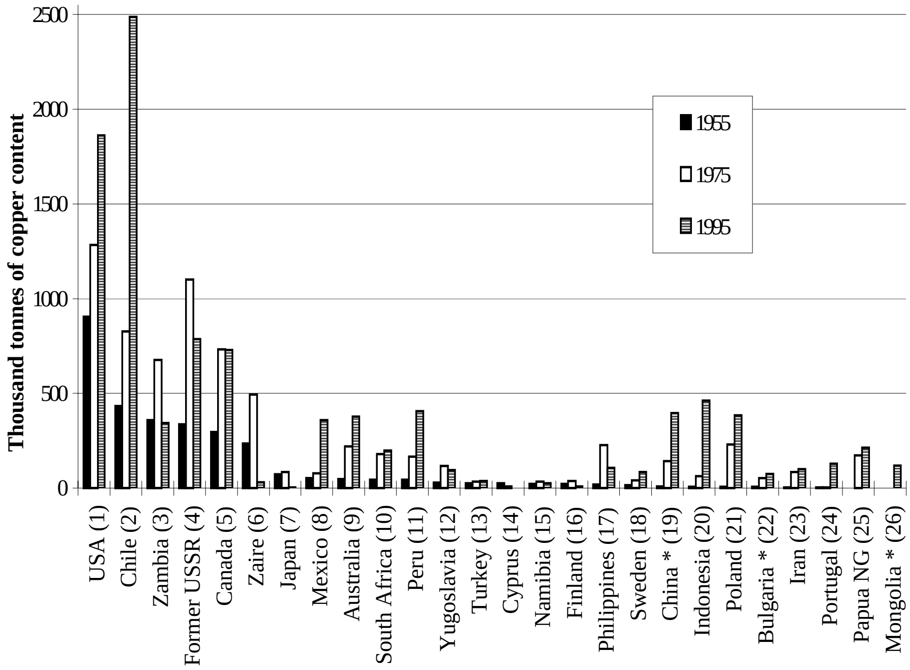
14 These average concentrations make copper the 23rd most frequent element in the earth's crust. Cf. Deutsches Kupferinstitut 1987: p. 2.

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.[15] 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).

Fig. 4: Mining Production of the Main Copper-Mining Countries in Thousand Tonnes of Copper Content (1955–95)



* Estimated
Sources: Metallgesellschaft AG (publisher) 1959: pp. 13–14; Metallgesellschaft AG (publisher) 1984: pp. 29–30 and
Metallgesellschaft AG/World Bureau of Metal Statistics (publisher) 1996: pp. 25–26.

The economic boom in the postwar 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

15 My own calculations using Metallgesellschaft (publisher) 1959: pp. 13–14.

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%.[16]

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.[17]

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).[18] 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

16 Cf. Mikesell 1988: p. 21-22 and my own calculations using Metallgesellschaft (publisher) 1984: pp. 29–30 and Metallgesellschaft (publisher) 1959: pp. 13–14.

17 Cf. Mikesell 1988: p. 13; my own calculations using Metallgesellschaft AG (publisher) 1984: pp. 29–30.

18 Cf. on Zambia: Messner 1996: pp. 416–422 and on the Congo: Körner 1993: pp. 514–522.

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.[19]

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.[20] 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.[21] 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 down to 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

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19 Cf. Göckmann 1992: pp. 731–733.

20 Cf. Mikesell 1988: pp. 21–25.

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

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.[22]

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 on 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 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; and corporate market muscle has partly been reduced by the emergence of new players and fierce competition in periods of over-capacity.

Environmental Implications of Copper Production and the Structural Transformation of the Copper Industry

The extraction of copper ore and the production of refined copper are highly environmentally intensive. As the concentration of copper in ore is currently on average less than 1%, more than 100 tones of ore have to be extracted, ground, crushed, washed, treated with chemicals

22 All details are based on my calculations using data quoted in Metallgesellschaft AG (publisher) 1975: pp. 26–33 and Metallgesellschaft AG/World Bureau of Metal Statistics (publisher) 1996: pp. 25–31.

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 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 km² (Metallgesellschaft AG (publisher) 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 causes numerous harmful emissions. Processing copper ores, which frequently have high sulphur levels, can cause 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 volume 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 (Young 1993: pp. 23–30 and p. 42). 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).[23]

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 which

23 Cf. BMZ 1994: p. 21, Warhurst 1994: pp. 20–25, Siepelmeyer 1991b: pp. 102–103 and Messner 1999: pp. 447–451.

have accompanied the structural change of the copper industry within the world economy, and which are dealt with below.

Stagnating demand in the copper-rich 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 in force since the 1970s, threatening the competitive position of various mining locations (cf. Messner 1999, pp. 437–446). It was not easy for 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[24], 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.[25]

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24 For instance, the net costs of copper production in the US has been 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).

25 Cf. 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.[26] 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.[27]

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 in force 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

26 The INCO corporation is one of the largest air polluters in North America. Significant damage to vegetation is visible on an area of 104 km^2, 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.

27 Cf. Warhurst 1994: p. 42 and Supplement to Mining Journal 1990: p. 2.

enables the large-scale, eco-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.[28] 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.[29] 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

28 For more examples cf. Warhurst 1992: pp. 42–45 und Messner 1999: pp. 497–507.

29 Cf. Messner 1996: pp. 417–421; Mikesell 1988: pp. 97–99 and Fozzard 1990: p. 103.

damage caused by state copper companies. In addition to the lack of innovation in terms of environmental technology, the obsolete 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).[30] 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.[31] 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

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

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

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 doubtless 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) with the usage of 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.[32]

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 usage of substitute resources. The price mechanism hence ensures a smooth process of substitution (Dasgupta/Heal 1979: chapter six).

The evolutionary economic theory school 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

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

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 by itself a 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 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 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 among materials in various applications which mainly raged in 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.[33] Aluminium has characteristics in the areas of electrical and thermal conductivity which 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%),[34] 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 Fig. 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.

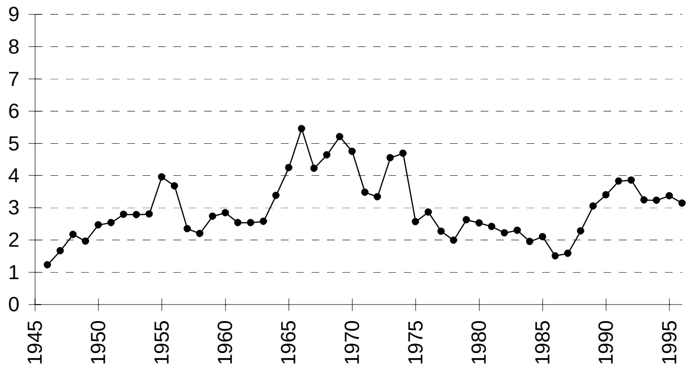
Fig. 6 indicates the pattern of material substitution in the area of electrical applications. The figure shows the weight-related usage ratio of copper to aluminium in the production of

33 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.

34 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.

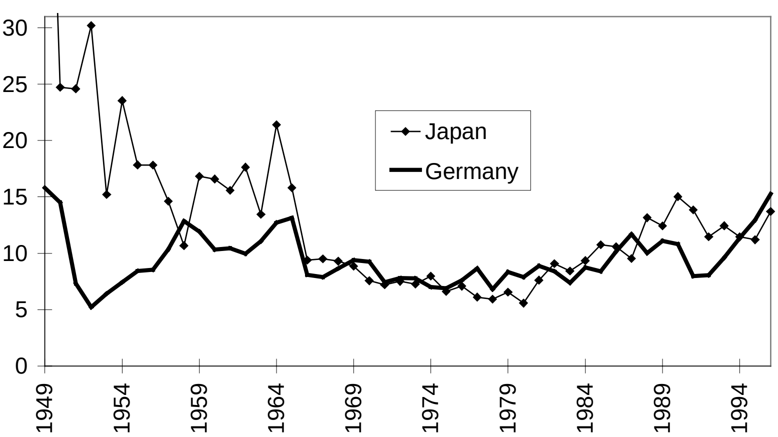
conductors in Germany and Japan in 1946–96. It can be seen that the development of the usage ratio in both these copper-processing countries was similar, especially after 1965. The usage ratio of the two competing conducting materials dropped significantly after 1949 in favour of aluminium, reaching 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.

Fig. 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 (publisher) 1994: p. 460 and p. 469; Metallgesellschaft AG/World Bureau of Metal Statistics (publisher) 1997: p. 460 and p. 469, and own calculations.

Fig. 6: Weight-related Usage Ratio of Copper to Aluminium in Conductor Production in Germany and Japan (1949–96)



Data sources: Metallgesellschaft (publisher) 1958: pp. 47, 71, 117, 145; Metallgesellschaft (publisher) 1967: pp. 53, 85, 143, 175; Metallgesellschaft (publisher) 1977: pp. 65, 115, 185, 225; Metallgesellschaft (publisher) 1984: pp. 73, 133, 219, 264; Metallgesellschaft AG/World Bureau of Metal Statistics (publisher) 1994: pp. 72, 157, 261, 325 und Metallgesellschaft AG/World Bureau of Metal Statistics (publisher) 1997: pp. 72, 157, 261, 325.

This development trend highlights that between 1949 and 1980 copper was replaced for various electrical applications by aluminium. 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 copper's price 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 regression analysis of the link between the relative price and usage ratio of copper and aluminium for 1946–96 fails to indicate a statistical link.[35] 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 second regression analysis in which the relationship between the relative price and the usage ratio of copper to aluminium is studied with a time lag of up to 15 years, statistical links were revealed in Germany with a lag of 8–10 years and in Japan with a lag of 6–10 years (Messner 1999, pp. 631–36). These findings can also be confirmed in Figs. 5 and 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 prices in the 1990s the 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.[36] 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

35 For a full presentation and a discussion of the regression analysis and its results, cf. Messner 1999, pp. 531-536 and 631-636.

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

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) 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's substitution by aluminium, Messner (1999, pp. 536–548) showed with the help of an eco-balance 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 objective 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 are outlined which need to be eliminated if the copper industry is to be made genuinely sustainable.

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.[37] 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 thing 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 source 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

37 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 further training for personnel", "Involvement of the local population", "Selection of the best technologies with the lowest environmental impact", etc. See also in this context and concerning the contents of these mining guidelines: Wälde 1992: pp. 4–8.

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 times 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.

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