Materials and energy : a story of linkages

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Chapter 2
A short history of the importance of metals for humanity and the debate on their scarcity

Metals that occur in their metallic form in nature have probably been used for as the long as humans roam the world. It was probably some time in the 6th millennium BC that humans managed to develop the technology required to release metals from their ores. Since then, metals have had a profound impact on human society, most prominently through improvements in agriculture, the development of new technologies and in warfare. Today metals are an integral part of society and in many applications it is hard to imagine non-metallic substitutes.

For as long as metals have been used, scarcity has been an important issue. Precious metals are precious because they are scarce. In our time, gold, silver and the platinum-group metals are considered *precious* simply because ore deposits of these metals are relatively scarce. Their scarcity, together with their relative inertness, makes these metals eminently suitable for making jewelry. This, in turn, makes it a useful object for investment. In the time of the Egyptian pharaohs, however, iron was much scarcer simply because the technology to free iron from its ore was not yet available, despite iron-ore resources being very common. The same is true of aluminium, which was not freed from its ore until the late 19th century.

Shortages of metals have led to several periods of scarcity. The causes of these shortages have varied throughout history. Security of supply routes is one of the key issues that has caused shortages ever since metals were first introduced, right up until current times, with export quota for rare-earth elements currently a topic of discussion within the WTO. Today, the combination of the scale of the use of metals, the interdependency throughout global supply chains and the concentration of mining and refining in a limited number of countries mean the supply of metals is quite vulnerable. Another aspect of supply insecurity relates to the linkages between various different resources. In particular, the availability of energy and a suitable reducing agent have acted as limiting factors in the past. Until 1740 metal smelting was entirely dependent on wood as a source of energy and charcoal, which led to massive deforestation. In our era we face a deterioration of ore grades, which is increasing the demand for energy, water and land per kilogram of metal produced. At the same time, these resources are themselves under pressure from other types of use and through the environmental impacts associated with their use.

Finally, shortages of supply may be caused by the fact that supply simply cannot keep up with growing demand. Demand shocks have been the major cause of the supply shortages encountered over the last century. Until now these shortages were solved though additional investments and innovations in mining and exploration but, looking into the future, declining ore grades together with the linkages with other resources will make this considerably harder.

This chapter provides a brief summary of the historical development of the importance of metals for humanity and the scarcity associated with that use[1].

2.1 The importance and scarcity of metals pre-1740

For every living being the availability of sufficient resources is important to sustain its existence and that of its offspring. In nature this relates mainly to the availability of resources that fulfil basic needs, i.e. air, water, food and shelter.

Before the introduction of agriculture, around 8000 B.C., humans were dependent on the availability of game that could be hunted and food that could be gathered from nearby ecosystems. Key materials included animal products like bones and skins, and wood and other plant materials that could be used for providing shelter and fabricating simple tools. The main mineral resources used during what is now called the Stone Age were silicon-based: mud, clay, stones (e.g. flint) and rocks. The only metals that were used were those that could be found in their metallic or alloyed form: gold, silver, copper and meteoric iron/nickel alloys (Craig et al. 2011; Raymond 1984). Because of the scarcity of these metallic metals, their use was generally limited to ornaments. Use of these metals to be found in nature in their metallic form was widespread and occurred everywhere people and metals co-existed.

Climatic changes, population growth and the mass extinction of megafauna at the end of last ice age triggered a transition to an agricultural society, which in turn paved the way for the development of more complex societies (Ruddiman 2005; Tainter 1988)[2]. During the period between 10,000 and 5,000 years ago, early agricultural societies were still Stone Age communities lacking the technology for metal smelting. From a mineral resource perspective, little had changed compared with the hunting and gathering era. Clay, stone and rock were still the main mineral resources in use. Around 9000 B.C. the techniques for making pottery from clay were developed, providing superior means of storing and transporting food and water. They also led to improvements in building methods, because of the development of bricks and glass. The techniques for freeing copper and other metals from their ores were probably discovered accidentally in fireplaces and pottery ovens made partially from ore-containing rocks. The heat together with charcoal as a reducing agent provided the right conditions to free the metal from its ore. Metal had three big advantages over stone: it was not as brittle, it could be readily formed into the desired shape and it

[1] A more comprehensive overview of the impact of metals on humankind can be found in a volume by Raymond (Raymond 1984). A more complete overview of the literature on resource scarcity is provided in an essay by Krautkraemer (Krautkraemer 2003), the works of Barnett and Morse, the revisit of the 1963 Barnett & Morse analysis by Simpson, Toman and Ayres (Simpson et al. 2005) and the works of Robinson, Geiser, Tilton and Radetzki (Robinson 1989; Geiser 2001; Tilton 2003; Radetzki 2008).

[2] Whether this transition from hunting and gathering to agriculture was by choice or a necessity caused by a growing population, and whether or not this was a good thing for humanity is debatable, as Jared Diamond does in his essay "The worst mistake in the history of the human race" (Diamond 1987).

could be recycled after a tool, ornament or weapon was broken (Raymond 1984; Craig et al. 2011). Early metallurgy was developed more or less independently at different times in different locations. The earliest metal smelting probably dates back to the 6th millennium BC in Mesopotamia. As in biological evolution, there is a growing body of evidence that the development of metallurgy not only proceeded through incremental improvements but also through a series of periods of rapid change and innovation. One example is given by what Chernykh calls an explosive development in the northern Balkans and the Carpathian basin during the Copper Age of the 5th millennium BC. He also describes how pastoral nomads formed an important link for the spread of metallurgical processes between what are now called Europe and the Middle East and China. However, he also notes that although some of the early technologies were imported from the West, the development of metallurgy in China proceeded in a fairly independent manner, spawning metallurgy that in many ways was much more advanced than in the West (Chernykh 2009).

In South America, both Peru and Colombia were rich in placer deposits[3] of pure metals, mainly copper and gold. Beaten gold objects have been found that date back to around 2000 BC. Around the year 0 the technologies to smelt and cast metals were developed in Peru. In Colombia a material called 'tumbaga', an alloy of about 30% gold and 70% copper was very common. This alloy had the advantage that its melting point was lower (800 ºC) than that of the individual metals (1064 ºC and 1084 ºC respectively) which made casting much easier. The Colombians were probably the first to use platinum, mixed with gold, which also occurred as small grains in placer deposits. In Australia there is no evidence of the use of pure metals until the arrival of the Europeans (Raymond 1984).

By 3000 BC other metals like silver, tin, lead and zinc were regularly extracted from their ores and bronze and bronze-like alloys were being produced in Eurasia. Metals became important mineral resources for society (Craig et al. 2011; Raymond 1984). Lead only became important when the Greeks and Romans started using it for piping and storing water. By combining copper with tin to form bronze a far less ductile metal was produced that gave societies the opportunity to produce more sophisticated craftwork, tools, weapons and armour. The start of the Bronze Age coincided with the development of the first major cities in Mesopotamia. Because of the dispersion of sources of copper and tin, the Bronze Age also marked the first time in human history that civilizations were dependent on foreign resources and long-range transport of minerals (Craig et al. 2011).

After bronze, some time around 1300-1000 B.C., iron (in the form of wrought iron) became the material of choice for tools, weapons and armour because it is much stronger and tougher than bronze (Craig et al. 2011; Raymond 1984). Although iron is far more abundant than copper, it is harder to extract from its ores. The fires that were used to melt bronze and copper were not hot enough to melt iron (1537 °C), but the soft iron that was produced was pounded and forged into the desired shape. There

[3] Deposits of metals that are released from rocks through erosion and have accumulated in river beds.

is evidence that this technique was already known from the start of the Bronze Age, but that iron was avoided because of the inferior quality of the iron that was produced in the rudimentary production processes of the time. It was only after (local) shortages of copper and tin occurred that iron was used as an inferior substitute and that technologies to produce the superior-quality iron were gradually developed (Raymond 1984). This may have been the first time in human history that societies were confronted with the scarcity of metal resources that were truly important to their functioning. In this case the problem was solved by substitution of one metal by another, which led to a technological breakthrough and to the development of superior materials (wrought iron).

The Eurasian practice of iron extraction from ores probably had a common origin in Asia Minor in the early 2nd millennium BC. In pre-modern times, iron production from ores was confined to Eurasia; on other continents only meteoric iron was used, as a rarity. The basic invention of iron smelting was further developed along three different lines in Europe, the Middle East and central southern Asia and China (Gilmour 2009). In the 8th century BC the scale of the industry can be illustrated by a find of 163 tons of the metal in the form of mainly fish shaped bars in the palace of a neo-Assyrian ruler. Iron was probably introduced in China in the 9th to 8th century BC, probably through cultural interaction with western Asia. In China, which had a very rich tradition of bronze casting, the production of cast iron followed soon after the introduction of the metal. Cast iron objects have been found at a site in the province of Shangxi that date back to the 8th century BC (Han and Duan 2009; Guo 2009). In China, blast furnace technology was in use in the 1st century BC, almost 1500 years before it was introduced in Europe around 1340 (Wagner 1999). In a blast furnace, ore and charcoal are introduced at the top together with the *flux*, a mineral material that serves as a reducing agent and impurity absorbent, while air is blown in from the bottom. The main advantages of a blast furnace are that the temperature easily reaches the melting point of iron and that it can be used in a continuous process: ore, charcoal and flux can be added at the top while molten iron can be poured into casts from the bottom. This innovation made it possible to substantially increase the production of (cast) iron objects .

Steel, an alloy of iron and carbon (0.2-2%), which is much stronger and tougher than wrought iron and cast iron, was known long before its large-scale introduction in Europe in the 18th century. There are still many gaps in our knowledge about the development and dissemination of the technologies for producing steel. Steel swords dating back to the late 2nd millennium BC have been found in western Iran (Gilmour 2009). In India high-carbon steel artifacts have been found that were made between 800 and 400 BC (Srinivasan et al. 2009).

The first steel was probably made during *bloomery* iron production[4]. In this process part of the end-product, *the bloom*, with a high carbon content (1.2-1.7%), is separated

[4] A bloomery is a simple chimney-like oven with an air inlet at the bottom (blown or draught) in which a mix of charcoal and iron ore is ignited. In its simplest form the bloomery creates conditions such that the

and subjected to a process of controlled decarburization consisting of repeated heating, forging and folding. This process is stopped when the carbon content has been reduced to 0.7-0.8%. There is some evidence that this process, which today is still used to make traditional Japanese Samurai swords, was used by the Romans to produce steel. Later, steel was produced by heating a mixture of pure or wrought iron together with a (biotic) source of carbon in a crucible (carburization) (Gilmour 2009). This process allowed for a more homogeneous distribution of the carbon, resulting in higher-quality steel. The crucible process was first developed in India around 600 BC and it was used to produce 'wootz', a type of steel that was highly valued throughout the world from 600 BC until the middle ages. In the Middle East, Indian wootz was used to make so-called 'Damascus steel' swords and daggers, which were far superior to other steels produced at that time owing to elemental impurities in the ores (including rare earths) and the accidental formation of carbon nanotubes in the production process (Tripathi and Upadhyay 2009; Raymond 1984; Reibold et al. 2006).

In Europe the large-scale application of cast iron started with the introduction of the blast furnace around AD 1340. This led to the ample availability of cheap iron objects, an important factor in the later industrial revolution. The main disadvantage of cast iron is that it has a high carbon content (2-4%), making it brittle. The development of the technology for larger-scale crucible steel production in the mid-18th century and the Bessemer process in 1858, both in England, marked two major breakthroughs for the truly widespread use of metals in society. Steel is now one of the most commonly used and most versatile materials. Iron mining now accounts for over 90% of all primary metal production (U.S. Geological Survey 2010). By changing its composition and by adding different kinds of alloys, the properties of steel can be tailor-made for many applications.

Although the large-scale use of metals was of key importance for military successes and for manufacturing tools and craftwork, until the industrial revolution the material basis of societies was still very much bio-based. Building and construction were based a on combination of wood and silicon-based materials like rocks and clay. Wood was the main source of energy and biomass was the main source of fibres. Even the economies of the ancient civilizations like the Greeks and Romans in Europe, the Shang and Zhou dynasties in China and the Maya civilization in the Americas were dominated by agricultural production (Tainter 1988). However, metals did play an important role in both in the military and agricultural realm, providing tools that allowed a significant increase in yields (Han and Duan 2009). Military success was important in economic terms only as long as the marginal returns of territorial expansion were favourable. When opponents were encountered that were of equivalent strength or of very low wealth, war become a bad investment (Tainter 1988; Han and Duan 2009).

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iron oxide is reduced to iron, but with the temperature not high enough to actually melt the iron. The product is a mix of iron and slag, from which pure, carbon-free iron is then produced through a process of repeated hammering (Raymond 1984).

2.2 Metals and wood: interlinked until 1740

The fact that wood/charcoal was the only fuel that could be used for the smelting of metals created a strong link between abiotic and biotic resources. Perlin describes how Cyprus, which at the time had huge copper ore reserves, was deforested twice because of the need for fuel for copper smelting: during the Late Bronze Age between 1500-1200 BC and during the Roman annexation, starting in 50 BC. He also argues that Roman wealth was to a major extent financed through silver production in Spain, which led to the deforestation of over 18,000 km^2 of woodlands. He blames part of the economic problems of the Roman empire after 200 A.D. on declining silver production as result of fuelwood scarcity in Spain, even though ample quantities of ore still remained (Perlin 2005).

Perlin describes how the close link between iron smelting and wood remained intact until 1750, leading to massive deforestation in England from the 16th to 18th century. The scarcity of wood became a serious constraint on economic growth, even after coal had become an important energy source. Halfway through the 16th century the navy started complaining about the shortage of timber for shipbuilding. In the late 16th century coal starts to replace wood for heating, despite the 'foul fumes' it produced. Perlin quotes Josiah Tucker, an economist of the time, who attributes this scarcity to "*the superior numbers of people and to the rapid progress which the inhabitants of the island have lately made in all arts and sciences, trades and manufacturers.*" The impurities in coal made it impossible to make iron of sufficient quality from unprocessed coal. Only after the process to derive coke from coal was optimized in the 1740s could coal substitute for charcoal. This allowed for the tripling of iron production in England in the period from 1750 to the end of the 18th century (Perlin 2005). Again, the substitution of one resource by another was forced by scarcity, but again it led to a significant technological breakthrough that allowed for increased growth. Wood remained an important resource during the industrial revolution, though, since it was extensively used in coal mining, where timber props were used to hold up the mine shafts (Perlin 2005).

2.3 The industrial revolution, conservationism and resource economics (1740-1930)

Just prior to the industrial revolution, the scarcity of wood paved the way for the use of (inferior) coal as a household fuel. In coal mining, pumps were needed to pump off water, which led to the development of the steam engine: perhaps the key ingredient of the industrial revolution. This revolution triggered a period of rapid economic expansion in the Western world that was literally fuelled by the availability of a relatively cheap and apparently inexhaustible source of (fossil) energy. This economic growth coincided with a huge increase in the consumption of base metals such as iron, copper, zinc, tin and lead. These metals were needed for building new infrastructure, railways, bridges and modern cities as well as steam engines, trains, ships and cars. At the same time, these new inventions and infrastructure provided a means of bulk transport and the heavy equipment and industry required for large-scale mining and refining (Burke 1978; Lundgren 1996).

Until the 18th century only nine metals were known to man: antimony, tin, lead, mercury, silver, copper, gold, iron and arsenic. From the time of the discovery of iron smelting, some 3000 years ago, it took until the late 19th century to find a way to free the only metal which is more abundant in Earth's crust: aluminum. The main reason for this late development was that aluminum oxide cannot be reduced to form aluminum metal by using carbon (charcoal or coke) as a reducing agent (the common process used to free other metals like iron and copper from their ores), simply because the chemical bond between aluminum and oxygen is stronger than that between carbon and oxygen. The industrial revolution and the introduction of cheap electricity paved the way for the electrolysis process that was used in the first commercial aluminum smelters, which became operational in the final decade of the 19th century (Raymond 1984).

About a century after the start of the industrial revolution the issue of fast-depleting (national/continental) resources, biotic, mineral as well as environmental, was recognized by governments and scientists. This resulted in a strong movement of conservationists, led amongst others by Theodore Roosevelt. In the US this resulted in the regulation of the use of natural resources and the creation of national parks. In 1908 Roosevelt called a special Governor's Conference on Conservation at the White House which focused on the depletion of natural resources within the US (Geiser 2001).

During the same period economists like Gray (1914) and Hotelling (1931) developed the first theoretical economic frameworks of so-called exhaustion theory (Gordon and Tilton 2008; Robinson 1989). One of the results of their efforts was the idea that a mine owner will always maximize the returns of the deposit by distributing the extraction over time (Hotelling 1931). The cake should thus be eaten at just the right rate to maximize the returns. For example, if the price of a resource is expected to rise in the future, the mine owner will halt extraction and wait for these higher prices. The reduced rate of extraction would drive up prices to a level equal to the anticipated future price. If this simplest version of Hotelling's exhaustion theory indeed holds, current resource prices would be a good indicator for future scarcity. However, Hotelling assumed completely rational actors with access to perfect information about the future and in practice, therefore, his theory does not hold.

A good example is the discovery of a giant gas field in the north of the Netherlands in 1959. This discovery was made at a time that the mainstream opinion was that science in general and nuclear power in particular would make energy virtually free. The Dutch government therefore decided that the natural gas in the Groningen field should be capitalized as soon as possible, i.e. before it became worthless. It started a huge infrastructural project to introduce natural gas as a fuel for domestic heating and cooking, for industrial and horticultural use and for power production. A dense distribution network of pipelines was constructed and long-distance pipelines were built to export the gas to other European countries. Of course, energy never became a free resource and current natural gas prices are much higher than those in of the 1960s, when this strategy of quick capitalization was implemented.

Since the publication of Hotelling's theory it has been refined frequently within the field of mineral economics which emerged as a separate academic discipline after World War II (Gordon and Tilton 2008).

2.4 World War II and the take-off of consumerism (1930-1970)

World War II led to huge worldwide destruction and rapid technological development. After the war this led to an increased demand for mineral resources for rebuilding the lost infrastructure and producing all the newly developed consumer goods. In addition, the supply of minerals was hampered by the dwindling resources in developed countries, the weakening or severing of colonial ties and the disruption of normal trade patterns caused by the start of the Cold War (The President's materials policy commission 1952; Geiser 2001). In the US *The President's Materials Policy Commission* (known as the Paley Commission after its chairman[5]) was established in 1951, during the Korean War. The commission was charged "*to make an objective inquiry into all major aspects of the problem of assuring an adequate supply of production materials for our long-range needs and to make recommendations which will assist me in formulating a comprehensive policy on such materials*" (Truman 1951). The commission's report laid down the basic principles of the material scarcity debate, including the formulation of possible policies and research agendas. It framed the depletion problem as a problem of resources that are harder to retrieve: "*The threat of the Materials Problem is not that we will suddenly wake up to find the last barrel of oil exhausted or the last ton of lead gone, and that economic activity has suddenly collapsed. The real problem and deeply serious threat is that we shall have to devote constantly increasing efforts to acquire each pound of materials from natural resources which are dwindling both in quality and quantity; thus finding ourselves running faster and faster in order to stay standing still. In short, the essence of the Material Problem is costs. The real costs of materials are not measured primarily in money; they lie in the hours of human work and the amounts of capital required to bring a pound of industrial material or unit of energy into useful form*".

[5] William S. Paley was best known for his turning CBS into one of the largest broadcasting corporations in the US after he bought the company in 1927.

In many areas the commission's conclusions can easily be translated to current times. For example, it was stated that:

- technologies should be developed in the areas of exploration of new deposits, recycling, bio-based materials and substitution of scarce materials by more abundant ones;
- resources should be used less wastefully and that waste should be treated as a source of materials;
- there should be a shift of focus in the research community (both in academia and in private firms) from the generation of basic knowledge to the application of this knowledge;
- there is a trend towards more complex alloys and electronics that will require more exotic materials;
- there is a gap between developed Western nations that have depleted the best of their own resources and the developing world that is poor but still resource-rich. The commission argued that free trade and the income generated by exporting raw materials will help these developing countries to increase their standard of living, which in turn will lead to more exports of US high-tech products to these countries. It also emphasized the need to invest in resource-rich countries to improve their industrial capacity and infrastructure;
- despite many decades of resource depletion and wasteful resource use, resources had never before been in more ample supply and that therefore this might well be true for coming generations;
- the resource base of societies shifts over time and it is therefore hard to predict which resources should be saved for coming generations;
- industries are only interested in materials research when confronted with a crisis;
- the problems of resolving the scarcity of materials do not lie in the realm of high scientific difficulty but in costs;
- the problem of material scarcity cannot be solved only by physical science; social science, economics and political science are just as important and a combined effort by industry, academia and government is needed to resolve this issue;
- oil is a great energy source for now, but sooner or later a return to coal (possibly via underground gasification) and/or shale oil will have to be made. Energy efficiency is key to a sustainable energy supply and cars should be made far more efficient.

The commission took a strong stand against self-sufficiency as a leading principle for securing supply. In contrast, it propagated the Least Cost Principle as leading: the main aim of any resource policy should be to supply the nation's industry with the cheapest resources. It therefore also focused on international free trade and investing in resource-rich countries as something that should be promoted by policy makers. It also stated that tariffs and other restrictions on trade would have a detrimental effect on the resource availability. However, at the same time it proposed the expansion of national stockpiling of materials and bilateral agreements with resource-exporting countries, both of which disrupt free markets and trade. The stockpiling strategy that followed until the end of the 1950s was in fact used to keep resource prices high in support of domestic mining in an attempt to retain self-sufficiency, and thus against the advice of the commission. It was driven by fears that the Cold War might turn into a hot war and that domestic supply of materials would be essential for victory. This policy resulted first in artificially high world market prices and, after the policy was abandoned, in huge stocks with a much depreciated value. In turn, these high prices gave foreign producers a chance to build there own mines and refineries, which after this period of stockpiling outcompeted US mines, with a disastrous effect on US mining (Huddle 1976).

All in all, the report of the Paley commission was a landmark in the debate on resource scarcity. Many of the arguments and analyses can readily be translated to the current debate. However, after the Korean War commodity prices relaxed and a period of relatively little concern about materials scarcity followed until the oil crisis of the 1970s (Radetzki 2008).

2.5 Environmentalism, the oil crisis and the framing of sustainability (1960-1980)

In 1952, mainly as a result of the Paley report, *Resources for the Future Inc.* (RfF) was established as *a non-profit corporation for research and education in the development, conservation and use of natural resources.* It was financed by the Ford Foundation and Paley himself took the job as Chairman of the board of directors. In 1963, RfF published a book by Barnett and Morse in which an empirical analysis was made of resource scarcity for the US in the period 1870-1958 (Barnett and Morse 1963). Their main conclusion was that no empirical evidence could be found for increased scarcity, but that in fact the availability of all resources had increased during that period, with the sole exception of forests.

However, the 1960s also marked the start of awareness of the environmental consequences of exponential growth in industrial activities and connected material flows. With her book “Silent Spring” Rachel Carson brought the environmental problems caused by the widespread use of persistent pesticides to public attention (Carson 1962). In 1968 Paul Ehrlich sketched a Malthusian doom scenario for the decades ahead (Ehrlich 1968). In his analysis, global food production would be unable to keep up with exponential population growth, and starvation would be the fate for millions.

In 1968 the Club of Rome was founded as a global think-tank on a variety of issues and in 1972 its report "The Limits to Growth" was published (Meadows et al. 1972). The report demonstrated the interdependence of the world’s economies and the vulnerability of resource-importing countries to supply disruptions. As with the Paley report, the Club of Rome triggered a debate about materials scarcity and again much of the discussion of the 1970s can easily be translated to the debate underway today. Security of supply, strategic stockpiling, self-sufficiency, recycling and dematerialization were back on top of the political agenda.

The "Limits to Growth" report, which was published as a book, was unique because the first computers made it possible to create system dynamic models that could be used to calculate the effects of different scenarios on resource depletion and emissions. About a year later, in October 1973, the first oil crisis was a fact and the resource dependency that had been described by the Club of Rome moved from being an academic exercise to an event that disrupted everyday life in many parts of the world. If there was ever a time that resource scarcity received wide public attention, it was then. The report's main conclusion was that if the exponential growth of population, industrial activities and resource use remained unchecked, the result would be resource depletion and collapse of environmental quality by the middle of the 21st century. Although the report received a lot of criticism and certain assumptions were over-pessimistic, recent updates and analysis have shown that in many respects the global economy is still following the path of the scenarios described in "Limits to Growth" (Turner 2008).

The scientific community regained interest in the topic, which in February 1976 culminated in an entire issue of Science (Volume 191, Number 4228) containing 25 articles devoted to materials but with a focus on scarcity. Again, as with the Paley report, many of the articles can easily be translated to the current debate. The range of topics addressed in these articles show that the discussions of the problem, including possible strategies for solutions, are very similar to those at the time of the Paley Commission and the ongoing discussion today.

Cook discusses the limits to the exploitation of non-renewable materials (Cook 1976). His first observation is that in the previous two centuries the cost of resources has decreased and reserves have increased. However, he also finds that over the same period the energy intensity of resource recovery has increased as ore grades have declined. He argues that this can be explained by decreasing real costs of energy. He does not believe this trend will continue much further in the future, because of decreasing efficiency of the production and conversion of energy resources. He argues that the efficiency of energy conversion is approaching the thermodynamic limits, while the energy required for recovering certain resources is increasing exponentially. Similar arguments concerning thermodynamic limits of mining and refining efficiency can also be found in more recent work (Ayres 2007)

Blum discusses the possibility of tapping the resources present in municipal waste (Blum 1976). He recognizes that recycling is a means and not an end in itself. While terming municipal solid waste an "*urban ore*", he considers that although we have the technology to recover most of the components it contains it is not always economically prudent to do so. Urban mining is now a common phrase that is used by waste processors and industrial ecologists when they discuss recycling and urban materials stocks (Kapur and Graedel 2006; Krook et al. 2011).

Chinoweth describes the importance of electronic equipment with respect to both the demand for more exotic materials and its potential to reduce demand for materials and energy (Chynoweth 1976). He starts by pointing out the enormous potential of miniaturization. As an example he takes the pocket calculator that replaced the electromechanical desk-top calculator, which was far bulkier and more materials-intensive. At the same time, however, he recognizes that electronics are more complex in terms of materials composition. In a telephone he counted 42 chemical elements, present as 35 metals and alloys, 14 types of plastic, 12 varieties of adhesives and 20 different semi-conductor devices. A similar study of current mobile phones has also found over 40 elements in these devices (Meskers and Hagelüken 2009). Chynoweth also discusses the vulnerability of the electronics industry to the export policies of raw material-producing countries. He concludes, though, that these risks for the sector are probably low, because the value of the materials is relatively low compared with the price of the products. The electronics industry would thus be better able than other industries to absorb raw materials price increases. When it comes to the potential for of raw materials substitution he is fairly negative, because the materials have already been chosen in such a way that the overall performance of components is optimized. More generally, he argues that "*the more a society depends on complex and sophisticated equipment, the more vulnerable it is to scarcities of certain key materials, even if these are used in very modest amounts*". He also includes a Life Cycle thought in his analysis when he discusses, in quite similar fashion to Williams and Ayres a quarter of a century later (Williams et al. 2002), that although the amounts of materials in semi-conductor devices are themselves very small, a far great quantity of materials is required for their production: *"It could well turn out that the principle material constraint on the availability of electronic devices will not be in the electronic material itself, but the availability of the necessary processing chemicals. Also, it should be kept in mind that the small quantities of electronic materials often represent not insignificant expenditures of energy in obtaining them*". He also examines the potential of electronics for reducing demand for materials through functional innovations. He mentions innovations that are common practice today, e.g. the potential for telecommunications to reduce personal travel, including telecommuting ("*communicating to work rather than commuting to work*") and the internet ("*wired community*"). He goes on to give other examples that can now be found all around us: sensors that increase the efficiency of vehicle fuel combustion or monitor room occupancy to control lighting and heating.

Claassen describes the material needs of advanced energy technologies (Claassen 1976). Although climate change was not yet on the political agenda, he focuses on the materials required to increase the efficiency of existing energy technologies and the technologies to decrease dependency on exhaustible fossil fuels. Since many elements of energy infrastructure require thermal conversion processes, he argues that there is a need for materials that can resist higher temperatures. In general, higher temperatures would allow for more efficient thermal energy conversion. Although in general he is not worried about shortages of supply of the materials needed to increase the efficiency of the energy system, he points out a number of examples where these problems might occur: 1) chromium, used in the alloys required in many parts of the system, mainly because it comes from a limited number of countries with unknown future political stability; 2) gallium arsenide, needed for thin-film PV cells, for which it is easy to calculate that reserves would not allow for substantial scale-up, and 3) platinum for fuel cells, for which the same holds true. He expected that solar cells would be based on abundant materials like silicon, copper and sulphur and that molten carbonate fuel cells with nickel-based electrodes would be a good alternative for fuel cells with platinum electrodes. Interestingly, all these issues are still being discussed today (Wadia et al. 2009; Råde and Andersson 2001; Kanan and Nocera 2008). He also sees a problem in the supply of equipment made from abundant bulk materials. To illustrate this, he points to shortages of steel pipes, generators and turbines, as well as draglines and mine trucks and other items with a long delivery lead time. Today, the extractive industry is still haunted by a triple pork cycle between material demand, mining investments and supplies of draglines, mining truck tyres and other mining equipment.

Carpenter describes the tension between materials and environmental quality (Carpenter 1976). He starts by framing the problem as a problem of rapidly increasing demand for raw materials, combined with a lack effective management of material flows which results in both depletion and pollution. He also discusses the fact that ore grades are deteriorating and that this will cause increasing energy requirements and environmental impacts of mining and refining. Again, these are issues that are still being debated today (Mudd 2010, 2007; Norgate and Haque 2010; Norgate 2010). He is not very positive about the bio-based economy and notes that agriculture is in itself an important source of diffuse pollutants like fertilizers and pesticides. He believes that economic instruments and the internalization of environmental costs in raw material prices are the best way to manage the environmental effects due to the production of these materials. This discussion is well reflected in today's debate on biofuels and bioenergy (Doornbosch and Steenblik 2007).

Fried discusses the international trade in raw materials (Fried 1976). He describes how the enormous fluctuations in raw material prices are due mainly to rapid changes in demand. He eases fears that resource-exporting countries might use their exports as a political weapon, as the OPEC did during the 1973oil crisis, arguing that oil is unique in both in its importance and its unequal distribution over the globe and in the fact that there is an international organization governing exports (OPEC). He favours the free market without trade barriers as the best way to achieve an adequate supply of materials and does not believe in resource diplomacy. We have now seen that this depends very much on the type of mineral resource cocnerned and on the organization of the production chain. Although deposits of rare-earth elements can be found in many places on every continent, the fact that 95% of production is now in the hands of a single country makes it a possible to use it as political weapon. Chinese export quota have led to official complaints within the framework of the WTO.

In 1980 a famous wager was entered by Julian Simon (with a background in business administration and business economics) and Paul Ehrlich (with a background in population studies and biology). In the late 1960s and 1970s Ehrlich had written a number of books and papers on the disastrous consequences of an exponentially growing population, predicting Malthusian collapse. Simon, a true cornucopian, believed that population growth should be regarded as growth of human capital, which he calls *the ultimate resource,* and thereby a source of innovation (Simon 1981). Simon asked Ehrlich to pick any raw material and any date in the future, further than a year away, and he would bet that the material's price on that date would be lower than at the time of the wager. Ehrlich and some of his colleagues chose copper, chromium, nickel, tin and tungsten and a period of 10 years starting in 1980. The outcome of the wager is illustrated in Figure 1-1.

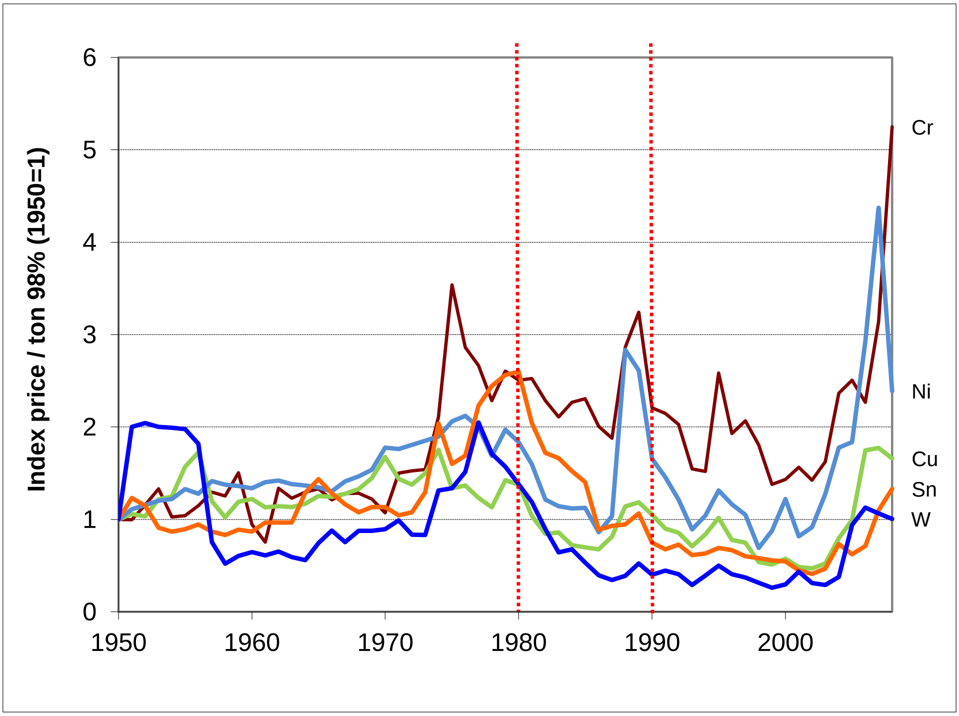

Figure 1-1: Index of price/ton 1998$, 1950=1 for the metals included in the Simon - Ehrlich wager. Data source: USGS.

Figure 1-1 shows that Ehrlich and his colleagues lost the wager and that their timing was not very good. If the wager had been accepted two years earlier or five years later, Ehrlich would have won. Ehrlich explained the loss of the wager as a combination of the drop in oil prices in that period and the economic recession in the 1980s (Ehrlich and Ehrlich 1998). However, in the period of the wager only the price of tin actually correlates well with the oil price. Furthermore, metal prices kept on decreasing through the 1990s, a period of global economic growth. Looking at the development of mining of different bulk metals (see Chapter 5) it seems more reasonable to assume that the reason that Ehrlich lost the wager was that metal demand per capita in the OECD stabilized in the period from 1975 to 2002.

2.6 Dematerialization in the OECD and the metals boom (1980-2011)

Again, this period of high commodity prices was followed by a period of relative abundance of cheap commodities. Bulk carriers were still getting larger and combined with low fuel prices this led to a period of extremely low transport costs (Lundgren 1996). The scale-up of mining also provided economic advantages, which pushed down metal prices despite annual growth rates in mine production of 3-6%. Metal prices remained low until what is referred to as the 'great metals boom' (Humphreys 2010), which in fact was a big boom of all commodities, as can be seen in Figure 1-2. The rapid exponential growth in emerging economies in the 1990s and 2000s increased demand in those countries from negligible to substantial around the year 2000. This boom in demand was mainly a result of the rapid build-up of the so-called BRIC countries, most notably China. During that period the prices of non-fuel commodities almost doubled in real terms.

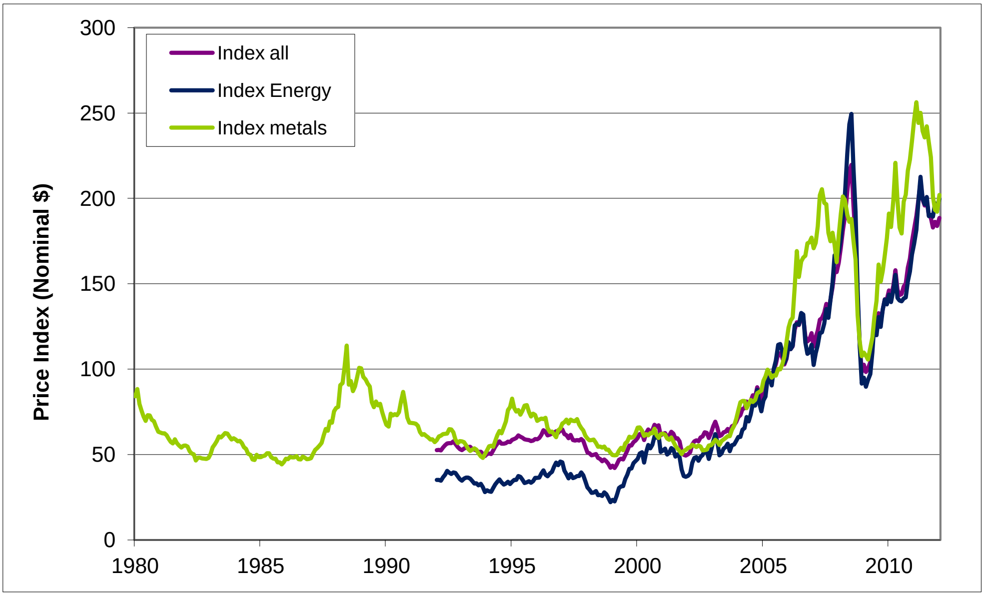

Figure 1-2: Price index of commodities, nominal $. Data source: IMF.

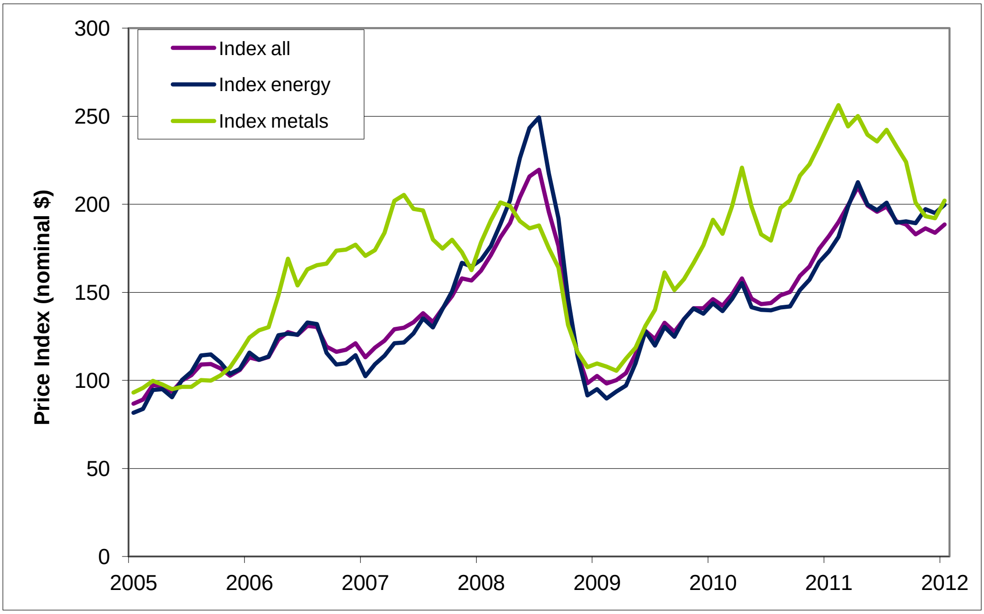

Figure 1-3: Price index of commodities, nominal $, Data source: IMF.

Although the global financial crisis that started at the end of the summer 2008 caused a significant price decrease, prices only very briefly reached pre-2002 levels (Figure 1-2). Although the crisis lasted until mid-2009, non-fuel commodity prices started rising again as early as March 2009 (Figure 1-3). Prices peaked again in February-March 2011 at a level almost 20% higher than that of the 2008 peak. After that the European sovereign debt crisis again caused concern about the global economy, leading to a fall in commodity prices. In November 2011 non-fuel commodity prices were back at the level of the 2008 peak (Figure 1-3).

In the period between 2002 and 2011 a number of publications by authors well familiar with the mining industry showed concerns about the supply of metals (Humphreys 2010; Mudd 2007; Norgate 2010). Degrading ore grades, the decreased deposit size of newly found deposits, constraints in the supply of water and energy, and increased local and global environmental concerns were all cited as causing cracks in the supply lines.

As a result of the 2002-2008 metals boom and recent supply constraints on certain rare (earth) metals, many governmental organizations, NGOs and research organizations have issued reports in which critical materials for the local and global economy have been defined[6]. All the world's major economies are now assessing the

[6] (RWI et al. 2006; National Research Council 2007; Morley and Eatherley 2008; National Institute for Materials Science 2008; Angerer et al. 2009; Ad-hoc Working Group on defining critical raw materials 2010; Statistics Netherlands 2010; U.S. Department of Energy 2010; American Physical Society &

possible impact of metals scarcity and policy measures, including the mechanisms of the WTO, to ensure free commodity trade, national stockpiles for strategic materials and bilateral agreements with supplier countries. The establishment of the UN Resource Panel is a clear sign that the international community deems resource-related issues to be a major concern for the coming decades.

The question is whether the current episode of apparent metals scarcity is any different from the scarcity episodes society has faced in the past. In the past, scarcity has always been a temporary issue and was followed by periods of abundance, either through technological progress increasing mining efficiency and allowing access to formerly unsuitable deposits, or through the scope for accessing new materials to replace the old ones. Will this happen in the present period of scarcity? There are some indications that solutions from the past now no longer work. This question will be addressed further in Chapter 5.

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