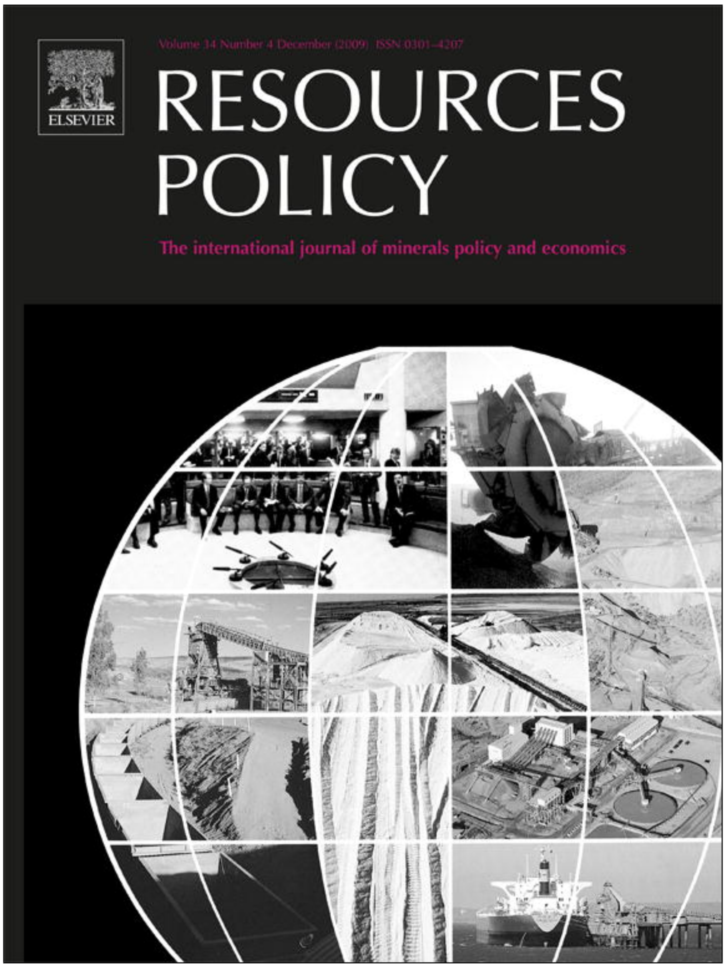
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Seven thousand years in the service of humanity—the history of copper, the red metal ☆

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ABSTRACT

Measured by weight, copper is the third most important metal used by man. The annual value of its 2007 output was on a par with the GDP of e.g. Ukraine. Copper is also one of the oldest metals, its employment going back 7000 years. For millennia, it was predominantly employed for decorative purposes, coinage and in warfare. Technical breakthroughs in antiquity, like smelting and alloying, expanded its production and enhanced its utility. Copper's true heyday occurred after 1850, with the usage of electricity. In the period since then, volumes increased 300-fold, while costs and prices declined. With impressive progress in the technology of its production and consumption, the red metal has been able to hold its own, despite the emergence over history of formidable substitutes like iron, aluminum, plastics and optic fiber.

Now

In 2007, world refined copper consumption added up to a total of 18 million tons (Cochilco, annual). With the world's population a bit above 6 billion, that corresponded to some 3 kg per head, making copper the third most important metal (in terms of weight) in the service of man. Only iron (940 million tons) and aluminum (43 million), two comparatively new arrivals in a long historical perspective, were produced and consumed in greater quantities. In comparison with zinc (11 million tons), lead (4 million), nickel (2 million), tin (0.3 million), molybdenum (0.2 million) and silver (0.02 million), the red metal appears as a true giant (USGS, annual).

2007 was an exceptional year for most commodities, with greatly inflated prices and profit levels. The average price of copper, $7130 per ton, exceeded the annual quotations in any year since 1850 by a wide margin. Even when measured in constant dollars, the 2007 price emerges as one of the highest on record since 1920. The value of refined copper consumption in 2007 works out at $128 billion, a huge amount, only slightly below the GDP of the Philippines (population 88 million) or Ukraine (population 46 million).

The worldwide average total cost of refined copper production in 2007 has been assessed at $2305 per ton (Cochilco, annual), yielding a profit of $4825 per ton, or $87 billion in aggregate, a number which can be compared to the global foreign assistance flows in that year, amounting to a bit more than $100 billion.

The 2007 copper volumes and values presented above are of course dwarfed (BP, 2008) by those of oil (consumption of 3950 million tons, valued at $2000 billion) or hard coal (4800 million tons, valued at $340 billion), but even so, the copper industry emerges as a significant player in the mineral world.

Given its malleability, ductility, conductivity of both heat and electricity, ability to withstand corrosion, and its esthetic characteristics, copper has established numerous crucially important uses in virtually all branches of mature industrial or more newly industrializing economies, most notably construction, transport, telecom, and all kinds of electrical and electronic appliances. Even though substitution in favor of aluminum, plastics and glass fiber is always a threat to copper demand, it is hard to conceive a modern society managing without a large-scale and secure copper supply.

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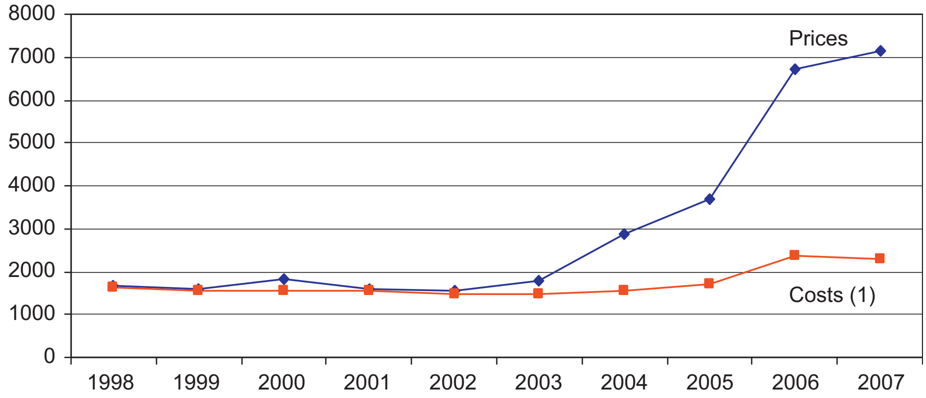

Fig. 1. Copper prices and costs, current $ per ton. (1) Brook Hunt's composite total costs (C3) which include direct cash costs, depreciation, interest and indirect costs. For mines where more than 65% of revenue comes from copper, this includes a credit deduction for copper byproduct sales. In all other cases, copper and copper byproduct costs are prorated per share of revenue. *Source*: Cochilco (annual).

The decade since 1997 has been quite dramatic for copper. As is apparent from Fig. 1, the exceedingly elevated prices and the concomitant high profits are very recent phenomena.[1] Prior to 2004, the average annual price level was stubbornly suppressed at below $2000 per ton, and the profits of the industry remained quite meager. In 1998, the output of 13.4 million tons yielded sales worth no more than $27 billion and an aggregate profit of less than $400 million. The following year was even worse. In the period until 2004, shown in the figure, the industry was in deep depression, and had to implement savage cost cutting measures to assure corporate survival, sometimes to the extent of neglecting maintenance or cannibalizing existing installations (Crowson, 2008).

The developments which followed in 2004 and onwards came as a completely surprising blessing to the raw materials suppliers. The trigger to the sharp shift in the markets for many commodities in that year was a sharp jump in demand, to which suppliers with dilapidated production facilities could not respond. Consumption of copper expanded by an average of 3.5% per year during the decade under scrutiny. In 2004, however, it rose by an exceptional 8.8%. The expansion of supply in response to rising prices has been slow and drawn-out, so inadequate supply and high prices have characterized the copper market during several following years.

China and Chile dominate the contemporary dynamics of the copper world (Cochilco, annual). Chinese refined copper consumption expanded by an annual 15.3% in the 1998–2007 period, and in fact accounted for three quarters of the global consumption increase in that decade, reducing the rest of the world growth to 1.2% per year. The period since 2000 records an even more dramatic development, for in these seven years, consumption growth in China equalled 100% of the global total, implying complete demand stagnation in the rest of the world (copper usage in the US between 2000 and 2007 actually fell by 28%). By 2007, China's share of global copper usage was 26.9%, up from only 10.5% ten years earlier, importantly as a consequence of the wholesale shift of the world's manufacturing capacity to that country.

In 2007, Chile's copper mine production (Cochilco, annual) had reached 5.6 million tons, expanding by 1.9 million over the preceding decade. The country's output represented 35.8% of the global total, up from 30% in 1998. This is the latest phase, going back over several decades of an increasing Chilean role as copper producer.

With China and Chile so dominant as consumer and producer respectively, it is not surprising that international trade plays a very important role in the world of copper (Cochilco, annual). Exports in 2007 comprised 13.4 million tons, almost three quarters of global output. China imported a total of 2.8 million tons, close to a quarter of global imports, up from its share of global imports of only 5.7% in 1998. Germany, the US, South Korea, Italy and Taiwan each purchased in excess of 5% of global imports in 2007.

Exports of copper were even more concentrated than imports, with Chile selling 5.7 million tons, 42.2% of global exports in 2007. Peru and Australia came in as distant second and third, with 9.4% and 5.0%, respectively.

The control of the world's primary copper output has been dominated by a group of colossal, internationally active miners. The Raw Materials Group (RMG) has collated data to determine this dominance, and Table 1 provides the results for 2007. Freeport in the USA and state-owned Chilean Codelco dominate among the copper mining giants, each with an annual output of close to 1.7 million tons. RMG's cumulative share for the eight largest miners in 2007, 53%, can be compared with 54% in 1974 (Mikesell, 1979), 70% in 1956 and 65% in 1935 (Herfindahl, 1959), suggesting a decline of concentration over time. Corporate concentration has not been exceptional compared with other metal industries in recent decades. Competitive conditions characterize the international market for copper.

The brief account of where copper currently stands in humanity's social, economic and technical endeavors, though reasonably well known to those directly involved with the metal, nevertheless provides an essential context to what follows. However, even the specialists seldom know where copper has come from, and when, to assume the important positions it holds today. There is a need, therefore, to tell the metal's history, from its humble beginnings some 7000 years ago and until now. This, then, is the purpose of the present paper.

From the dawn of history to the industrial revolution

The very early human usage of metals is surrounded by haze, but archeologists believe that the employment of copper as well as of silver and gold took place as early as 7000 years before present time (7000BP),[2] in the Middle East as well as in America (Patterson, 1971; Geology Project, 1996). It may appear a bit

[1] In the fourth quarter of 2008, copper prices fell sharply, and by early 2009, as the paper is going through final revisions, the price is about $3300, less than one half of the 2007 level.

[2] The notation BP (before present) is used for all dates older than 1000BP. For more recent dates, the conventional notations are employed.

Table 1
Corporate concentration in world copper mining, 2007.

Rank	Company	Country	Controlled output[a] (kt)	Share of global (%)	Cumulative share (%)
1	Freeport	USA	1680	11	11
2	Codelco	Chile	1670	11	22
3	BHP Billiton	Australia	1160	7	29
4	Xstrata	Switzerland	940	6	35
5	Rio Tinto	UK	800	5	40
6	Grupo Mexico	Mexico	780	5	45
7	Anglo American	UK	670	4	50
8	KGHM	Poland	460	3	53
9	Norilsk Nickel	Russia	430	3	56
10	Antofagasta	UK	430	3	58

Source: RMG (2008).
[a] Defined as either a majority ownership of a production unit, or a minority ownership with no other dominant owner.

paradoxical that these rare metals (copper's content in the earth's crust amounts to 0.006%, that of silver and gold considerably less) were the first to be used rather than e.g. iron and aluminum, representing some 6% and 8% respectively, of the crust (Alexander and Street, 1972). The explanation is that the former sometimes occur in nature in a pure nugget form, simply to be picked up and beaten to the desired form, given their malleability. The earliest usage of copper was geographically determined by its occurrence in this "native form", e.g. in Cyprus, Northern Iran and the Upper Peninsula in Michigan. The nuggets were shaped by hammering into ornaments or primitive tools like knives or axes.

Two interrelated technological breakthroughs, occurring maybe 5000BP greatly increased the copper supply, spread its use, and improved the quality of the goods in whose manufacture it was used. Both were possibly accidental.

The *first* was the invention of smelting, resulting from a copper containing mineral making contact with fire, whereby the copper ore was reduced into metal, leaving slag as a waste product from the operation (Alexander and Street, 1972). The occurrence of native copper is rare, so before smelting it imposed a severe limit on supply. This limit was greatly relaxed as humans mastered the technique of extracting the metal through smelting of abundantly available copper ores.

The *second* invention, the development of bronze, probably arose in smelting operations involving ores that contained both copper and tin. It was discovered that the resulting alloy, containing a few percent tin, was much harder than either of its components, and could hold a better edge for much longer, thereby overcoming the softness of pure copper. Unsurprisingly, regions with mineralizations containing both copper and tin, e.g. Northern Iran and Iraq developed a lead in bronze production and usage over other ancient cultures like Egypt, which obtained its copper from the Sinai peninsula, based on ores which did not contain tin (Geology Project, 1996). Brass, another alloy of copper and zinc, came to use much later, not until Roman times, about 1700BP (Copper, Technology and Competitiveness, 1988).

For about 2000 years, until the metallurgy of iron was mastered around 3000BP, copper and bronze were the dominant metals, employed predominantly for weapons, tools, weights and measures, water pipes, roofing for the nobility, household utensils like vessels, polished mirrors, even razors, and for artistic decoration, like jewelry and statues (Babylon to Birmingham, 1959, p. 26). Trade and the transfer of metallurgical technology spread their use through much of Asia and deep into Africa, while developments in the Americas occurred independently of those in the Old World. The discovery about 4500BP of immensely large and rich deposits of copper, silver, gold and iron at Rio Tinto in Spain, ascribed to the Phoenicians, significantly expanded global metal supply. The complex mining operations at Rio Tinto during antiquity resulted in a kilometer-wide crater, with a depth of more than 200 m and numerous remnants of Roman tunnels, shafts, and water wheels with bronze axles to pump water out of the pit. Remarkably, the deposit is still being mined (Geology Project, 1996).

Around 3000BP, iron production started to expand, and the new metal emerged as the first formidable substitute to copper, a precursor to aluminum 2900 years later (see following section). To begin with, the progress of iron was restrained by its costs, for although the new metal had superior characteristics in many uses, primarily somewhat lesser weight, and ability to maintain a hard edge, it was prohibitively expensive. An anecdote dated circa 2800BP tells about an Egyptian knife blade of steel with a handle of bronze, to save on the high cost of the former. However, the costs declined as the emerging iron metallurgy was mastered, and by 2700BP, the Assyrians are reported to have had successes in their war efforts due to the use of iron in the soldiers' helmets, the protective armor plates and the daggers (Babylon to Birmingham, 1959, p. 27, 42).

In the course of the following millennium (2700–1700BP), the usage of iron (later enhanced by the invention of steel) came to surpass the consumption of copper, with a widespread effect on the world's civilizations. Construction of all kinds of machinery on a large scale was not practicable before iron (and much later steel) had become cheap and plentiful. As noted above, bronze gear wheels and shafts had been used on occasion in Roman times, but since both bronze and iron were prohibitively expensive at the time, inferior wood was regularly used instead (Babylon to Birmingham, 1959, p. 26, 55). By the 16th century, when global copper output was below 10,000 ton, the output of iron had already reached about 300,000 ton (Babylon to Birmingham, 1959, p. 473).

While copper lost important markets to iron in an extended period of substitution, its versatility permitted the development of new important uses, where iron was less suitable. One such use was coinage, originally developed in what is now Turkey and Iraq about 2500BP, with gold and silver for the higher denominations, and copper for lesser values. At the height of the Roman civilization (2000BP), coinage came to account for a significant share of total copper consumption as well as of consumption growth (Healy, 1988). Coinage played an important role for copper demand in later times as well. At the end of the 14th century, Spain, then the economic giant of Europe, introduced copper as its standard of coinage. This resulted in a very strong price increase for the red metal, which in turn provided incentives for an extraordinary expansion of copper output in Sweden, making the latter country a virtual monopolist in Europe. Spain's decision as well as Sweden's, taken a few decades later, to use copper as their coinage standard, is surprising, given that both were important producers of silver, and that the copper coins were extremely cumbersome. The Swedish decision was internationally ridiculed. Some of its coins weighed up to 20 kg (Heckscher, 1954).

Additional important uses of copper prior to the industrial revolution involved roofing and bells for the churches that proliferated as Christianity gained a dominant foothold in the Western World. Iron, of course was unsuitable for these purposes on account of its corrosion characteristics and inadequate clang. Beginning about 1350, increasing amounts of copper were also consumed in the manufacture of bronze cannons, an implement that became decisive in warfare from the middle of the 13th century (Babylon to Birmingham, 1959, p. 113). Bronze dominated both land-based and naval cannon production well into the 19th century, when the Bessemer process dramatically reduced the cost of steel. Cast iron, since long far cheaper than bronze, and a competitor to the copper alloy in cannon production (Babylon to Birmingham, 1959, p. 255), was less suitable for cannons, since it was brittle and risked being cracked under the force of any explosion. The brittleness required iron cannons to be quite thick, and hence much heavier than those made of bronze, a clear disadvantage where cannons had to be moved, e.g. on ships or across terrain (private communication with Phillip Crowson).

Based on an extensive review of existing literature, Hong et al. (1996) make an heroic attempt to reconstruct global copper production over 7000 years, with some surprising conclusions. The most important surprise is the absence of a continuous expansion of output and usage. Instead, there are two spectacular production peaks surrounded by extended periods of much lower output levels.

In summary, the authors fail to quantify output in the first 3000 years covered by their investigation, but suggest that global production rose slowly between 4000BP and 2700BP (1300 years), with an average of 400 ton per year. Their assessment for 2650BP and 2350BP (300 years) points to a substantial increase to some 2000 ton on average. However, a truly impressive expansion took place only in the ensuing 600 years, marking the peak of the Roman civilization, based on production districts in Spain, Cyprus, Central Europe and Britain. Thus, between 2250BP and 1650BP, global output averaged 8000 ton, with an annual peak of 16,000 ton in the 150-year period straddling the birth of Christ. East Asia's annual contribution to the totals between 2250BP and 1650BP is assessed in the region of 1000 ton.

Production of all metals including copper began to decline with the disintegration of the Roman Empire from about 1600BP, so that by 1100BP, in the midst of the dark ages, the global total did not exceed 2000 ton. A very strong expansion then occurred in China in the following centuries, leading to a global peak late in the 11th century of about 14,000 ton per year (13,000 ton in China), which the authors attribute to the use of Chinese copper coins as standard money for international trade. Chinese production subsequently fell sharply, while that in Europe revived slowly, with the global total rising from a low of 2000 ton in 1300 to 6500 ton in 1650. In the latter year production in Sweden alone reached 3500 ton, with the export revenue providing the country with the finance to conduct its far-reaching European military endeavors (Heckscher, 1954).

By 1750, at the very beginning of the industrial revolution, global output was some 10,000 ton, of which 3000 ton in Europe. In that year, global per capita primary copper consumption amounted to 12 g, down from 70 g at the Roman peak (population numbers extrapolated from Maddison, 2001), and no more than 0.5% of the per capita level recorded in 2007.

The historical evolution of output recorded above must fairly reflect the developments in copper usage. However, it is important to point out that the overall copper availability has always been higher than the output of primary copper, given that recycling of old scrap from discarded copper containing products throughout history has added to the total (see Section 3).

Over the millennia prior to the industrial revolution, mining and metal extraction had of course undergone many improvements. Thus, better tools had been developed to work the rocks. Pumping drainage was introduced in Roman times. The Romans also widened the resource base from the easy-to-smelt oxide ores to the harder to handle but widely available sulfide ores. Thus, they introduced crude methods for extracting copper from sulfide ores through primitive heap leaching, and later through smelting. Explosives came to use early in the 17th century, and gradually replaced the traditional method of cracking the rock by fire heating and then drenching with cold water (Geology Project, 1996). Nevertheless, the technology of mining and metallurgy was still quite primitive, and the improvements introduced over long periods of time were quite insignificant compared to what would occur after 1750.

The Industrial Revolution until present times

1750 marks the beginning of Modern Economic Growth (Kuznets, 1966), a process of continued economic expansion based on science and technological innovation, that began in the UK, and then spread gradually to the rest of Europe and North America, to encompass over the last 50 years most of Asia and Latin America. Modern Economic Growth has fundamentally transformed the conditions of humanity. The Industrial Revolution, and its concomitant explosive expansion of all kinds of minerals and metals production and usage has been a key manifestation of the new era, and the copper developments to be accounted for in what follows are an inherent part of Modern Economic Growth. Table 2 updates for the most recent 250 years the very long-run supply numbers that were presented in the preceding section.

The present section is divided into two parts. The *first* discusses the demand explosion after 1850, a consequence of the many new uses and needs that arose as industrialization gained pace, and that absorbed copper in increasing quantities. It also provides accounts of the emerging substitutes that have repeatedly threatened copper demand and constrained the growth of its usage. Supply expanded in response to the explosive demand trends, and the *second* part of the section tracks the stupefying increase of production and availability, along with its geographical shifts in the modern economic growth era, recorded summarily in

Table 2
World mine production of copper.

Year	Kilotons	Cumulative growth (%/year)	Main producing countries (% share)
1750	10		China 70, Europe 30
1800	15	0.8	Europe 53, China 47
1850	53	2.6	UK 23
1900	490	4.5	USA 56, Spain 11
1910	890	6.1	USA 56, Mexico 6
1920	960	0.8	USA 58,Chile 10
1930	1540	4.8	USA 42, Chile 14, Canada 9
1940	2360	4.4	USA 34, Chile 16, Canada 13
1950	2490	0.5	USA 33, Chile 15, Zambia 11
1960	4420	5.9	USA 22, Zambia 13, Chile 12
1970	6340	3.7	USA 25, USSR 15, Chile 11
1980	7740	2.0	USA 15, Chile 14, USSR 13
1990	8990	1.5	Chile 18, USA 18, USSR 10
2000	13,230	3.9	Chile 35, USA 8, Peru 7
2007	15,520	2.3	Chile 36, Peru 8, USA 8

Sources: 1750–1800: Hong et al (1996); 1850–1960: Schmitz (1979); 1970–2000: Metallgesellschaft (annual); 2007: Cochilco (annual).

Table 2. The account then turns to the revolutionary technological achievements that made it possible to raise global output 300-fold since 1850, without encountering cost-increasing depletion.

Demand

Modern economic growth along with the industrial revolution, its main manifestation, may have started already in 1750, but its impact on copper was not fully felt until 100 years later. There are two reasons for this retardation. First, the industries that became the main absorbers of copper, did not emerge until this later time. And second, since the industrialization process began in a geographically limited area from which it spread only gradually, its initial impact on overall copper demand was slow. Even by 1800, the global consumption of copper was probably no higher than at the peak of the Roman Empire, almost 2000 years earlier.

There are reasonably reliable records of world mine production of copper since at least 1800, and Table 2 has provided the numbers. Overall copper consumption is somewhat harder to define and identify, certainly for the earlier parts of the investigated period. Clearly, consumption is higher than the output from mines, for the recycling of old scrap has to be added to the latter. The significance of old scrap in total consumption is directly related to the copper price, and inversely to the rate of growth of consumption and the longevity of copper products (Radetzki and Van Duyne, 1985). Numbers for recent decades suggest that old scrap contributed some 15–20% of overall refined consumption (Metallgesellschaft, annual; Cochilco, annual). The significance of old scrap must have been considerably higher in the 19th century and before, given the higher price, the slower expansion of demand, and the likely more extended longevity of copper products. This complex issue will not be pursued any further in the present context, and it will be simply assumed that the production numbers in Table 2 provide a rough proxy for consumption levels as well.

The modern history of copper is closely linked to the emergence and growth of electricity. Until about 1850, copper was regarded as a splendid metal with a somewhat limited use in roofing churches, making bronze bells, massive doors and brass hardware (Alexander and Street, 1972). All these uses have remained until the present. But the subsequent decades saw the evolution of electricity. A few landmarks in this industrial evolution should be mentioned. In 1866, a telegraph cable made of copper was successfully laid across the Atlantic. In 1876, Alexander Graham Bell transmitted speech through a copper telephone wire, and two years later Thomas Alva Edison produced an incandescent electric lamp requiring electricity to be brought to it through a copper wire (McMahon, 1965, p. 35). There followed in the next 100 years, waves of electrification that have covered virtually the entire globe in the most recent decades. Since high conductivity of electricity is one of the distinguishing features of copper, this path of industrialization led to a massive increase in demand for the red metal.

In the 20th century, copper's versatility has spread its use very widely among industrial and service activities that dominate prosperous societies. About half of total usage has remained in applications related to electricity. Copper cables and wires have been carrying electric current for power, light and telecommunications across long distances as well as inside buildings, cars, aircraft and appliances like washing machines, refrigerators, TV sets and computers. But copper's heat conductivity, corrosion resistance and malleability has also made it an attractive material in plumbing and heating applications, e.g. in car radiators, defrosters and air conditioners.

On several occasions, the evolution of copper usage has been restrained by the emergence of substitutes that successfully invaded some of its markets. The ancient story of the first such substitute, iron, has been briefly recounted earlier in this essay. To begin with, iron emerged as a superior alternative to copper in some applications, e.g. tools and weapons, but its use was constrained by costs—iron was considerably more expensive than copper. As the technology of iron production was perfected, its cost declined, making it a favored material in mass applications, e.g. for structural purposes, with volumes of consumption rising to many times those of copper. The role of iron as a substitute to copper was greatly enhanced by the perfection of steel production through the Bessemer process, brought into use in the 1850s, eventually reducing the cost of steel by 80% (Alexander and Street, 1972). Substitution of steel for copper in an increasing number of applications has continued to the present, importantly through the development of a plethora of specialty and alloy steels with tailor-made characteristics to suit particular needs. For example, the mass production of stainless steel from early on in the 20th century has lost substantial markets for copper in uses where anti-corrosion is of essence.

The story of aluminum as a substitute to copper is somewhat similar to that of iron and steel, though of a much more recent vintage. As recently as the 1860s, aluminum was produced in minute quantities, sold at very high prices, and used predominantly as a precious metal in the manufacture of jewelry and other decorative objects. Then, in the 1890s, its extraction technology experienced a breakthrough, which led to a dramatic price decline, followed, with a lag, by an equally dramatic expansion in its output.

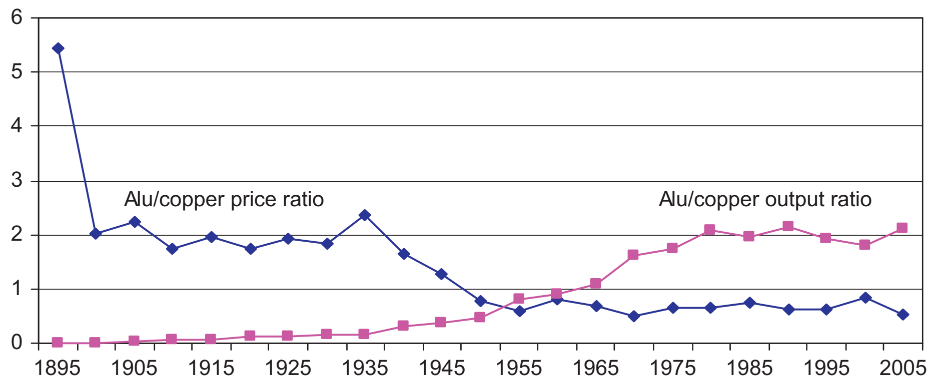

Fig. 2. Aluminum/copper price and output ratios. *Sources*: 1895–1970: Schmitz (1979); 1975–2005 prices: World Bank data; 1975–2005 volumes: Metallgesellschaft (annual) and USGS (annual).

Fig. 2 tracks the relative price and output ratios per ton of aluminum versus copper. Despite the sharp price fall at the turn of the century, aluminum remained twice as expensive as copper well into the 1940s, but since the 1950s, the price of aluminum has persisted well below that of copper. Until the mid-1930s, output remained insignificant, but the ensuing surge took aluminum production above that of copper by the 1950s, with levels twice as high as those for copper in the most recent 25 years.

Over the past half century, aluminum has undoubtedly been copper's most formidable substitute, taking over substantial market segments, on account of its conductivity of electricity and heat, its low weight, corrosion characteristics, and suppressed relative price. The incursions have not always been entirely smooth, however, and far from complete, as the following two examples indicate.

One important market in which the two metals have competed is that for car radiators. The substitution aluminum for copper has been restrained because copper, though more expensive to use, has superior corrosion and heat conductivity characteristics. Hence, a copper radiator will last longer, and less metal will be needed for a given cooling performance. More important, however, is that copper is malleable and easy to work with, simplifying and cheapening the manufacturing process, especially where soldering and brazing are involved. Even after 40 years of competition, copper is maintaining a 40% share of the car radiator market (Copper Development Association on the Web).

Aluminum has been taking over copper's traditional markets in important electrical applications. One such market is for overhead conductors and underground cables for carrying electricity. Though aluminum is not as good an electrical conductor measured per unit of weight, its lightness and tensile strength makes aluminum cables of a given carrying capacity both lighter and stronger and far cheaper than cables made of copper. For these reasons, aluminum has come to dominate long distance electricity transmission in recent decades. On the other hand, where space, cross section, ease of jointing and ability to stand high temperatures are of concern, e.g. in bus bars, switchgear, transformers and electrical generators, copper has been able to hold its own.

As these examples show, substitution is prompted by many characteristics apart from price. Nevertheless, sometimes price overwhelms other considerations, as the aside of silver demonstrates. Silver is superior to copper in terms of malleability, anti-corrosion and as electric conductor. Yet, on account of its high price, the ability of silver to penetrate copper's electric markets has been limited to minuscule segments where these characteristics are particularly important.

Over the past half century, copper has also faced challenges from plastics and optic fibers in some market segments. Thus plastics have partly replaced copper in piping fresh water into and waste water out of buildings. Plastics in such uses were initially introduced as an inferior, but substantially cheaper material than copper. Plastics have experienced faster product development than copper, because they represent a relatively new human invention, amenable to adjustments to specific human needs. Thus, plastics have been tailor-made for piping uses, improving such characteristics as durability or ability to withstand chemicals and heat, thereby strengthening their competitive position versus copper. There are even reports about aluminum–plastic composite water piping (http://www.toolbase.org/Design-Construction-Guides/Plumbing/copper-prices). Such pipes, made of aluminum tube that is laminated with interior and exterior layers of plastic, are said to be lightweight, flexible, strong and corrosion resistant, and particularly well suited for hot and cold water distribution indoors and outdoors.

The replacement of copper by optic fiber for message transmissions in telecommunication has proceeded at fast rates ever since their commercial introduction in such uses by the late 1970s (http://www.arcelect.com/fibercable.htm). The substitution process was initiated by telephone companies, later joined by cable television systems and local area networks. So far, it has mainly involved long distance trunk lines, while the ultimate local connection has, remained the preserve of copper. Substitution was prompted by the much higher productivity and substantially lower overall cost of optic fiber. Copper's losses in these market segments are deemed to be definitive. Like in the case of plastics, the fast product development of optic fiber is likely to strengthen its competitive strength and result in further incursions into copper's markets in the telecoms sector.

Copper has been in human use since the dawn of history, and is constantly under threat by materials of more recent origin, sometimes specifically created to satisfy a particular human need. All else alike, this characteristic of the substitutes, along with their relative recency can be expected to facilitate and speed up product development and innovation to a pace that the old copper industry may find hard to match. The repeated incursions of substitute materials into copper's various markets, recounted above, may provide a partial explanation to the brief nature and the ultimate lack of success of any attempts to exercise market power by coordinating producers. High prices stimulate substitution, and the market segments, once lost, may be hard to reconquer. The historically very high prices between 2004 and 2008, though not a result of monopolistic coordination, have clearly constituted a threat of demand shrinkage, if they had persevered.

But despite losing important markets to a series of challengers, copper appears to be holding its own, as the evidence of continuing production (and consumption) growth recounted in Table 2 above confirms. The long-run growth trend since 1900 has remained at 3.3% per year, despite accentuated competition with aluminum, plastics and optic fiber that copper had to face in the period. This growth rate of 3.3% through the entire 20th century, it can be noted, substantially exceeds world population growth of 1.3% over the period (UN Population Division, 1999). The per capita availability of copper has risen substantially in the past 100 years.

Supply

As noted, the impact of the industrial revolution on copper production occurred in force only after 1850, in direct response to the demand generated by the emergence of electricity. Table 2 reveals a cumulative annual growth in global mine output of 0.8% in 1750–1800, rising to 2.6% in 1800–1850, but the total extracted in the latter year, 53,000 ton, was still quite small in the perspective of what would follow. Then, from 1850 and until 1900, the annual growth of copper production accelerated to 4.5%, and output multiplied more than 9-fold, to reach almost 0.5 million tons at the turn of the century.

Output expansion subsequently decelerated to an average of 3.3% between 1900 and 1950, and remained at this level until 2007. This stability, however, hides substantial decadal shift, tracked in the table. For instance, there was a complete stagnation in the decades of the two world wars, and if these decades are excluded, the series exhibits a clear deceleration in the most recent 57 years.

Table 2 also depicts the geographical shift in mining production. China lost its extraordinary dominance after 1750, as the country's role in the world economy contracted. The UK, the vanguard industrial revolution nation, attained 23% of global copper output in 1850, but its role as producer then declined, both on account of a limited resource endowment, and as other nations gained economic weight in consequence of the spread of the industrial revolution.

Developments in the US followed a pattern, shaped initially by the country's resource wealth, combined later by an emerging prominence in mining technology. Virgin copper in the Upper Peninsula of Michigan was used since antiquity by the indigenes, but the utilization of this resource by white man began only in the mid 19th century (Benedict, 1952), marking the beginning of modern copper production in the country. This so-called Lake Copper has been described as "free metal that required only mechanical separation from the rock—though in some instances the chunks of metal were so large that they had to be cut down to be removed, masses weighing from one to 25 ton being far from rare." (Babylon to Birmingham, 1959, p. 123). By the 1870s, Lake Copper production accounted for 86% of national output (Herfindahl, 1959). The latter reached 23,000 ton in 1879, 15% of the global total (Schmitz, 1979). Towards the end of the century the center of gravity of US output moved towards the very large but lean porphyry deposits in Arizona, Montana and Utah, with the three states accounting for two thirds of national output (at 624,000 ton) in 1911–1915 (Herfindahl, 1959). The country's share of global copper output exceeded 50% from well before 1900 and until 1926. This share subsequently declined, but as recently as 1990, the US was on a par with Chile, as one of the world's two leading copper producers, each accounting for 18% of world output (Table 2).

Chile became an important copper producer based on domestic and British investments from the 1850s onwards. Easily accessible rich veins were exploited, output peaked in 1869, and then declined by half until 1891, as the veins were depleted. Early in the 20th century a new generation of mines, employing mass mining methods was developed with the help of US investments. By 1920, Chile had attained a 10% share of global output, and that share continued to expand until 1945 when it reached 22%. Although total production continued to rise, Chile's share of the global total shrank in the following decades, to reach a trough of 11% in 1970. This was the time of dramatic nationalization measures which brought the copper industry under complete government control and aroused prolonged conflicts with the former foreign owners. Subsequent policy changes brought the foreign investors back to Chile's copper resources, and the country's share started to expand anew. In 2007 it attained 36% of global output, far above the 8% each, attained by Peru and the US, the world's second and third producers, in that year.

Zambia temporarily held an important position as a copper producer, with peak output at 815,000 ton and a 15% share of world output in 1968, but the inefficiencies of its state-owned enterprises that took over after the 1969 nationalization (Radetzki, 1985) resulted in an absolute shrinkage to a trough of 250,000 ton in 2000 and a share of less than 2% (Cochilco, annual). The records of both Chile and Zambia point to the importance of policy, apart from natural resource wealth as a factor for success or failure in mining (Tilton, 1992).

Other nations which temporarily attained importance as global suppliers of primary copper comprise Canada and the USSR. The latter empire reached a share of 13% in 1970, but after the fall of communism, Russia the main follower state, along with Kazakhstan and Uzbekistan, have accounted for only half that share early in the new century.

Copper being an exhaustible resource, one would expect that the 500-fold increase in the volume of output from copper mines between 1850 and the present would have severely depleted the resource base. This would have resulted in a deteriorating quality and dwindling quantity of the resources available for exploitation, but as the following account will show, such depletion effects have by and large been avoided by cost reducing technological progress that occurred in the period.

Technological progress has occurred throughout history, but its pace has accelerated in the modern economic growth era. This paper has no ambition to explore fully how this process has impacted on copper supply. Instead, the following paragraphs describe a few spectacular technological breakthroughs that have been instrumental for the relaxation of scarcity and the evolution of costs.

The most spectacular among the cost saving technological shifts has been the switch from selective mining where metal-rich veins are carefully extracted, into mass mining involving the full utilization of large low-grade ore bodies (Julihn, 1932). Mass mining was introduced around 1900, but its impact on the shape of the industry and on costs was not fully felt until after 1915. The switch was akin to a move from handicraft methods to large-scale industrial processes. Several ancillary developments were made possible with the introduction of non-selective mining methods. Open-pit mining became far more practicable, and so was heavy blasting, thus making exploitation of massive low-grade porphyry copper deposits an economic proposition. These methods were not practicable with selective mining because they involved too much loss of metal in the precious veins.

The average grade of ore under exploitation sank dramatically, as mass mining methods were introduced, while the quantities of economically exploitable metal in the deposits exploded, in a sequence of events akin to those in pre-history that followed upon the invention of smelting (some 5000 BP). Fig. 3 sketches the evolution of average grades of ores under exploitation. As recently as the beginning of the 20th century, the average grades were close to 4%, but by the early 1920s, they had fallen to less than 2%, primarily in consequence of the spread of mass mining. (In 2006, according to the RMG, 2008, 45% of world copper mine output is extracted from ores with a metal content below 0.5%.) But at the same time as grades fell sharply between 1910 and 1920, the cost of production also declined. Herfindahl (1959) asserts that the size and rapidity of this cost decline was substantial, while Morison (1924) compares cost assessments for 1918 with 1923 to demonstrate a reduction in global costs of at least 20%.

The history of El Teniente, one of the largest Chilean copper mines provides an instructive illustration of what happened to the copper resource base as mass mining was introduced and lean copper ores became economical. This mine was closed in 1897, after some 50 years of operation, during which all its high-grade ores had been exhausted. It was reopened in 1912, now on the basis of a much larger low-content ore body. By 1920, this once depleted mine produced 20,000 ton, 20% of Chile's overall output (Grunwald and Musgrove, 1970). In the 1970s, El Teniente's proved economic reserves were considered sufficient for more than 50 years' production, and for much longer if the inferred and hypothetical ore resources were added to the proved ones (Radetzki, 1975). In the 21st century, El Teniente has been producing about 400,000 ton per year (20 times the output in 1920), making it the 5th largest mine in Chile (Cochilco, annual), with no depletion in sight.

A decline in the grade of exploited mineral ores would typically be viewed as a deterioration in quality and a sign of depletion, but then technological progress sometimes has implications that counter such a view. Not only did costs decline as mass mining methods brought meager ores under exploitation. The new mining technology also made the old methods redundant and neglected, as is demonstrated by the cost analysis undertaken by the US Bureau of Mines, of a small high-grade copper deposit discovered in Alaska in the 1950s. This deposit, which would have been perfectly suited for mining in the early years of the 20th

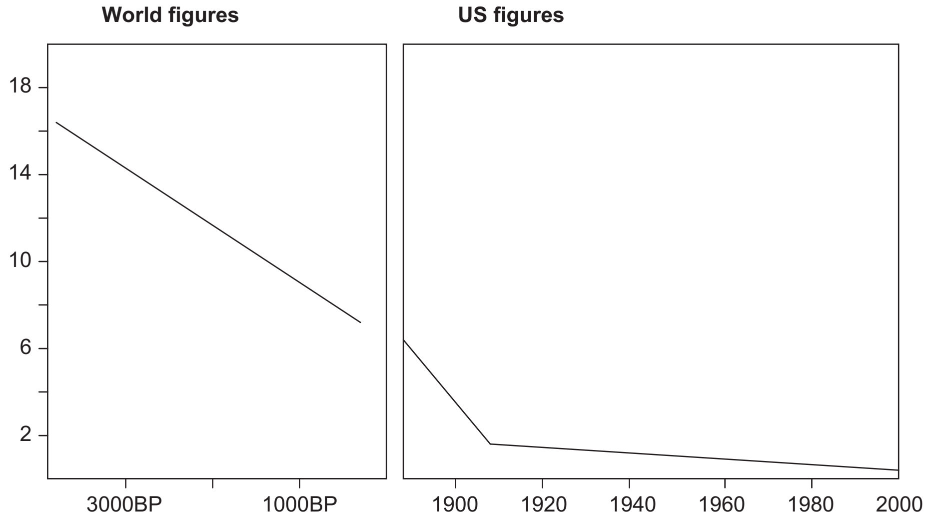

Fig. 3. Average grades of copper ore mined (percent). *Source*: Lowell (1970), updated by the author.

century, was proved to be utterly uneconomical 60 years later. Technological progress had moved in a different direction during this period, strongly favoring the size of ore bodies and reducing the importance of grades.

Not all deposits are suitable for open-pit operations, and a significant share of output continues to be generated in underground mines. Large-scale underground operations, e.g. Olympic Dam in Australia and Palabora in South Africa, typically employ non-selective mining methods such as block caving. The economics of open pits deteriorate with depth, sometimes necessitating going underground. The huge Chuquicamata open-pit mine may go underground in the coming decade, to access the deep parts of the ore body. Nevertheless, the share of underground output has continued to decline even in recent times. The assessments of the Raw Materials Group, covering 80% of global mine output in 1987, attribute 35.6% to underground operations. By 1997, that share had fallen to 30.1%, and to 24.5% in 2007 (RMG, 2008). The 1997 and 2007 assessments covered 90% of global output.

The introduction in the 1910s of fine grinding methods and milling by flotation to concentrate the copper carrying material to a metal content of some 30%, greatly facilitated the development of mass mining. It constituted another important, cost reducing and recovery-enhancing technological breakthrough in the production of primary copper (McMahon, 1965). Earlier methods of concentration involving a piece-meal and laborious process of mechanical separation could now be replaced by a continuous and far more productive process. Chance rather than conscious efforts with clear aims, was responsible for this innovation, just as it probably was for the introduction of smelting and the development of bronze during antiquity. When miners' dusty clothes were washed, it was discovered that the soap bubbles rising to the surface of the wash vessel were particularly rich in metal content, and thus the new technology of flotation was born.

Pyrometallurgy (smelting) and hydrometallurgy (leaching) are the two main alternatives for obtaining an almost pure copper metal. Smelting came first and continues to dominate the production of primary copper.

Crude leaching methods were employed already in antiquity (Geology Project, 1996). In the 20th century, these methods have developed along several paths, including, intriguingly, the use of microbes in the solution that is used to extract the metal. The main advantages attributed to leaching compared with traditional smelting comprise (Copper, Technology and Competitiveness, 1988):

- simpler installations, lower capital cost and faster start-up times
- lesser environmental harm
- the economic ability to operate small, shallow and very low-grade deposits
- extraction of metal from mining waste dumps for which the mining costs have already been incurred.

The important breakthrough that has come to dominate leaching is the SX-EW technology (solvent extraction–electrowinning), first taken into commercial use in the US in 1968, and still increasing its market shares. In 1980, the SX-EW technology accounted for 6% of US primary copper output, but by 1995 the share had risen to 27% (Tilton and Landsberg, 1999), and to 43% in 2007 (Cochilco, annual). The SX-EW technology has also attained a very wide international spread. In 1995, its output, 1.1 million tons, corresponded to 11% of global primary copper production. By 2007, the numbers had risen to 2.8 million tons and 18%. Chile accounted for two thirds of the SX-EW output in the latter year (Cochilco, annual). The fast expansion of SX-EW is not surprising, given that the global total average costs of this technology have been assessed at less than two thirds of those incurred in the traditional and still dominant production route (Copper Technology to Year 2000, 1996). Nevertheless, this technology is not suitable to all types of ore, and its global share appears to have stagnated in the present century (Bartos, 2002; Crowson, private communication). A new spurt to leaching can be envisaged once a cost-effective process to treat sulfide ores has been developed.

The adequacy of the economic and physical resource base to satisfy future copper needs

Mass mining, flotation and leaching have been chosen among the myriad of technological improvements in exploration, extraction and processing, with a cost reducing impact on primary copper output. How can all these improvements be summarized and juxtaposed against rising costs for whatever reason, to obtain an impression of the overall long-run cost evolution? This is an issue of some importance, for rising long-run costs represent accentuated scarcity and are a sign of economic depletion.

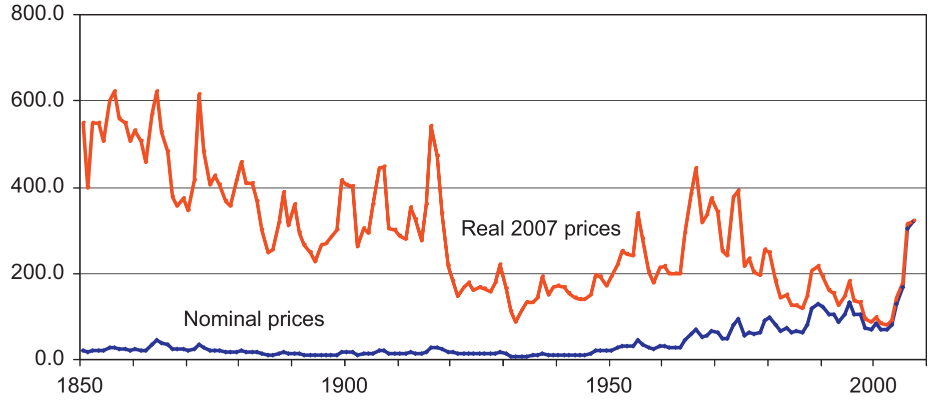

Fig. 4. Nominal and real copper prices 1850–2007, US cents/lb. London quotations converted into US$, and deflated by the US CPI. Data kindly provided by Jim Lennon, Macquarie Research Commodities, London.

Costs are not easy to observe and record, but in a reasonably competitive industry like copper the evolution of prices does provide a rough proxy of long-run cost developments (Radetzki, 2008). Fig. 4 tracks the nominal and deflated copper prices from 1850, when the major new industrial markets for copper started to develop, and until the present. A reminder on the produced primary copper volumes is in place: in 1850 it was 53,000 ton. By 2007, it was 15.5 million tons, 300 times more. The data do not support a case of economic depletion. The figure depicts a declining long-run trend in deflated prices through the entire period, even when the high prices of the 2004–2008 boom are taken into account.[3]

Economic depletion aside, one can consider the volume of proved reserves to get an impression of impending physical depletion. Proved reserves originate from mining companies and are the result of assessment practices that may vary over time and place. Nevertheless, the annual *Mineral Commodities Summaries*, currently published by the US Geological Survey (formerly by the US Bureau of Mines) have provided an extended series of reserve data. These sources indicate that global reserves have risen from 190 million tons in 1960 to 350 million in 1990 and 490 million in 2007. The latter figure corresponds to 32 years' production at current rates a reserve/production ratio considered to be comfortably adequate by the mining industry. The growing reserve numbers reflect net additions after deducting the very sizable extraction that has occurred between the years. Gross additions, through new discovery and appreciation of existing deposits must obviously have been considerably larger.

The cost and price conditions as well as the expanding physical resource volumes should assure the availability of copper to consumers, to match demand developments, and at prices not much different from the average of the past decades, once the present commodity boom has ended. Increasing amounts of copper will continue to provide useful services to humans for the foreseeable future, and probably far beyond, just as the red metal has done over recorded history and before.

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[3] This claim has recently been challenged, based on the assertion that commonly used deflators exaggerate inflation (Svedberg and Tilton, 2006).