Non-regenerative natural resources in a sustainable system of energy supply

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Following the lead of the European Union in introducing binding measures to promote the use of regenerative energy forms, it is not unreasonable to assume that the global demand for combustible raw materials for energy generation will be reduced considerably in the second half of this century. This will not only have a favourable effect on the CO_2 concentration in the atmosphere, but will also help preserve fossil fuels – important as raw materials in the chemical industry – for future generations. Nevertheless, associated with the concomitant massive shift to regenerative energy forms, there will be a strong demand for other exhaustible raw materials, in particular metals, some of which are already regarded as scarce. After reviewing the debate on mineral depletion between "cornucopians" and "pessimists", we discuss the meaning of mineral "scarcity", particularly in the geochemical sense, as well as of mineral "exhaustion". The expected drastic increase in demand for mineral resources due to demographic and societal pressures, i.e. due to the increase in in-use stock, is emphasised. Whilst not discussing the issue of "strong" vs. "weak" sustainability in detail, we conclude that regenerative energy systems – like nearly all resource-consuming systems in our society – do not necessarily satisfy generally accepted sustainability criteria. In this connection we discuss some current examples, namely, lithium and cobalt for batteries, rare earth-based permanent magnets for wind turbines, cadmium and tellurium for solar cells and even copper for electrical power distribution.

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Introduction

There is widespread agreement that developing (and even subsidising) regenerative energy forms is an important weapon in combating CO_2 emissions. Thus, the European Union has committed itself to achieving a 20% contribution of regenerative energy to overall energy production by 2020.[(1)] The individual targets for electricity generation, transport and heating in the various member states vary.[(2)] In Germany, for example, the 2020 target for regenerative energy forms is 18% with a 39% contribution to electricity generation. (The latter figure was 16% in 2010). For the UK the corresponding targets are 15% and 31%, respectively; for Denmark, with its strong contribution of wind energy, they are 30% and 52%, respectively. In coming decades it is expected that these levels will be further increased. The German government has already announced (non-binding) national policy targets of 50% and 80%, respectively, for 2050. Although most other countries at present still lag behind the EU member states, it is not unreasonable to assume that by the end of this century considerable progress will have been made globally towards achieving a sustainable energy system and that the demand for combustible raw materials, i.e. fossil fuels, will have been considerably reduced. These have accumulated over hundreds of million years in the earth's crust and are also a valuable source of carbon and its compounds for the chemical industry. De-fusing the anthropogenic CO_2 crisis will also leave some of these valuable natural resources for future generations. Moreover, the hope exists that this can be achieved, despite the expected massive increase in energy demand in the mainly non-OECD countries in coming years. Although we are still uncertain about the relative weighting of the regenerative energy forms constituting the supply system in the second half of this century, some assumptions can be made. Wind and hydro will obviously still play an important role; photovoltaic electricity production will be augmented by solar thermal arrays. Biomass, geothermal, tidal and wave energy may contribute substantially. Moreover, nuclear fusion, which has claims to the epithet "sustainable", [(3)] could also form part of the energy mix later in this century. Chemistry will be involved, for example, in the production of liquid or gaseous fuels using solar photons, as will bio-engineered photosynthetic organisms such as algae. Chemistry will also be important in the provision of electrochemical storage capacity or, perhaps in a more "conventional" way, in the development of new materials for energy generation technologies. Nonetheless, despite a new paradigm in the future energy supply system, there will still be a considerable demand for (non-combustible) raw materials, so-called mineral resources, some of which are already regarded – correctly or incorrectly – as geochemically scarce.

Unlike the other papers in this proceedings volume of the *ChemEner* conference the present invited paper is not concerned directly with the chemistry (or even physics) of energy conversion and storage. Rather, we discuss the concepts of "mineral depletion", "sustainability" and "scarcity" both generally and then specifically in the context of materials required for the production, transmission and storage of regenerative energy forms. It is noted that there are two opposing, and possibly non-reconcilable, schools of thought concerning mineral resource depletion and that more precise boundary conditions are needed for a satisfactory definition of "sustainability". Subsequently, we consider geochemical scarcity, which already appears to have some effect on markets, and adopt a pragmatic definition of mineral exhaustion. We then go on to consider in more detail a few examples of elements, such as lithium, the rare earths, cobalt, cadmium, tellurium, indium and even copper, which are, or may become, crucial for the regenerative energy industry and for which concern about geochemical scarcity has recently been expressed. The case of gold is also examined: although it is less relevant for the energy industry, there are interesting data to consider.

Several studies on the possible scarcity of mineral resources have appeared in the last two years,[4-7] whereby not only depletion, but also the specific requirements of new technologies as well as the issue of security of supply receive attention. The EU Joint Research Centre (JRC) report by Moss et al [7] deals specifically with several rare metals required for the generation of energy using low carbon technologies as defined in the EU Strategic Energy Technology (SET) Plan. (We prefer the adjective "rare" in this article, rather than "scarce", which is actually more usual, in order to avoid confusion with the term "scarcity" which we use here solely in the sense of economic or geochemical scarcity.) There is, as expected, some overlap with the list of examples above. Unfortunately, we only became aware of this report during the final stages of revision of the present paper and have not been able to make use of some of the interesting data compilations it contains.

Mineral depletion, scarcity, and sustainability

The first warning that the non-regenerative resources of the earth's crust cannot be exploited indefinitely is normally attributed to Meadows *et al* in their Club of Rome Report in 1972.[8] In fact, the discussion is much older and dates back to the beginning of the twentieth century, at least in the US. We cite here the economist Hotelling, for example, who wrote in 1931:[9] *"Contemplation of the world's disappearing supplies of minerals, forests, and other* *exhaustible assets has led to demands for regulation of their exploitation. The feeling that these products are now too cheap for the good of future generations, that they are being selfishly exploited at too rapid a rate, and that in consequence of their excessive cheapness they are being produced and consumed wastefully has given rise to the conservation movement."* We thus learn from Hotelling that something like the concept of "sustainability", although not yet formulated as a single word in the English language, had already given rise to a (socio-political) movement that advocated prudence in the utilisation of non-regenerative resources. Such observations were, however, not confined to the Anglo-Saxon world. Schottky, the well-known German physicist wrote in 1929 in the Foreword to a book on thermodynamics: [(10)] *"This period of uninhibited exploitation of energy and mineral resource, which Nature has put at our disposal, will – for our children – probably only have the significance of a bygone economic age. We can only wish that the optimists are right in their hope of finding new, previously unthought-of ways of producing energy and of creating new materials."* If World War II and the ensuing Cold War produced concerns of a different nature in our (Western) society, the topic of mineral depletion emerged again in the 1950's and 1960's, at least in geological and mining circles in the US. It was considered urgent enough in 1962 for the US National Research Council (NRC) to commission a report.[(11)] (This concern has continued: an NRC report published 35 years later is an interesting discussion on so-called sustainable mining[(12)].) Frasché, the author of the 1963 report concluded that total exhaustion of mineral resources would never occur. He noted, however, that the grade of ores mined (in the US) was continually declining and that this would present significant technical challenges in the future.

What did Meadows and colleagues actually say about mineral depletion in their book in 1972? As input data for their "world model" they took figures from the US Bureau of Mines for the then known reserves of 16 mineral resources as well as of oil, coal and natural gas. These included two of the most common elements in the earth's crust, iron and aluminium, as well as elements such as copper, cobalt and tungsten, which are (still) regarded as "rare", i.e. having a crustal concentration of less than 1000 ppm (by mass). They calculated the number of years these would last at the then current (exponential) growth in the rate of usage. Assuming the true reserves were a factor of five higher than those estimated at the time, they arrived at an "exponential reserve index", now usually termed "dynamic lifetime" or "lifetime expectancy", of between 50 and 200 years for most metals, before such reserves would be largely exhausted. Despite the optimism of some geologists concerning the discovery of new, large and rich deposits, their main conclusion was that mankind was heading for a crisis of supply in the 21st century with serious economic consequences: *"Given present resource consumption rates and the projected increase in these rates, the great majority of the currently important non-renewable resources will be extremely costly 100 years from now."* This included incidentally coal, gas and oil; the dynamic lifetime for the latter was thought to be 50 years. Because of the oil crises in the 1970's the book of Meadows et al acquired considerable renown, although the drastic increases in the price of oil in that decade were political in origin. Recently, it has been claimed that Meadows et al used the word "sustainable" in their book for the first time in its new, ecological and socio-economic sense.(13) This is not correct. The word was already known in the English language, but used exclusively in the sense of "maintainable", e.g. "sustainable" economic growth, or a "sustainable" source of income. Meadows et al employ it several times without the connotation of intergenerational equity which "sustainable", and more so "sustainability", have now come to mean today. Nonetheless, the book represents an outstanding milestone in discussions on the utilisation of natural resources and on man's relation to his planet, even if the direst predictions of the world model have not, or not yet, come about. The reason for the incorrect predictions concerning mineral depletion was the inaccuracy of the data then available on reserves or, more important, on what we term today, resources. Moreover, Meadows et al assumed a fixed stock, rather than an effectively infinite one with a range of concentrations (mineral grades) going down to that of the average crustal abundance.

These were, however, not the only warnings about mineral depletion. Amongst others, Arndt and Roper (14) also noted that, as an increasing amount of any mineral is extracted from the earth, it becomes steadily more difficult to extract the remainder. "More difficult" means of course that more sophisticated technologies and more energy are required and that more environmental damage occurs. Specifically, they carried out model calculations for mineral depletion both for fossil fuels and minerals. Most metals from US deposits were found to already have passed their production peak in the mid-70's; the situation for the world as a whole was judged to be somewhat less critical. Nonetheless, Arndt and Roper named the 1990's as the decade in which a world minerals crisis would occur. Even at this time, however, there was considerable criticism of the so-called "pessimists", or "catastrophists", i.e. those who proclaimed that mineral depletion was an urgent geological and economic issue, among others by Maddox15) in his broadside against the prophets of doom, as he saw them, and later by Simon.(16) The debate between the "pessimists" and the "cornucopians", as the optimists have been dubbed, continues today, even if the positions are no longer quite so far apart. It is therefore useful to summarise the points of view of each side. Fuller accounts are given by Tilton[17] and Ayres.[18]

The optimistic view, i.e. that of the cornucopians, is firstly that the amount of any given element in the earth's crust is sufficiently high to last mankind for thousands, if not millions of years. Tellurium for example, which we will encounter again below, is one of the rarest elements with an abundance in the earth's crust of 0.001 ppm (by mass). This corresponds to a total quantity in the continental crust of 15 Gt, without even considering seawater, the ocean floor or the oceanic crust. Global tellurium consumption is estimated to be currently about 1 kt per annum,[19] a factor of 10^7 difference! Admittedly, more energy (and water) would be required to extract the element from progressively lower grade ores and eventually from rocks in which the element concerned is only a very minor constituent, but sufficient energy at least would be available from the sun and perhaps also from nuclear fusion. Simon,[16] one of the more outspoken cornucopians, and an economist, pointed out, that the real prices (i.e. the inflation-adjusted prices) of nearly all raw materials fell steadily for most of the 20th century, reflecting improved prospecting and production methods in resource exploitation. Moreover, he wrote in his *Science* article *"the term 'finite' is not only inappropriate but is downright misleading in the context of natural resources, both from the practical and the philosophical points of view. But the future quantities of natural resources such as copper cannot be calculated even in principle, because of new lodes, new methods of mining copper, and variations in grades of copper lodes; because copper can be made from other metals (sic); and because of the vagueness of the boundaries within which copper might be found – including the sea, and other planets."*

The second argument brought up to support the cornucopian case is the indestructibility of matter under normal conditions (the exception of course is provided by nuclear reactions in fission power plants and in possible future fusion devices). In the extraction, processing, utilisation and recycling of the element(s) from a particular ore, the atoms concerned are not "lost", but their degree of "dispersion" merely increases. It thus follows that increased efficiency of extracting and processing, and most importantly, of recovery and recycling,[20,21] combined with careful bookkeeping (e.g. life-cycle analysis),[22] is necessary. In order to increase the end of life recycling rate (EoL-RR),[21] product design which specifically takes into account recycling requirements will also be an important factor. Again, as in the case of ores of low grade, it is assumed that sufficient regenerative energy will be available for all the chemical and physical processes involved in recycling. For eighteen of the sixty elements (almost exclusively metals) for which data are available,(21) the globally averaged recycling rate is estimated to be higher than 50%. For iron, chromium, titanium and lead the recycling rate could be currently as high as 90% and for aluminium and cobalt 70%. Recovery and recycling are perhaps not the definitive answer to the resources problem, but they too can in the cornucopian view postpone indefinitely the date of complete resource depletion. Ethical reasons can also play a role even from the standpoint of an optimist: it is incumbent on mankind to use sparingly and with prudence the precious resources of the planet.

The third point concerns substitution, for which the argument is simple: before the very last ton of a particular ore were to be extracted from the earth's crust (the subjunctive is important!), the price of that metal would be so high that demand would be drastically reduced and eventually eliminated. Under these conditions a substitute material – combined perhaps with some new technology – would long since have been found. Such substitute materials, perhaps also elements themselves, might not have the same optimal properties and might also require in their extraction and utilisation more energy, but would effectively replace the extremely scarce element in its main uses. It is but a short step to the postulate of unlimited substitutability, which was described by Goeller and Weinberg in the following way:(23) *"most of the essential raw materials are in infinite supply: as society exhausts one raw material it will turn to lower-grade, inexhaustible substitutes. Eventually, society will subsist on renewable resources and on elements, such as iron and aluminium, that are practically inexhaustible. According to this view, society will settle into a steady state of substitution and recycling."* Goeller, cited in Ref. [23], actually investigated several rare elements with respect to their substitutability and came to the conclusion that for most of their applications, substitutes deriving from inexhaustible, or nearly inexhaustible materials would be available. Mercury is the specific example given in Ref. [23]. We should note, however, that this paper was written in 1976 and it is unclear whether in view of the many new, sometimes unique applications of rare elements in many modern technologies this statement still holds 35 years later. Simon's position is similar: the notion that resources (plural) are effectively infinite is not based on any one particular material, but rather on the capability of mankind to invent and adapt.(16) This discussion takes us over, almost effortlessly, into the similar definition of unlimited substitutability given at approximately the same time by the economist Solow which is contained in two papers published in 1974(24, 25) and, subsequently, in the light of the then unfolding debate on environmental sustainability, in a later essay in 1993.[26] (For pointing out the significance of this work the present authors acknowledge their debt to a paper of Ayres.[18]) Solow claims that natural capital, of which mineral resources form a part, can be substituted to any arbitrary extent by “man-made” capital, whereby in the definition of the latter not just manufactured but also intellectual capital is included. In other words, it is unimportant if natural capital is depleted or degraded by economic activity, as long as an equivalent amount of man-made capital is created as a substitute. Solow formulated this eloquently as *“the presumption that the elasticity of substitution between natural resources and labour-and-capital goods is no less than unity - which would certainly be the educated guess at the moment. The finite pool of resources (I have excluded full recycling) should be used up optimally according to the general rules that govern the optimal use of reproducible assets. In particular, earlier generations are entitled to draw down the pool (optimally of course!) so long as they add (optimally of course!) to the stock of reproducible capital."* [25] There may be new technologies involved. These would be capable of producing or substituting for a mineral resource, probably at very high costs, but on the basis of inexhaustible resources. Such a “back-stop” technology in the energy sector would be, according to Solow, the fast nuclear reactor which would allow a huge increase in the life expectancy of the uranium reserves. Citing Pezzey and Toman,[27] Ayres describes this approach as “weak” sustainability, as opposed to “strong” sustainability which characterises the position of the pessimists.[28]

How have the “pessimists”, i.e. those who are concerned that society’s hunger for mineral resources will lead to serious, if not catastrophic geochemical scarcities, reacted to these arguments? The pessimists appear of course in various shades.[e.g. 8,18,28-32] There are also some points of view, which might be described as more pragmatic and seem to lie between the two positions.[17,33,34] But, in general, the pessimists maintain that the mineral deposits in the earth’s crust are indeed finite and that, despite increased resource efficiency, recycling and substitution, they will be largely depleted within the next few centuries, some perhaps even within the next few decades. Only very low-grade ores or other rocks in which the metal of choice substitutes for some other element that is less scarce will be available when the conventional deposits are exhausted (see the Skinner thesis below). The energy (and water) requirements for extraction and refining will be vast.[35] Moreover, it is unlikely that ore and rocks of such low grade can be exploited without there being lasting damage to the environment. The cyanide process for mining gold, as discussed below, is a case in point.[36]

Nor are recovery and recycling, although essential, as simple as the cornucopians might claim. Particularly the energy requirements for recovery are very high due to the very low concentrations with which some rare metals are present in many applications, particularly in modern electronics. The improvement of the recovery rate (using the terminology of the International Panel for Sustainable Resource Management this is the old scrap collection rate, CR[21]) is actually a social or political problem, unless the metal concerned is so valuable, as in the case of gold, that economic considerations are paramount. Recycling can never be 100% efficient: there are always losses somewhere. Moreover, in optimising the chemical or physical processes involved there are sometimes limits imposed by the characteristics of the phase diagrams of the melts involved in refining.[37] In other words, for an element which is repeatedly recycled – over decades or centuries – the amount of "waste", i.e. the amount of very low concentration material, which is land-filled or deposited arbitrarily in the surface region of the earth's crust, including the oceans, will grow exponentially with time.

A further aspect is future demand. Whilst it is certainly correct that metals which are currently being utilised could be, and hopefully will be, recycled at a higher rate than hitherto, the total amount of in-use stock will increase drastically in the next few decades. Not only is it thought that the world population will increase from at present 7 billion to possibly 10 billion by the end of the century, but the per capita standard of living is also expected to rise, above all – and drastically – in those parts of the world where it is at present very low. Ernst refers to this as the *"American world of 10 billion people"*, since it is the US which at present has the highest per capita consumption of natural resources.[30] This factor will inevitably result in a several fold increase in the amount of refined metals in current utilisation (in-use stock) and, concomitantly, in further increases in demand. This important factor is often neglected in discussions of resource depletion.

Finally, we turn to substitution. According to the pessimists, the principle of substitution, when applied judiciously in a way intended to preserve precious resources, is of course a positive thing, but the notion of unlimited substitutability is deeply flawed. The existing stock of natural capital must be maintained as far as humanly possibly because many of its functions and characteristics cannot be replaced by man-made capital, as proposed by the advocates of "weak" sustainability. Natural capital consists of atoms which have unique properties. In the case of mineral resources we cannot say to what extent these unique properties will be required by future generations for specific purposes, the nature and scope of which we cannot at present foresee. Nor can we judge whether their possible complete exploitation (in the sense of effective exhaustion of resources – see below), resulting in a high degree of dispersion in the earth's crust, would seriously affect their future utilisation. Moreover, the observation is allowed that future generations must also take part in the decision-making process concerning the disposition of natural capital and not be confronted with a *fait accompli*. The reader is referred to the strong sustainability debate initiated by Daly[(28)] and to Ott and Döring's discussion of the fair bequest package.[(38)]

Clearly, some kind of compromise is necessary between the two positions on sustainability.[(e.g.17,33,34)] In a recent discussion paper Steinbach and Wellmer consider the in-use stock as the future source of most metal resources.[(39)] They assume that a some point in the future, the rate of consumption of mineral resources flattens out, or stagnates, and that demand can largely be satisfied by recycled material from the "technosphere" supplemented by only small quantities from the geosphere. This is sustainability of the stronger sort, even if the necessarily very high recycling rates might be optimistic. However, in emphasising functionality as the desired characteristic, rather than specific metals, they come dangerously near to Solow on substitutability! Strong sustainability is probably most people's first choice, but the potential roadmap involves so many stark choices that we automatically shrink back at the prospect, particularly in an "American" world of 7 billion, or even 10 billion people. As far as mineral resources are concerned, all measures which reduce depletion of rare elements (efficient extraction and refining, recovery and recycling, substitution by less rare materials) should be implemented globally. However difficult this might seem politically at present, at least an attempt should be made to institute the necessary industry standards on a global basis. Most useful would be some quantitative measure of sustainability, but discussions on this topic are still in their infancy. In an earlier paper we have proposed that the present age of the genus *homo* (ca. 2 million years) is an "order of magnitude" measure of the necessary lifetime of raw materials.[(3)]

What is actually known geochemically about the extent of mineral resources, over and above the simple crustal abundances? The US Geological Survey (USGS)[(19)] publishes annual updates on global "reserves" and "resources". Reserves are defined as the quantity of an element in the Earth's crust which has been identified and can be extracted at similar cost to that mined at present. Identified resources include not only the reserves, but also that quantity of the element which requires a higher energy per kg to be mined, probably on the basis of a more advanced technology and in any case at higher cost. From hereon, we use these two terms only according to these definitions. (An earlier term "reserve base" is no longer used by the USGS.) The big unknowns are the extent of undiscovered resources and the grade of the ores concerned. Skinner has surmised that for scarce metals there is a step, which occurs in a log-log plot of the energy required to extract a particular metal against the grade of the corresponding ore(s).[40] The diagram shown in Figure 1 is a version in which Skinner has calculated specifically the steps involved, namely, mining, concentration and smelting for copper.[41] The energy required to extract a kilogram of copper rises as the grade of the conventional ore (chalcopyrite, $CuFeS_2$ in a silicate matrix) falls. The horizontal axis in this plot could also be time, as we will see in the section on copper below. Below a grade of 0.1% separate copper-ore minerals do not occur, and if such deposits were exhausted, it would be necessary to extract copper from Cu-containing minerals which are found in small quantities in solid solution in other rocks. At least a factor of ten more energy would be required to produce copper from such a solid solution than from a chalcopyrite ore. This step is known as the mineralogical barrier. Also shown in Figure 1 are the estimated energies for the extraction of copper from manganese nodules and from some deep sea ocean muds.[42] More recent work has indicated that in the case of copper there is probably a wide range of copper-containing rocks and minerals which also require an energy intermediate between the two branches of Figure 1 to extract the copper, i.e. in the region of the mineralogical barrier.[31] Whilst Skinner points out that such diagrams are only conjecture, they highlight the fact that the recovery of rare metals will inevitably be more difficult and expensive in future. In a few cases there are geology-based estimates[43] (as opposed to production-based estimates, as in the case of Arndt and Roper above) of the size of the total resources (discovered + undiscovered). We discuss briefly the case of copper below. Clearly, more geochemical prognoses of this nature are required. We now turn our attention to the definition of scarcity.

In economic terms, the scarcity of a metal or mineral resource is due to decreased availability, leading to increased prices on a real, inflation-adjusted basis. In most situations supply will match demand: If the mineral resource is perceived as effectively inexhaustible, then output will expand until the extra cost of producing just one more ton equals the current market price. If the consumer is not in a position to pay the price for the amount he needs, he switches to another metal or material, which we have defined above as "substitution". Hotelling's 1931 paper,[9] mentioned earlier, was the first attempt to formulate an economic theory of <u>exhaustible</u> natural resources. In the case of a firm selling exhaustible resources, such as a mining company, the so-called Hotelling rent will also contribute to the costs and thus to the market price. The Hotelling rent equals the (estimated) present value of future profits that the mining company would lose by mining and selling the resources at this point in time. (Amongst other assumptions the quality of the resource, i.e. the grade of ore, is taken to be constant in this picture.) Moreover, these mineral resources in the ground are assets and are expected to yield interest at the same rate as other investments, such as in property, shares or government bonds. This in turn reduces the availability of the mineral resources, since their value rises exponentially with time. In practice, the situation is more complicated, because, for example, the grade of the ore may fall and/or mining efficiency may increase with the result that the value of the mineral resource in the ground could actually fall. Tilton[17] explains these aspects very well for non-economists and, since the present article has another emphasis, it suffices to leave the matter at this stage. There are, however, other factors which do not derive *per se* from the operation of economic mechanisms, but which also lead to reduced availability and thus scarcity. These "external" influences on both the supply and demand sides are sudden strong economic growth in a country or region, new applications following the introduction of new technologies, monopolistic situations involving companies or countries, speculation, politically motivated embargos (the "security of supply" issue) and, indeed, geochemical scarcity. The list is well-known and requires no special explanation. We note that speculation is a special case: not only gold, but also silver, platinum group metals and possibly others can be the subject of speculative buying, particularly when investors seek a safe haven in times of economic uncertainty. In the following we discuss specifically geochemical scarcity and, in particular, the question as to whether it has so far been observed in practice.

Geochemical scarcity would be expected to occur when production costs increase because mining companies are forced to use ore of increasingly low grade (see Skinner, Fig. 1) and when these costs are not, or not fully, counterbalanced by the introduction of new, innovative techniques for mining and processing. It is the direct result of physical depletion: the number of newly discovered (and subsequently mined) deposits of high grade is not sufficient to lift the average grade mined globally. We will see in the sections on copper and gold below that, regionally, i.e. for specific countries, data are available which demonstrate this effect. Unfortunately, there are little or no geological data available on a global level, although we can look at the prices of raw materials in recent decades. As we noted above, Simon[16] drew attention to the fact that real (inflation-adjusted) prices of nearly all raw materials fell steadily for most of the 20th century, which he attributed to the use of improved prospecting and production methods. Arndt and Roper[14] had also noted the effect, but it seems to have been Barnett and Morse[44] a decade earlier who first pointed out the influence of new technologies on mineral supply. In particular, they recognised that deposits of low-grade ore which are known, but were hitherto regarded as uneconomic, become in the course of time competitive. (The same applies, of course, to tailings from previous mining operations.) Recent, readily accessible inflation-adjusted price indices for raw materials confirm this picture. The GMO commodity index for 33 commodities, 12 of which are metals, fell by 70% between 1900 and 2000,[45] despite blips for both world wars and the oil crises of the 70's. The same development can also be seen in the non-oil commodity price index of *The Economist.*[46] However, Grantham – amongst others – has pointed out that the trend has recently reversed, in fact quite sharply.[45] This turn-around is not only visible in *The Economist* index, but also in a plot from the same magazine showing that the US average price of a basket of rare metals consisting of chromium, copper, nickel, tin and tungsten has risen by over 100% since the late 90's.[47] The price of copper alone rose by a factor of five in this period. (Because of changes in exchange rates the increase in terms of the Euro is not quite as large.) It is not clear at present whether this is just due to buoyant demand, mainly in China, India and S. E. Asia, or a sign of geochemical scarcity. *The Economist* concludes *"the surge in commodity prices is simply the result of exploding demand and sluggish supply"*.

Two caveats must be mentioned; the first concerns scarcity. When the production of a rare element is coupled to the mining of more plentiful elements, such as zinc, copper, lead or iron, the supply of these "by-products" will depend on the demand for, and thus on the supply of, other ores. Indium and germanium, for example, depend on the production of zinc and could become scarce if the demand for zinc were to fall. This is referred to by Hagelüken[48] as "structural scarcity". The second caveat concerns external costs, or externalities, which are the environmental and social costs associated with mining and mineral processing. Much progress has been made in recent years in developing clean technologies in the mining industry. For example, about 80% of copper is now produced by a hydrometallurgical process using phenolic oxime extraction rather than by smelting with its accompanying SO_2 emissions. Since mining is difficult to classify as "sustainable", at least in the sense of "strong" sustainability, it is certainly in the interest of society in general that there is legislation to ensure that all external costs are properly identified and that mining companies actually pay them. This in turn furthers the development of new technologies and, as Tilton[17] points out, ultimately increases the long-term availability of mineral resources due the reduction of environmental constraints. (It goes of course without saying that mining activities should be prohibited in areas where environmental and cultural heritage are endangered.)

Finally, in this section we consider, or rather summarise as a result of the foregoing, what is meant my "exhaustion" of mineral deposits. The cornucopians are correct when they maintain that the mineral resources of the planet are effectively infinite. Complete exhaustion of a particular mineral will never occur. If, however, unbridled usage continues, we will reach a situation, which could be termed "effective" exhaustion, where the cost of producing a further ton in terms of energy, water and environmental damage will be so great, that mining activities will cease. Our society, or world economy, will switch to a cheaper, more readily available, but for the purpose, less appropriate substitute. As explained above, this process could in principle go on indefinitely and was described by both scientists and economists as "unlimited substitutability". Ayres(18) termed it "weak" sustainability although the use of the term in this connection is hardly warranted, weak or otherwise! It seems to the present authors to be necessary that society does not drift automatically and unprepared into this situation, particularly since we have just seen that there is already some evidence for geochemical scarcity. Efficient use of resources, increased product lifetimes, improved recovery and recycling, as well as timely substitution are indeed necessary. Whether such policies can be administered globally, and on the time scale required, is unclear. The threat of a global population of 10 billion at an "American" pro capita level of consumption with its vast increase of in-use stock also looms large.

Scarce metals in the sustainable energy industry

General

The German government has, as noted above, set a target of 80% for the contribution of regenerative energies to electricity supply by 2050. Several authorities believe that a figure of almost 100% is possible by this date. The Greenpeace/Energynautics 2050 HIGH GRID scenario for the EU27 with a new, efficient and "smart" grid is shown, for example, in Figure 2.(49) On the basis of an installed capacity of 1.52 TWe there would be in this scenario contributions of 45%, 23%, 12% and 10% from photovoltaic sources, wind, biomass and hydro, respectively. Only a few percent might still come from coal, oil or natural gas. Despite this massive shift away from fossil fuels in the future energy system, there will still be a very high demand for raw materials. These are needed for the production, transmission, storage and utilisation of energy obtained from regenerative sources. As might be expected, the elements concerned are geochemically rare, i.e. they have a crustal abundance of less than 1000 ppm (by mass). Almost all of them play a vital role in our modern, technology-dominated society, sometimes for very specific applications. For example, the transition metals vanadium, chromium, cobalt, nickel, molybdenum and tungsten are used in making special steels. The rare earths (which are not quite so rare as the name might suggest: the most abundant, cerium, has a higher crustal concentration than copper!) are required, amongst other applications, for manufacturing strong permanent magnets. Lithium and cobalt are used in lithium-ion batteries, niobium in superconductivity, indium in computer displays, tantalum in electronic components, platinum, palladium and rhodium in automobile catalytic convertors. (Whereas this application of the platinum group metals is more connected with direct environmental issues, and of course with the way in which we use energy, their use as electrode materials for the electrolysis of water is becoming a strategically interesting research topic. The production of hydrogen from excess electricity generated by intermittent energy sources is a potential technique for energy storage. Platinum is the material of choice on the hydrogen side {cathode} and the oxides of ruthenium and iridium on the oxygen side {anode}.[50] Ruthenium and iridium are by-products of the mining of platinum and palladium, occurring each with about 5%. Unfortunately, space does not permit us to take up this question in more detail below.) The rare elements are not necessarily used in great quantities (there are of course exceptions), but their particular electronic, structural or chemical properties have been the necessary pre-requisite for almost all the major technological advances of the last hundred years. They are also required in the "sustainable" energy industry. In the series of examples below we begin with gold, which is not of overriding importance in the energy industry, but there are some interesting statistics available from which we can perhaps learn something.

Gold

Gold is a dense, chemically unreactive and ductile metal. Its rarity and durability have made it not only coveted for jewellery, but also important for coinage, currency reserves and investment. According to the GFMS Gold Survey 2,689 t were mined in 2010, the supply from scrap being ca. 1,600 t.[51] (GFMS Ltd, formerly Gold Fields Mineral Services is a precious metals consultancy.) There was practically no growth in mine production in the last decade. Because of its value and durability, the recycling rate of gold is almost 100%. Since gold is not consumed, we thus have a good overview of the in-use stock, which amounts to ca.

166,000 t and probably represent at least 80% of all the gold ever mined. 52% of this is in the form of jewellery, 11% in other sorts of non-jewellery fabrication, 19% in private investment and 16% in official currency holdings. In 2010 ca. 2700 t were used for fabrication (jewellery, coins, industry). Industrial applications required 250 t, up 19% on 2009. This strongly expanding market is due to the widespread use of gold in ensuring good electrical contacts in the electronics and electrical industry, due to its corrosion resistance, high conductivity and ductility. According to the USGS, global gold reserves amount to 59 kt; there are no figures for the resources. In the US, where the reserves are estimated to be 3 kt, it is assumed that the identified and unidentified resources are ten times as high. This would imply global resources of ca. 0.6 Mt. It is particularly interesting to note that in the last few years new extraction techniques have enabled gold ores as low in grade as 1 ppm to be mined economically.

A short digression is warranted at this point. Gold, although generally unreactive, is soluble in weakly alkaline solutions of sodium cyanide due to the formation of the complex $Na[Au(CN)_2]$. This is the basis of the process with which most gold is extracted today. The crushed ore, containing small gold particles of typically 5 - 20 μm diameter, is tipped into heaps on plastics sheets and a 0.1% NaCN solution allowed to percolate through. After collection at the bottom of the heap, metallic zinc is added, which causes the gold to be precipitated. It is understandable that this process, termed "heap leaching", involving such highly poisonous ingredients under conditions not necessarily supervised by health and environmental authorities in remote areas of the globe gives particular cause for concern from the environmental standpoint.[(36)]

The average grade of gold ore mined in the last 100 years has steadily declined. Although no figures seem to be available for the global situation, Craig et al[(42)] and Mudd[(52)] have published curves for the US and Australia, respectively, as shown in Figure 3. They show that the average grade has decreased in the US, for example, from about 12 – 15 ppm to 1 – 2 ppm over this period. After the abolition of the gold exchange standard in 1971 the gold price went through a speculative peak in 1980 of over 800 $ per troy ounce, after which it declined continuously to the middle of the last decade (after adjustment for inflation). Since then, there has been a further substantial increase in price due to the bank crisis, the US deficit, the Eurozone crisis, as well as to general economic uncertainty. The gold price peaked briefly at 1,900 $ in August 2011. (The gold price is at present similar to that of platinum, incidentally.) The unique role played by gold means that price increases – unlike the case of copper – are not likely to tell us very much about possible geochemical scarcity. The curves in Figure 3 are more useful, particularly if they can be generalised to the global situation. (Clearly, reserves are expected to dwindle more quickly in safe and stable environments such as the US and Australia.) Recent figures on the costs of mining gold are interesting in this respect. *The Economist* has recently noted,(53) quoting the GFMS,(51) that average grades of gold have fallen 30% since 1999. Not unexpectedly, the average cost of extraction, then 200 $ per ounce, reached 860 $ per ounce in 2010. Moreover, for the first time ever, the FTSE gold mines index has failed to keep pace with the price of gold. (FTSE = Financial Times Stock Exchange) *The Economist* commented *"All the easy gold has been mined already"*! Gold is of course untypical in many ways, but despite a record global exploration budget of 5.4 billion $ in 2010 – a factor of ten higher than a decade earlier – less gold deposits are being found.(54) It is hard not to believe that some part of the recent rapid rise in the gold price is due to geochemical scarcity.

Copper

A material of greater relevance to the energy industry is copper, which, on account of its high electrical conductivity, is the material of choice for power cables, electrical equipment generally and many electronics applications. Moreover, many other applications derive from its high thermal conductivity, relatively low reactivity and malleability. In the transition to an economy dominated by regenerative energy forms, which will be characterised by smaller, widely distributed sources, new grids will be required. This in turn will result in a massive increase in the demand for copper. Moreover, new developments in the energy area require very large amounts of copper: electric cars will require 60 – 80 kg copper per unit as opposed to ca. 20 kg for petrol-driven vehicle; a wind turbine with an asynchronous generator and gears needs something like 8 t of copper! In many cases, aluminium can substitute for copper, because of its good electrical and thermal conductivity; the problems involved have recently been summarised by Messner.(56)

The (continental) crustal abundance of copper is 55 ppm. The present main sources are sulphide ores, chiefly chalcopyrite, $CuFeS_2$ and chalcocite, Cu_2S. The main copper-producing country is Chile, which mines about one third of the world total, followed by Peru, China and Australia. Total world mine production in 2010 was 16 Mt.(19) Due to the massive increase in the copper price in recent years (see below) – and the fact that copper is used either pure or in copper-rich alloys – recycling now plays an important role. Approximately 3 Mt copper were recycled in 2010. Copper recycling has been discussed by several authors.[55-57] The global reserves are estimated by the USGS to be 630 Mt. (Due to new extraction techniques, partially oxidised copper ores, which "cap" the richer deposits, can now be exploited, which has done much to boost reserves in recent years.[42]) A geological prediction for global resources (discovered and undiscovered) for conventional deposits down to a depth of 1 km by the USGS gave a total of 9 Gt of minable copper.[19,31] More recently, using a geological model, Kesler estimated a value of 84 Gt for copper resources down to 3.3 km, corresponding to the depth limit in current mining activities.[31] This value would imply a static life expectancy of about 5,400 years. To what extent modern exploration techniques will be able to detect deposits down to such depths, and to what extent they will be minable, is at present unknown. We can safely assume, however, that copper, and indeed any other rare element, will be regarded as "exhausted" for cost-related and environmental reasons, long before the last ton is taken out of the ground!

The copper price remained almost constant from 1980 to 2002 at ca. 2,000 $ t^{-1}. (After adjustment for inflation it actually decreased, as we have noted above in connection with the "basket" of mineral resources considered by *The Economist.*) However, from 2003 onwards it rose drastically by a factor of five to top 10,000 $ t^{-1} in early 2011. Figure 4 shows that, similar to the case of gold, the average grade of copper ore mined in the US dropped in the course of the last century from 2.5% to 0.55%.[35] The *Financial Times* recently reported that money is currently "pouring into" copper exploration, but without there being many new discoveries.[58] We note that the grades of copper ore in one of the newest large projects, namely, in Oyu Tolgai, Mongolia (estimated reserves 36 Mt) lie between 0.5 and 0.8%. Similarly, the Sarcheshmeh deposit, the largest in Iran, has an average grade of 0.7%. (Iran, at present in ninth place in the table of copper-producing countries has apparently the potential to vastly increase its output and to take second place after Chile.) Is the decreasing average grade of copper ore mined reflected in the price development for copper observed in the last ten years, despite new efficient hydrometallurgical extraction techniques? In other words, is geochemical scarcity playing a role? This may be the case, but there are other factors. One of them might be speculation, and another of course the massive increase in demand in China, where copper consumption was 7.2 Mt in 2009, up 38% on 2008!

Lithium

The future potential of lithium-ion batteries for energy storage has led to a controversial debate as to the extent of lithium reserves.[59-62] Warnings concerning severe future scarcity have even appeared in academic journals.[63] In fact, the situation is not so dramatic as it first seems, but the future demand of the automobile industry could indeed be enormous and give cause for concern.

World lithium production was estimated to be 25.3 kt in 2010,[19] having increased at the rate of 5 - 10 % p. a. in the last decade.[64] The reason for this growth has been the rise in the use of lithium for both primary and secondary batteries, which currently accounts for 23 % of total lithium use. Mobile phones and laptops now use almost exclusively lithium-ion secondary batteries because of their high energy density and low weight compared to nickel-cadmium and nickel-metal hydride cells. The lithium-ion battery appears to be the device of choice in future automotive applications. The glass and ceramic industry continues, however, to be the major consumer (31 %), at least in 2009.[64] Other uses include aluminium production, lithium greases, continuous casting in the steel industry and pharmaceuticals. There are two primary sources: lithium minerals, mainly spodumene, but also petalite and lepidolite, and lithium-containing brines. Like petalite, spodumene is a lithium aluminium silicate. The minerals are used directly in the ceramics and glass industries, as well as for making certain Li compounds. High concentrations of lithium up to 1500 ppm are found in the salt brines under salars in North and South America and in China. Salars in Chile and Argentina have become particularly important in recent years and are the most important source of lithium carbonate, which is the main starting point for lithium compounds and for the metal itself .[64] Seawater has not been seriously considered as a commercial source of lithium (the concentration is on average 0.17 ppm), although the extraction possibilities have been discussed in general,[65] and experiments employing ion exchange with magnesium oxide substrates have been performed.[66] A possible commercial extraction process – were it to be realised in an environmentally friendly way – would probably be extremely expensive. On the other hand, the cost of lithium at present is only a very small part of the total cost of the battery.

How much lithium is available on or in our planet? The USGS gives a value of 13 Mt (2010), which is substantially increased compared to previous years largely as a result of a re-assessment of the potential of the salars in South America and China. Lithium reserves are divided up approximately 2:1 between brines in such salars and minerals.[19] The discovered lithium resources are given as 29 Mt. The extent of the undiscovered resources is unknown, but the feeling in the industry is that the potential of such salt lakes in the Andes and Himalayas is vast. Unfortunately, environmental considerations may not necessarily be given the highest priority in such regions. In seawater the total lithium content is 226 000 Mt.

How much lithium will be needed for energy storage in coming years? It is currently accepted that batteries, in particular for hybrid electric vehicles, will lead to a massive increase in demand, and this will dominate the market in the next few decades. For present purposes a "worst case" scenario is appropriate. If we assume that (i) the whole global fleet (cars, trucks and public transport vehicles) of approx. 10^9 units is "electrified" over the next 40 years linearly in time, (ii) plug-in hybrids with 16 kWh batteries as in the GM Volt are the system of choice (trucks and buses will of course require much larger batteries, as will completely electric vehicles, so-called BEVs, e.g. the Renault Fluence), (iii) 400 g Li are required per kWh[(61)] and recycling takes place every ten years with 80% efficiency,[(62)] then approximately 10 Mt lithium will be required by 2050. This figure is comparable to the present known reserves, but smaller than the (identified) resources. If lithium-ion batteries find large-scale application in non-automotive energy storage, then there is even greater cause for concern. At present, the costs are too high, although the American company A123 is already selling so-called smart grid stabilisation systems (modules of 500 kWh) to utilities with a high proportion of regenerative energy production.[(67)] Presumably, subsidies are involved. Lithium recycling has been discussed in the literature[(68,69)] and Umicore has already developed a process,[(70)] but at present there is no financial incentive since a kg of lithium carbonate costs only a few dollars.

Last but not least, we note in this section that nuclear fusion – a potential sustainable energy source in the second half of this century – would also require lithium as a fuel.[(3)] More exactly, ^{6}Li is needed, which is present to the extent of 7.5% in natural lithium. A typical future reactor (1 GWe) would have an annual ^{6}Li burn-up of about 250 kg, but 2,000 - 3,000 power plants, sufficient to provide 30% of global electricity would soon bite very deeply into the crustal reserves.

Rare earths

The market dominance of China in the production of the rare earths has become a very hot topic following recent articles in the financial press as well as in journals such as *Physics*

Today.[71] In particular, the restriction of exports by the Chinese government since 2006 (apparently in order to conserve supplies for their own manufacturers) has led to an increase in research funding in the US for new materials for permanent magnets. An excellent review of the availability, extraction and recycling of rare earths has recently been published by the German *Öko-Institut*.[72] Although the rare earths are not so rare, and the minable deposits are not confined to China, 98% of global production took place there in 2010,[19] in particular from a large deposit in Bayan Obo, Inner Mongolia.[42,72] The rare earths are produced mainly from the minerals monazite ($CeYPO_4$) and bastnaesite ($CeFCO_3$), whereby all the rare earth atoms can substitute for the cerium atom. The processes of extraction and separation on a large scale are complicated chemically and difficult to perform in a environmentally acceptable way. The resulting high costs have led to a closing down of mining operations in the US and Australia. The increasing demand for neodymium (the Nd price rose 200% in the first eight months of 2011!), dysprosium (where recent price rises have been even steeper) and for other rare earths means, however, that new mining projects are now being started in these countries and elsewhere.

In this Section we briefly consider the four metals cerium, neodymium, samarium and dysprosium (crustal concentrations 60, 28, 8 and 5 ppm, respectively), which, amongst the other rare earths, are particularly important for the energy industry. Cerium is probably best known in the form of the oxide CeO_2 as a polishing powder for glass as well as in numerous applications in heterogeneous catalysis. Because of its energy relevance we cite here the potential use of the CeO_2/Ce_2O_3 cycle for the solar-driven thermochemical production of hydrogen from water.[73] Neodymium and samarium form intermetallic compounds which are strong permanent magnets. On account of its very high magnetic field strength and high coercivity neodymium-iron-boride ($Nd_2Fe_{14}B$) is at present the material of choice for synchronous motors in a wide variety of applications, particularly in the automobile industry, including the main motor in all-electric and hybrid vehicles. The material also contains praseodymium, dysprosium and terbium, which substitute for the neodymium. Dysprosium is apparently very important (concentrations of about 5%), increasing the coercivity and extending the temperature range of the high magnetic field strength, but, as we will see below, is particularly rare. We note in passing that lanthanum (30 ppm crustal abundance) is also used in the nickel-metal-hydride batteries of some electric and hybrid vehicles, e.g. *Toyota Prius*. (The nickel-metal-hydride battery will probably soon be replaced by the Li-Ion battery in most applications.) An important recent development is the introduction of synchronous motors using $Nd_2Fe_{14}B$ in wind turbines instead of asynchronous motors (induction motors) with copper windings. Such generators are compacter and do not require gears, so that the whole structure and its nacelle are smaller, lighter and require less servicing, which is particularly useful in off-shore applications. Nd-based permanent magnets now have a 14% share of the wind turbine market and several major manufacturers are in the process of switching over from induction motors. We note, however, that wind turbines are thought to require 100 – 200 kg Nd per MWe. In the scenario of Figure 2 with its 350 GWe of wind power for Europe (EU27) in 2050 this would require up to 70 kt of neodymium. Making very rough estimates for the total demand for wind turbines, and for the many other applications of neodymium-based permanent magnets, it is not unreasonable to assume that at least 1 Mt neodymium will be required globally for permanent magnets in the next 40 years. The corresponding samarium compound, $CoSm_5$, has a lower field strength, but a higher coercivity, and can be used in a wider temperature range. Samarium could thus be regarded as a possible substitute for neodymium (apart from the fact that it is less abundant), but, as we will see below, there is a much more serious problem with cobalt.

Annual global mine production of the rare earths is given by the USGS as 0.13 Mt (in the form of rare earth oxides).[(19)] Reserves are estimated to be 110 Mt, half of which are thought to be in China. Schüler et al note that, principally, all deposits contain more light rare earths (yttrium to europium) than heavy rare earths (gadolinium to lutetium).[(72)] The reserves of an <u>individual</u> light rare earth, such as neodymium, would probably be an order of magnitude lower. A very rough figure for the reserves of dysprosium (a heavy rare earth) would be 1 Mt. There is no estimate for rare earth resources. According to the above criteria, there is at present probably no geochemical scarcity (the recent price rises have been of "geopolitical" origin!), but there is still an urgent need for increased resource efficiency and recycling, and above all, for environmentally compatible extraction and separation. It is not clear at present whether it is possible to extract the reserves under environmentally acceptable conditions and at acceptable costs. This might well be an even more critical problem for the resources.

Cobalt, cadmium and tellurium

We conclude this chapter with a few words about three other, even rarer metals, which at the moment play a role in the regenerative energy economy (there are certainly many others). *Cobalt* is on the list of elements of industrial importance for the EU, for which "security of supply" risks in the geopolitical-economic framework have been expressed.[(5)] (The rare earths are incidentally also on this list of 14 metals and minerals, as are beryllium, gallium, indium, tantalum and tungsten.) Cobalt is of great significance because of superalloys, which retain their strong mechanical properties at elevated temperatures and are used primarily in the jet engines of aircraft. An important application in the energy sector, which is thought to have precipitated price increases in recent years, is lithium-ion batteries, where lithium cobalt oxide is usually the cathode material of choice. Substantial efforts are being made to develop alternative cathodes. Most of the world's cobalt is produced from sulphide minerals obtained as by-products in the mining of copper and nickel. The crustal abundance is 25 ppm. At present, the Congo and Zambia produce about 50% and 15%, respectively, of the world supply.(19) However, it is China which is the leading supplier of the refined metal! The US has a Government stockpile. The global reserves are estimated to be 7.3 Mt and the resources 15 Mt.(19) The USGS also states: *"as much as 1 Gt of hypothetical and speculative cobalt resources may exist in manganese nodules and crusts on the ocean floor"*. Some degree of geochemical scarcity – according to the above definition – may already exist for cobalt, but it is not possible to ascertain this without further data.

Apart from the use of *cadmium* in Ni-Cd batteries (which is still the main application) this very rare, and toxic metal with a crustal abundance of 0.1 ppm has become of increasing importance in the energy industry. The company *First Solar*, which makes CdTe thin film photovoltaic devices, now has 18% of the world market. Cadmium is a by-product in the mining of zinc, where it substitutes for zinc to the extent of about 0.3% in sphalerite (ZnS). Refinery production was 22 kt in 2010.(19) The reserves, which depend on the estimates of zinc reserves, are given as 0.66 Mt, corresponding to a static life expectancy of 30 years. The situation with regard to *tellurium* (crustal abundance 0.001 ppm), is possibly even more critical. Also obtained as a by-product in copper refining, the annual production is probably about 1000 t with reserves of 22 kt. In view of the rarity, particularly of tellurium, it is remarkable that mankind might consume (and disperse) a large proportion of the reserves of these two elements, when there is a cheap and plentiful substitute with only a slightly lower efficiency available, namely, silicon.

Summary and conclusions

1. The European Union has committed itself in the next few years to an energy revolution, which, in the course of time, may be exemplary for the rest of the world. By 2020 many member states will have substantially increased the contribution of regenerative energy to

electricity generation. For Germany, for example, the planned figure for 2020 is 39% and a further (at present non-binding) target of 80% has been set for 2050.
2. Although the use of regenerative energy forms is by definition sustainable in the environmental/ecological sense, it is timely to look at the demand for mineral resources associated with such types of electricity generation.
3. On mineral resources generally: In a world with a population of 10-12 billion by the end of the century the strict application of "strong" sustainability is unrealistic. On the other hand, the principle of unlimited substitutability, which for some authors is part of the concept of "weak" sustainability, is unacceptable. A compromise has to be sought. In the case of mineral resources more attention must be given to quantifying sustainability within that compromise.
4. The metals required for the production and storage of regenerative energy such as lithium, copper, neodymium and other rare earths, cobalt, cadmium and tellurium, for example, have recently been perceived by the media, but also in part by the specialist literature, as being "scarce", without there being much discussion about the actual meaning of this term.
5. We examine the concept of geochemical scarcity, which can contribute to economic scarcity, and arrive at two criteria for its characterisation. These are (i) a continuous decrease in the average grade of the ore mined globally over time and (ii) rising real (i.e. inflation-corrected) prices that are not compensated by technological innovation. A potential consequence of (i) can be large-scale environmental damage resulting from mining operations. Otherwise, economic scarcity is caused largely by speculation and geopolitical factors.
6. In the case of copper we see evidence for geochemical scarcity, and thus potential exhaustion of (easily) minable resources; it may also already pertain in the case of certain rare earths, cobalt and tellurium. In other words, without even embarking on the strong vs. weak sustainability debate, it appears that regenerative energy systems do not necessarily satisfy generally accepted sustainability criteria.
7. More attention must be paid to the efficiency of extraction and processing, product lifetime, recovery and recycling, and to substitution by elements of higher abundance. The mining industry is aware of these problems and has thus developed the concept of "sustainable mining", but there is an apparent inherent contradiction in the term itself. Meadows has recently pointed out the same problem with the term "sustainable development"![(74)]

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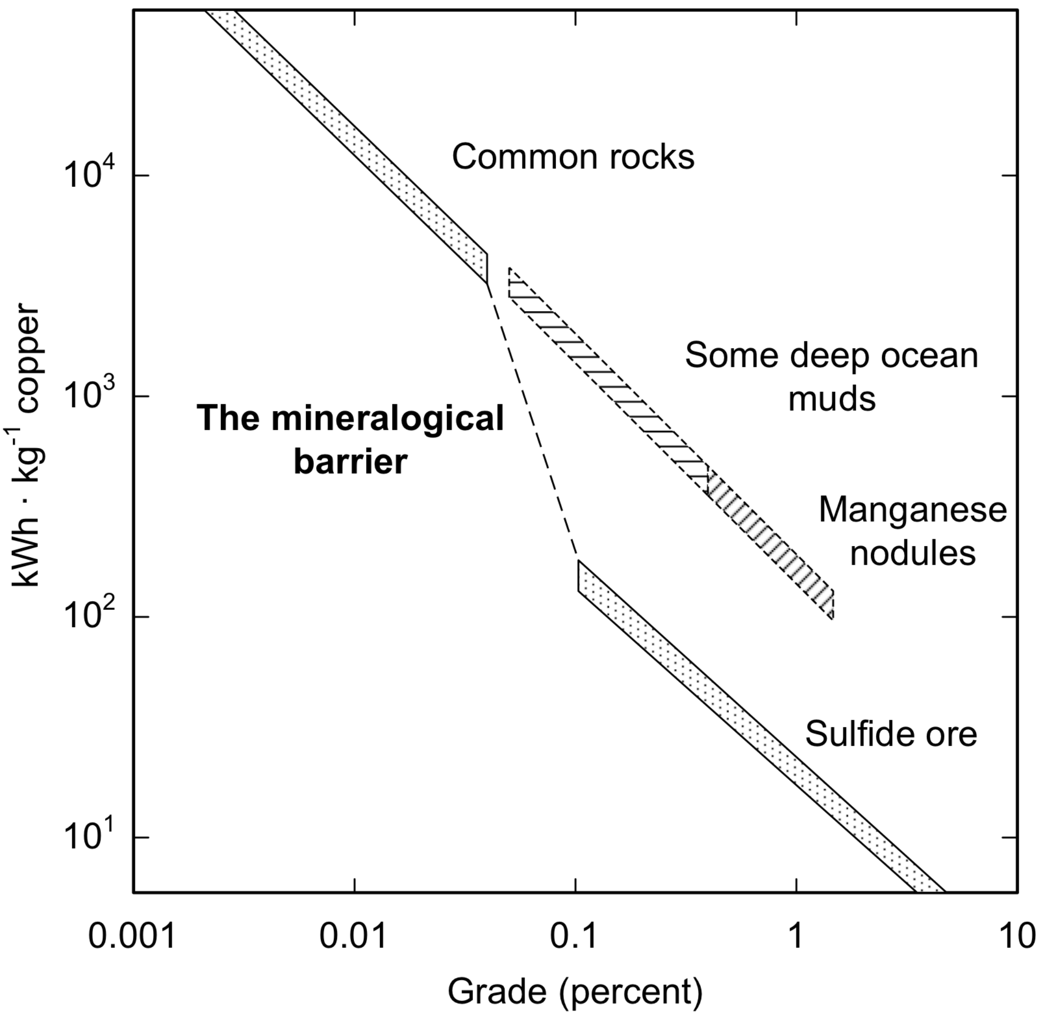
Figure captions

Figure 1: A hypothetical picture of future copper production. The energy required to mine, concentrate and refine copper from a sulphide mineral as well as from a silicate mineral solid-solution ore is plotted against grade. Also shown are the possible contributions from ocean muds and nodules. After Skinner, Ref. 41 and Craig et al., Ref. 42 (with permission).

Figure 2: A power generation scenario for the European Union in 2050 assuming 1.52 TWe installed capacity consisting almost entirely of regenerative energy forms. CSP = concentrated solar power. After Ref. 49.

Figure 3: The average grade of gold mined in (a) the US and (b) Australia since the beginning of the last century. After Craig et al, Ref. 42 and Norgate, Ref. 35, based on Mudd, Ref. 52 (with permission).

Figure 4: The average grade of copper mined in the US since the beginning of the last century. After Norgate, Ref. 35, based on unpublished work by Ayres (with permission).



Common rocks
Some deep ocean muds
The mineralogical barrier
Manganese nodules
Sulfide ore
kWh · kg-1 copper
10^4
10^3
10^2
10^1
0.001
0.01
0.1
1
10
Grade (percent)

Figure 1

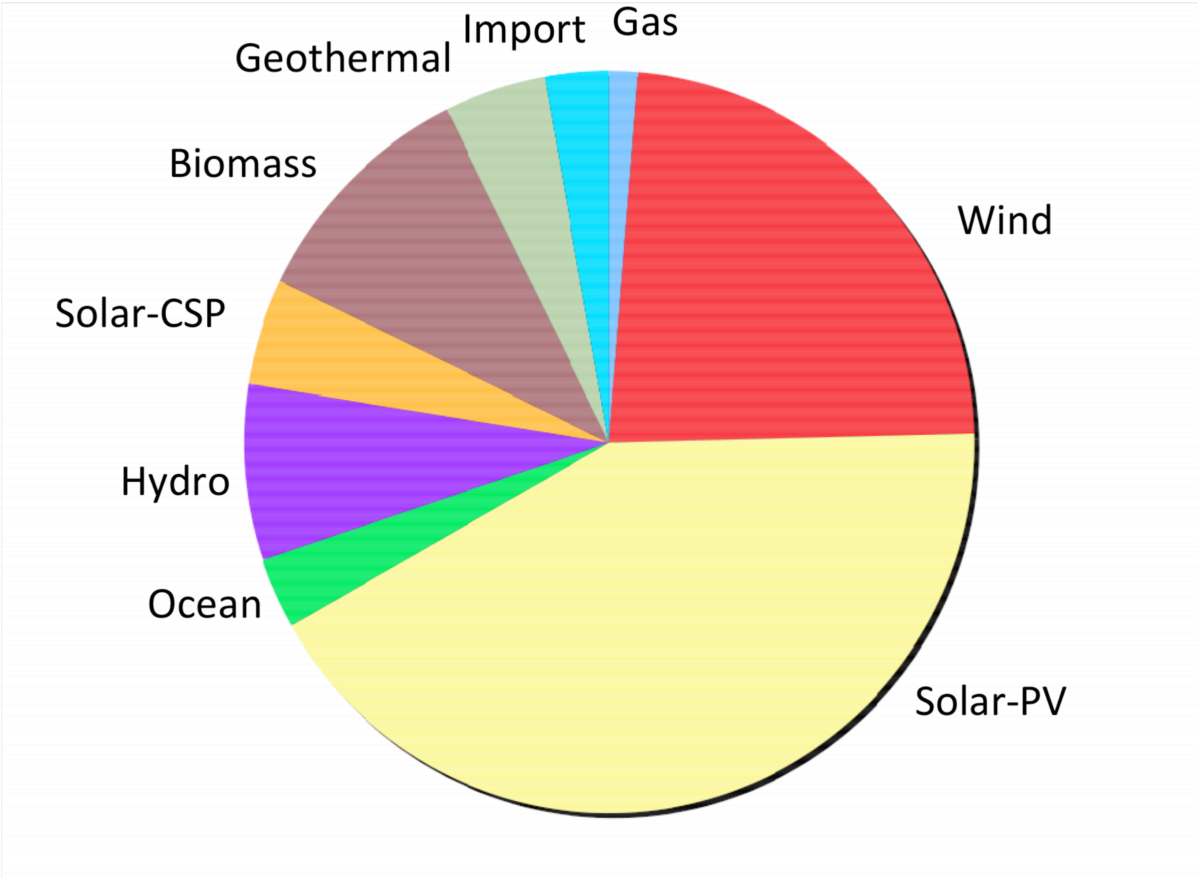
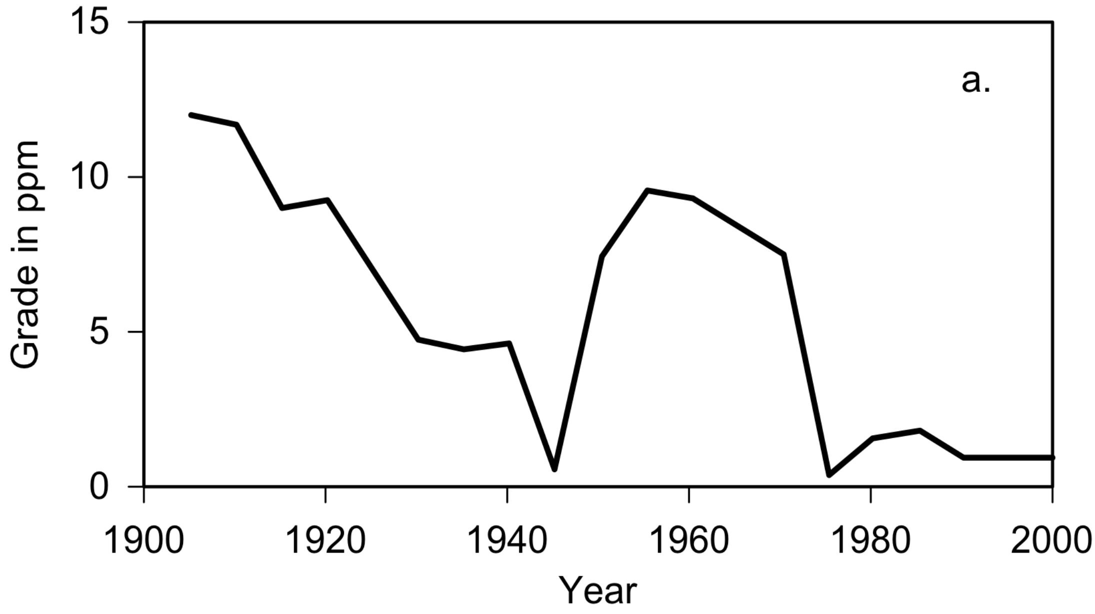

Import
Gas
Geothermal
Biomass
Wind
Solar-CSP
Hydro
Ocean
Solar-PV

Figure 2


a.
Grade in ppm
15
10
5
0
1900
1920
1940
1960
1980
2000
Year

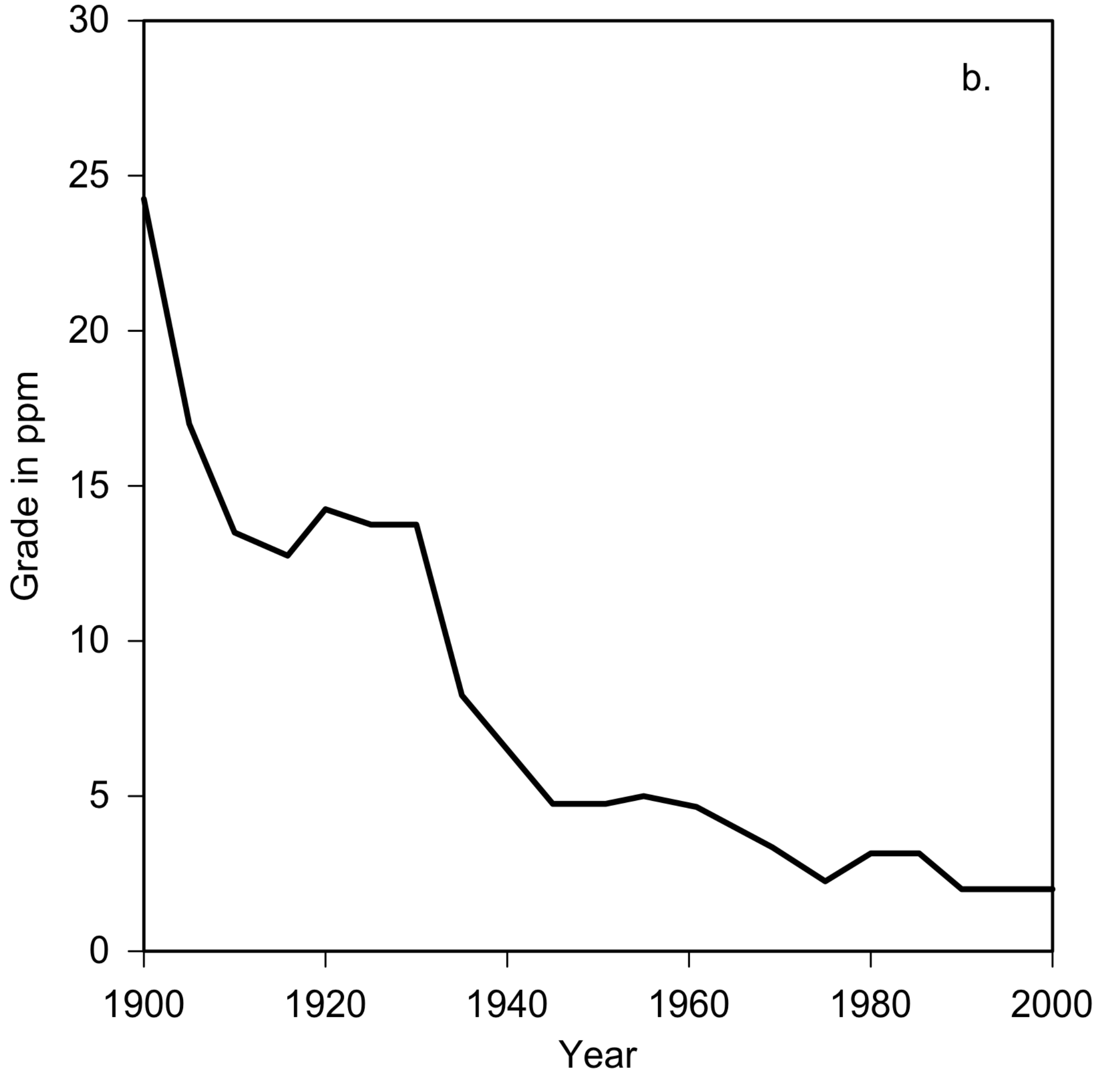
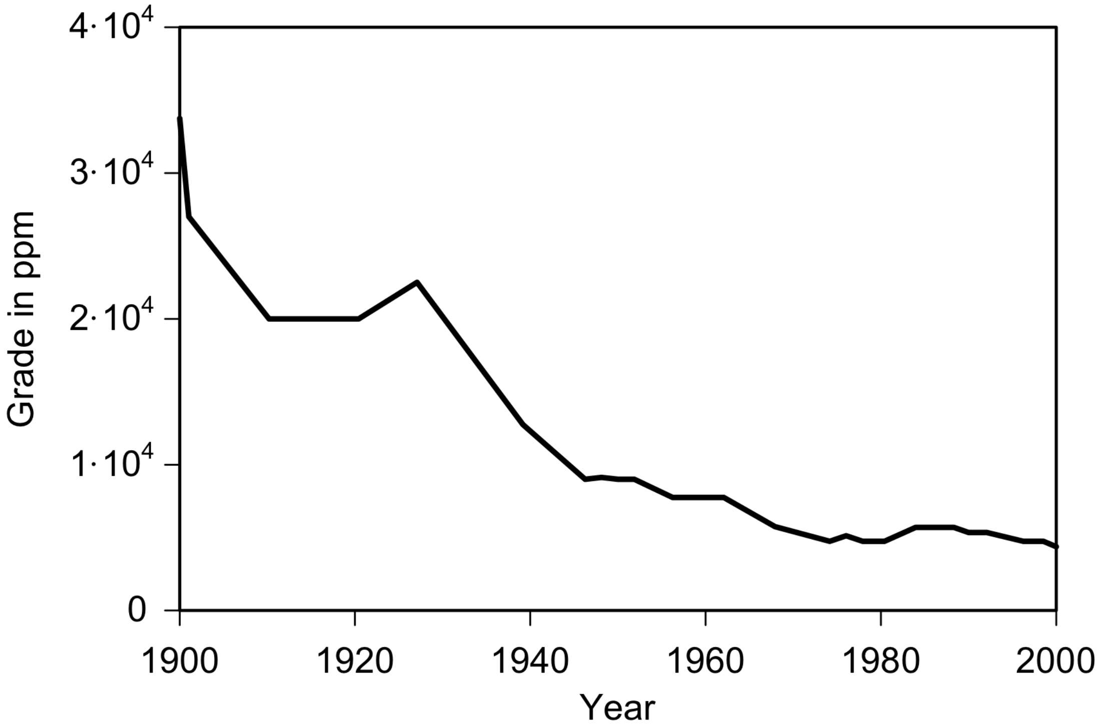

b.
Grade in ppm
30
25
20
15
10
5
0
1900
1920
1940
1960
1980
2000
Year

Figure 3



4·10^4
3·10^4
2·10^4
1·10^4
0
Grade in ppm
1900
1920
1940
1960
1980
2000
Year

Figure 4