

# The availability of rare elements for advanced energy technologies

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## Abstract

In the course of this century we expect to see a substantial global shift in electricity generation away from fossil fuels and nuclear fission towards renewable energy forms, including perhaps nuclear fusion. This shift in energy policy will be accompanied by a strong demand for non-fuel raw materials required for the generation, storage, transmission and exploitation of these energy forms. Whilst some of these materials could effectively become exhausted in the years (perhaps better centuries) ahead, some are already regarded, rightly or wrongly, as “scarce”. Many of them have been characterised by steep price increases in recent years. Examples are neodymium, praseodymium and dysprosium for rare earth-based permanent magnets in wind turbines; indium, gallium, selenium and tellurium for thin film solar cells; and possibly beryllium and helium for nuclear fusion. Various factors are expected to contribute to “scarcity”, which is an economic term describing a situation where supply is outstripped by demand. These include fluctuations in demand, investment constraints, geopolitical factors, environmental problems, the status of the mineral as a by-product and, possibly, geochemical scarcity. We suggest that the latter may pertain when average grades of ore are falling as a result of mineral depletion, but at the same time inflation-corrected mineral prices are rising.

## 1. Introduction

The German *Energiewende*, or energy transformation process, has attracted considerable attention internationally, since Germany is so far the only major industrial country which has made a commitment of this magnitude: In 2011 the German Federal government, and subsequently the German parliament – acting in the aftermath of the Fukushima disaster – decided to shut down immediately 8 nuclear reactors and the remaining 9 by 2022. This corresponds to about 25 % of electricity generating capacity, which has to be compensated as far as possible by renewable energy forms and increases in energy efficiency. Germany had already decided on a 18 % penetration of renewables into the *total* primary energy market by 2020, in compliance with the EU 20-20-20 policy [1], and to aim for 60 % by 2050. Although the possibilities of generating electrical energy in a “renewable”, or perhaps better, sustainable way are manifold, there is widespread agreement that wind and solar will be the prime carriers, particularly since the chances for the realisation of a large number of new hydroelectric projects are generally regarded as limited. Photovoltaic panels and wind turbines are, however, interesting examples of advanced technologies which require certain rare elements that have hitherto only been used in such small quantities for a limited number of applications that there has never been a supply problem. Many of these elements have even been regarded hitherto as “chemical curiosities”, to quote a recent report from the American Physical Society and the Materials Research Society [2]. It is estimated, for example, that mobile (or cell) phones contain around 50 different elements, including Li,

Be, Mn, Co, Ga, As, Sr, Y, Zr, Mo, Ru, Pd, Ag, In, Sn, Sb, Ta, Pt and, last but not least, Au. Up to and including 2011 about  $1.3 \times 10^{10}$  mobile phones have probably been produced worldwide. It is thought that these contain, or contained, total accumulated amounts of ca. 2,800 t, 28 t and 45 t of silver, gold and platinum, respectively. Of the other rare elements, tantalum, indium and gallium, for example, were used in total quantities of ca. 45 t, 23 t and 13 t, respectively [3]. (“Rare” elements are normally defined as those that have a concentration in the earth’s crust of less than 0.1 %. There is also a tendency to refer to such elements as “scarce”, but as we will discuss below, this is an economic term, describing the state of the market for a particular element or its compounds.) The very strong increase in consumption of rare elements in recent decades as a result of their many new applications in various advanced technologies is exemplified by figures for the annual global production of rare earth elements (REE). These are mined and traded as oxides (REO). In the first half of the last century annual global REO extraction was on average 2,000 t. There has been a phenomenal increase since 1950, namely by a factor of 60, as shown in Figure 1, which is based on data from the United States Geological Survey (USGS) [4]. In almost the same period (until 2005) the annual global extraction rate of metals in general (metal content) increased by only a factor of ca. 7 according to Krausmann *et al* [5]. Other rare elements, e.g. indium (see below), have also been extracted in recent decades at rates higher than the average, but no curve is quite so dramatic as that for the REE.

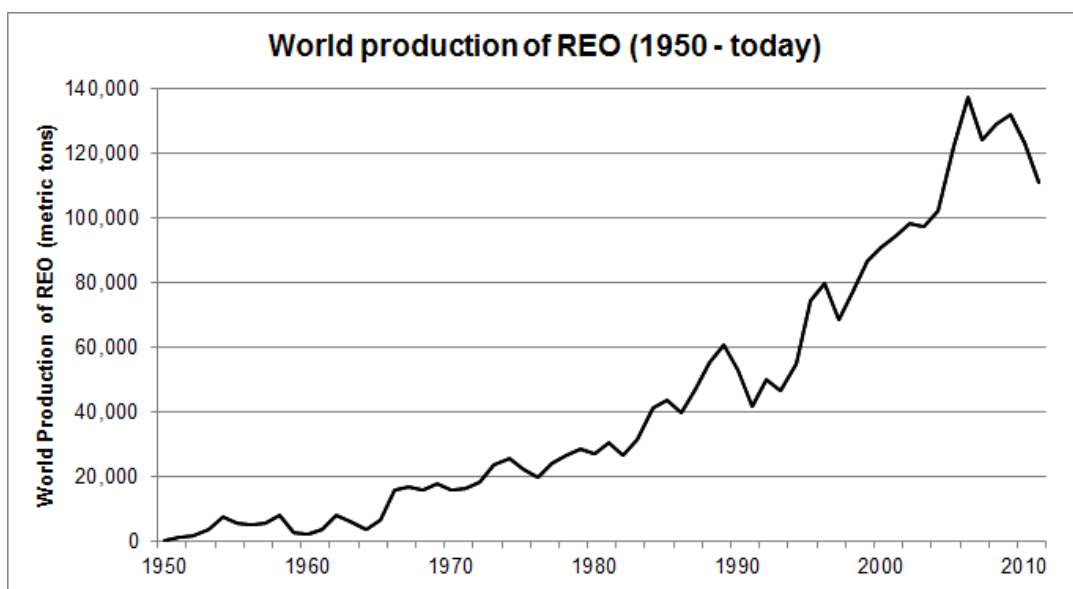


Figure 1: The large increase in the annual world production of rare earth oxides since 1960. Data from USGS tables [4].

In recent years concern has been expressed about the potentially difficult, or “critical”, supply situations that might develop – or in some cases perhaps, have already developed – in connection with mineral resources containing rare elements. (We return to the term “critical” below.) These range from alarmist articles in the popular press, to well-researched reports by various bodies, including learned societies, and to papers in the scientific literature. Moreover, at least five studies have been concerned specifically with energy-related materials [2, 6-8]. Probably most influential of the general reports on this topic was that of the National Research Council (NRC) of the US National Academies in 2008, with the title “Minerals, critical minerals, and the US economy” [9]. There are several factors or

criteria, which are potentially relevant in determining whether the availability situation of a particular element is likely to become “critical”; they have recently been discussed and categorised by Graedel et al [10]. On the supply side, these are “security of supply” (in the geopolitical sense), “extraction as by-product”, “environmental hazards” and possible “geochemical scarcity” due to mineral depletion. The monopolistic position of China on the REO market in recent years and the price bubble in 2011/12 (see Figure 2) have given new meaning to the notions of “security of supply” and “geopolitical factors”: Beginning in the early 2000’s the Chinese government had imposed restrictions on the export of REE in order to regulate their industry more stringently, in particular from the environmental point of view, and also to conserve supplies for their own manufacturers. The political connotations of this move have, however, also given rise to comment. Continuing with the criteria on the demand side, we have as factor the “vulnerability to supply restriction”, to which the “degree of importance” of the end product and the “substitutability” of the element concerned belong. These factors can in principle be used as indicators in a risk assessment exercise, of which a report of the EU Commission in our judgement is a very good example [12]. The latter uses a risk assessment matrix, based on the two composite indicators “supply risk” und “economic importance”, but sets threshold values for each. Materials exceeding both of these values are designated “critical”. 41 non-fuel materials were investigated. The 14 materials designated as “critical” are antimony, beryllium, cobalt, fluor spar, gallium, germanium, graphite, indium, magnesium, niobium, platinum group metals (PGMs), REEs, tantalum and tungsten. Space does not permit us to discuss in detail the indicators *per se* that are used in these studies, but we do return to specific ones below and discuss “geochemical scarcity” generally in the final Section.

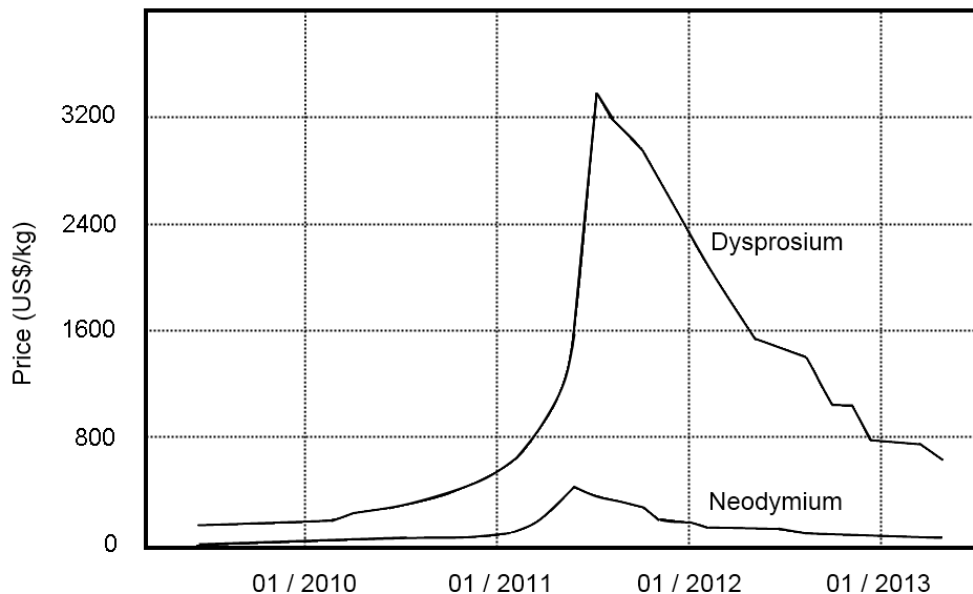


Figure 2: Price development for the REE dysprosium and neodymium in the period 2009-2013 (FOB China). After [11].

The adjective “critical” has been used for some years in the study of mineral resources. “Critical” minerals are economically important raw materials, for which there is a possibility of restricted availability, either at present or in the near future, or in the mid-term. Strictly speaking, minerals or the corresponding elements they contain cannot be “critical” in themselves, at least not according to the dictionary definition of the word. Rather, it is the situation, or state of a system, brought about by some attribute or property,

which is said to become critical. In the physical sciences the word “critical” is used almost exclusively in connection with a point at which the state of a system converts into a second state described by new parameters, as in a phase transition; hence, “critical point” or “critical mass”. By analogy, “critical” in the minerals context should therefore perhaps only be used to describe the situation that pertains when one or more indicators corresponding to particular attributes or properties cross a (previously determined) threshold value, as in the report of the EU Commission mentioned above [12].

The present article is concerned with rare elements, mostly metals and often referred to as “minor metals”, which might be required for a global *Energiewende*, or energy transformation process, on the assumption that wind and photovoltaics will be providing world wide 60 % of electricity supply by 2050. Similarly, we look at nuclear fusion, which may contribute to generating capacity in the second half of the century and also requires rare elements. In each of the three cases order of magnitude estimates are made of the required “in-use” stock of these elements and the possibility of geochemical scarcity is examined. Moreover, we also discuss the substitutability of rare earth-based permanent magnets in wind turbines as well as “extraction as by-product” for the minor metals used in thin film photovoltaics and for beryllium and helium that are required for fusion. The present account is based on several of our recent papers [13-16].

## **2. Wind energy and material requirements for strong permanent magnets**

In the last few years there has been a spectacular rise in the use of certain rare earth elements (REE) in the manufacture of high field permanent magnets, in particular for the transport and energy sectors. The REE consist of lanthanum and the subsequent 14 elements of successively higher atomic number, known as the lanthanides. Yttrium and scandium, occurring in the same vertical group of the Periodic Table as lanthanum, are normally included because they have similar properties. In the lanthanide series the 4f shell is successively filled, which gives rise to interesting spectroscopic and magnetic properties, but the chemical properties are very similar, which makes separation difficult. This turns out to be a particular problem for extraction because the rare earth elements never occur singly in the various ores. Rare earths are produced mainly from monazite ( $\text{CeYPO}_4$ ), as in the Mount Weld mine (Australia), and bastnäsite ( $\text{CeFCO}_3$ ), as in Bayan Obo (China) and Mountain Pass (California). (All the rare earth atoms can substitute for the cerium atom.) Both minerals consist almost exclusively of the light rare earth elements (LREE), yttrium to europium, in particular lanthanum, cerium and neodymium. The corresponding heavy REE, gadolinium to lutetium, are obtained from other minerals, in particular xenotime and the clay deposits in Southern China. The percentage of the much-coveted HREE dysprosium (see below) in xenotime can be as high as 9 %. We note in passing that most of the rare earth deposits also contain uranium and thorium and that this can constitute a serious hazard for personnel and for the environment. China has been the major producer of rare earths in the last decades with a 95-98 % market share. Largely because of environmental concerns, which apply not only to extraction but to a lesser extent also to separation, mining activities effectively came to an end in the US and Australia ten years ago. Due to the recent re-opening of the Mountain Pass mine in 2012, the dominance of China is now beginning to decrease and its share of global production fell to 86 % in 2012, according to the USGS [17].

Neodymium forms an intermetallic compound from which strong permanent magnets can be produced. On account of its high remanence and high coercivity neodymium iron boride ( $\text{Nd}_2\text{Fe}_{14}\text{B}$ ), developed by Sagawa [18] and Croat in 1983 is at present the material of

choice for synchronous motors in a wide variety of applications. This is particularly true for the automobile industry, including the main motor in all-electric and hybrid vehicles, and for wind turbines, although the market penetration here is probably at the moment only about 15 %. The material also contains normally praseodymium and dysprosium (and perhaps a little terbium). Dysprosium is very important, as it increases the coercivity and extends the temperature range. Hatch [19] gives the composition for various grades of magnet material: whereas, for example, a composition (by weight) of 23 % Nd, 8 % Pr and 1 % Dy gives a maximum working temperature of 80 °C, 14 % Nd, 5 % Pr and 12 % Dy extends the maximum working temperature to 240 °C and trebles the coercivity. Current R&D on this material focuses on the improvement of production techniques such that smaller quantities of dysprosium can be used (“Dy-saving technology”).

Global mine production of rare earths was 0.13 Mt (as REO) in 2012 [17]. The crustal abundance of cerium, the most plentiful REE, is 83 ppm, that of lutetium, the rarest 0.8 ppm [20]. Reserves are currently estimated to be 110 Mt, half of which are thought to be in China [17]. (“Reserves” are deposits in or on the Earth’s crust that can be exploited economically at the present time. “Resources” are defined as deposits in such a condition that economic extraction is potentially feasible. Resources can be further divided into “identified” and “undiscovered”.) The many new mining project proposals at the height of the bubble have probably not been taken into account in the figure for the reserves. The reserves of neodymium and praseodymium would probably be about 20 % of this figure. A very rough guess for the reserves of dysprosium would give about 1 % (1 Mt), since this REE is essentially only a trace element in most bastnäsite and monazite minerals. The extent of the resources is unknown. The USGS states: “Rare earths are relatively abundant in the Earth’s crust, but discovered minable concentrations are less common than for most ores. US and world resources are contained primarily in bastnäsite and monazite. (...) Undiscovered resources are thought to be very large relative to expected demand” [17].

We now make an order of magnitude estimate for the amount of rare earth elements, primarily neodymium and dysprosium, that could be required by 2050 as a consequence of the energy transformation process. Total global primary energy supply in 2010 was 12,717 Mtoe, or 147,900 TWh, according to the International Energy Agency (IEA) statistics [21]. We assume that this will double by the year 2050, as was roughly the case between 1973 and 2010 [21], to give 300 000 TWh. Furthermore, if renewables provide 60 %, we arrive at a contribution of 150,000 TWh, after taking into account a 10 % share of renewables in the form of bio-mass which is used for heating etc. After this point the assumptions become rather arbitrary, but it should be remembered that we are only attempting an “order of magnitude” estimation! Assuming that wind, solar thermal and PV will have equal shares and that hydro and various other renewable energy forms will only contribute 10 %, we obtain a figure of 45,000 TWh for wind energy. Converting to power and assuming a capacity factor of 50 %, we obtain for the “global wind park” 10 TW (compared to an installed capacity of 282 GW in 2012). A figure of 100-200 kg REE per MW is normally quoted as the requirement for neodymium-based permanent magnets [19, 22, 23]. This gives a figure of 1-2 Mt REE for the required in-use stock in the year 2050. This is only a small fraction of the reserves summed over all seventeen REE as currently estimated by the USGS. However, the requirement is for specific rare earths, such as dysprosium, one of the heavy rare earth elements (HREE). These are decidedly rarer than the light REE (which constitute roughly the first half of the lanthanide series), as is reflected in the relative prices of neodymium and dysprosium in Figure 2. The estimated 1-2 Mt requirement could be comparable to the total amount of dysprosium metal in the reserves (see above). In

connection with permanent magnets Alonso et al [23] have modelled demand for wind energy using various scenarios, but assume generally a much lower market penetration than our “order of magnitude” estimate here.

Are there alternatives to rare earth-based permanent magnets? We have noted above that the market penetration is so far not very high, so that the question of substitutability is clearly relevant. To answer this question we look briefly at electric motors in general (turbines are essentially identical, but the direction of energy flow is reversed). The two main categories of AC motor are the synchronous motor and the asynchronous motor; the latter is also termed induction motor [24, 25]. Synchronous motors have a rotor which contains either permanent magnets, or electromagnets constructed from copper windings. Induction motors have no windings on the rotor, which consists of iron, but contains a so-called squirrel cage which is usually made from aluminium, or sometimes copper. The stator is the same for synchronous and asynchronous motors and contains copper windings which generate a rotating magnetic field. These two motor types are compared in the schematic diagrams of Figures 3a and 3b. An inverter is used for converting the direct current from the battery into alternating current of varying frequency, resulting in a magnetic field with variable rotational velocity. As the name suggests, the rotor of the synchronous motor follows this magnetic field synchronously, whereas the rotor of the asynchronous motor turns at a lower rotational velocity, resulting in the so-called slip. Another electromagnetic phenomenon which can be used for electric motors is the so-called reluctance. This is the property of ferromagnetic material to align itself along magnetic field lines, similar to the magnetic needle of a compass. It is used in a motor with a so-called salient-pole rotor (see Figure 3c). In the stator a rotating magnetic field is created with which the poles of the rotor align. The rotation of the magnetic field in the stator is generated by successively activating and deactivating the copper windings; the rotor then follows. As in the case of the induction motor, no permanent magnets are needed; the rotor just consists of ferromagnetic material such as iron or steel.

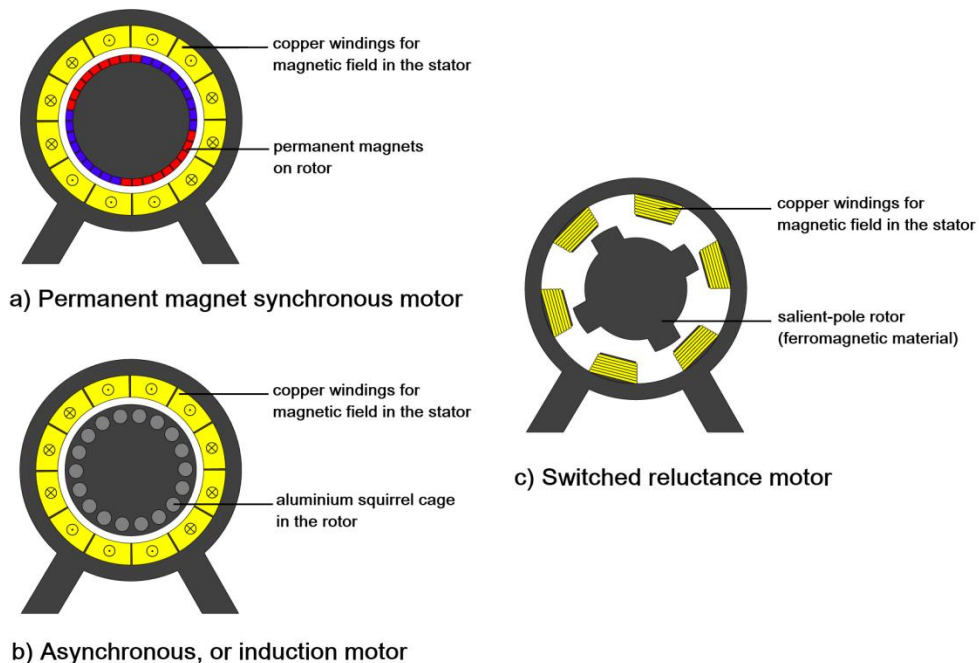


Figure 3: Three types of electric machine. After [14].

Wind generators have been traditionally located on land, but offshore wind generation, i.e. wind turbines located in the sea up to 40 km from the coast, has great potential, since average wind speed is higher and electricity is generated more continuously than at onshore sites. However, the current cost for offshore wind generators remains quite high (because of the additional expenses of installation, servicing and grid connection) which has resulted in an initially slow exploitation of off-shore possibilities. Just like the situation for any producer of electricity connected to the grid, the AC current from a wind turbine has to be synchronized with the grid. This means that the rotational speed of the generator must be compatible with the frequency of the grid. Traditionally, gearboxes have been used in wind turbines to connect the slowly turning rotor blades with the electric generator in the so-called nacelle. However, these gearboxes can be quite susceptible to faults, and even to complete failure, giving rise to considerable maintenance needs. Wind turbines without a gearbox have therefore been on the market since the mid 1990s. Here, the generator and the utility grid are connected via an AC-DC-AC converter, which allows the rotational velocity of the generator to be completely independent of the grid frequency. The alternating current (AC) produced in the generator is rectified to direct current (DC) in a first step and then converted into alternating current in accordance with the requirements of the grid in a second step. As the use of such power electronics makes the gearbox unnecessary, this technology is particularly advantageous for off-shore wind generators where the cost of maintenance is particularly high. Earlier types of wind generator were designed for only one rotational speed in accordance with the frequency of the grid. Generally speaking, all types of electric machines can be used in wind turbines. The gearless technology, however, was first implemented using synchronous generators with electromagnetic windings on the rotor. Since the size of wind generators has increased in order to raise the power output, this technology has led to a considerable demand for copper and a significant increase in the weight of the nacelle. This was the reason for substituting the electrically excited rotor by a rotor with permanent magnets, which allows substantial weight reductions and an improvement in the efficiency of the generator. However, the price of a generator using permanent magnets is higher (about 25 %) than the alternative with an electromagnet [25]. In summary, turbines without a gearbox are the preferred technology for off-shore wind parks. For this purpose, permanent magnets can be used, but do not necessarily have to be used. Thus, the development of the relative prices of REE and copper might well decide which of the alternative gearless wind turbine technologies will be utilized in the long run.

### 3. Rare elements for thin film solar modules

Globally, 27.7 GW of new photovoltaic (PV) capacity was installed in 2011. According to the US Department of Energy and other sources the thin film materials cadmium telluride, amorphous silicon and copper indium gallium diselenide  $\{Cu(In_xGa_{1-x})Se_2\}$ , or CIGS, had PV market shares in that year of 7 %, 3 % and 2.5 %, respectively. At the time of writing, figures for 2012 are not yet available. Schematic diagrams of the three cells are shown in Figure 4. Note that the thin film of transparent conducting oxide (TCO) in all three cases is usually indium tin oxide (ITO), the latter being a ubiquitous material in many display and conductive coating applications. In general, thin film modules have lower efficiencies than those based on single crystal silicon technology, but are cheaper to manufacture. Current module efficiencies are given as 10-12 %, 12-14 % and 6-9 % for CdTe, CIGS and a-Si, respectively, compared with a value of up to 20 % for crystalline silicon. Of the thin film modules CIGS has the highest manufacturing costs, but these can in principle – other factors being equal – be offset by the higher efficiency. In the context of the present article it is important to note that all five elements concerned are by-products in the production

process of a primary resource. For cadmium and indium this is zinc; for gallium, mainly aluminium; for selenium and tellurium, copper or lead [26]. In fact, they are extracted exclusively on this basis; there are no cadmium mines, for example, because there are few or no minable deposits of this element. By-products can be very important for the profitability of a mine, i.e. for the extraction of the primary product. Once the ore has been mined and the primary mineral concentrated, the additional expense of extracting low concentration by-products is relatively low. On the other hand, the fact that a rare metal is extracted as a by-product can entail a certain supply risk, if demand for the host mineral or element suddenly falls, as Graedel et al [10] have pointed out.

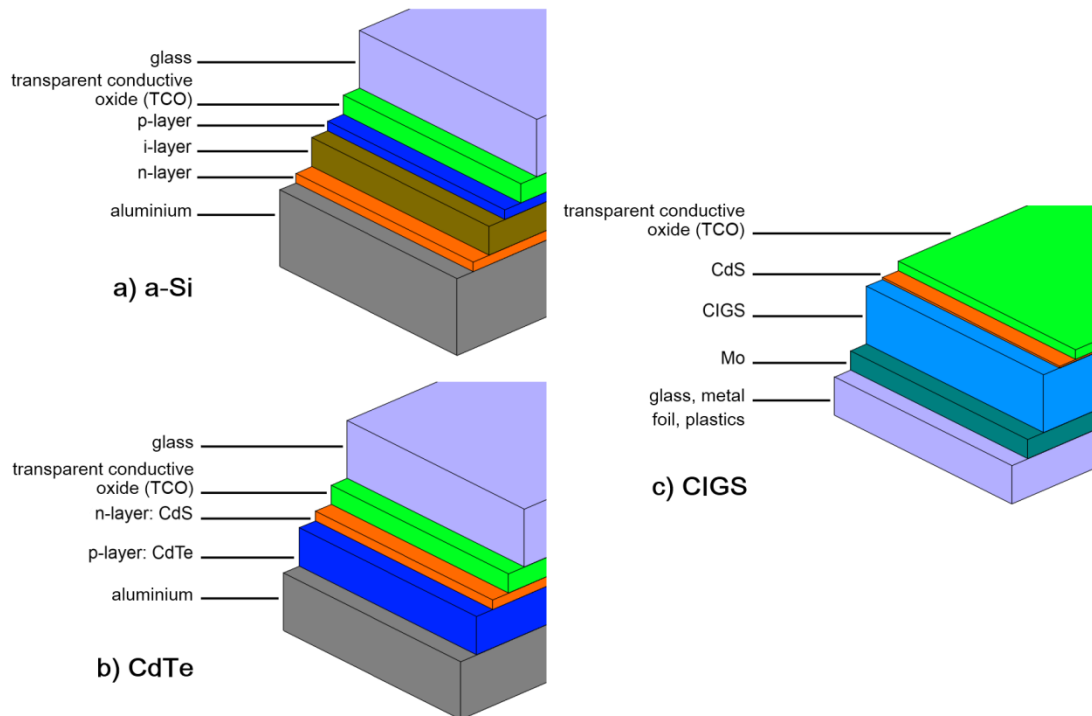


Figure 4: Thin film photocells, a-Si, CdTe, CIGS. After [14].

We now briefly review the availability of these five elements with the help of Table 1. The metal *cadmium* is used mainly for nickel-cadmium batteries, although inside the EU the sale of new batteries is forbidden because of the toxicity of cadmium (except for some special applications). Li-ion batteries are in any case replacing NiCd batteries in many consumer applications, because of the higher energy density, although the price is approximately double. As noted above, cadmium is a by-product in zinc mining, where it substitutes atomically to the extent of about 0.3 % for zinc in sphalerite (ZnS). Other rare elements similarly present in sphalerite in concentrations up to a few tenths of a percent include gallium, germanium and sometimes indium. The module manufacturer First Solar has just instituted “the industry’s first comprehensive, prefunded module collection and recycling program”, presumably in response to concerns about the toxicity of cadmium. The USGS gives a figure of 640 kt for the reserves corresponding to a reserves-to-primary production ratio (also known as the “static lifetime”) of 28 years. The situation with regard to the very rare metalloid *tellurium* can perhaps justifiably be described as “critical”. The source of 90 % of tellurium is copper ore, in which the element may be present in a concentration of up to  $1 \times 10^{-6}$  relative to the copper. (Other by-products of copper mining may include gold,



selenium, antimony and the platinum group metals.) A small amount of tellurium is also obtained as by-product in the mining of zinc, lead, gold, nickel and platinum. Potential primary ore sources have also been identified. Tellurium and the other by-products are extracted from the anode slime produced in electrolytic copper refining. If, as in the case of cadmium, we assume 2.5 GW<sub>p</sub> freshly installed CdTe capacity in 2011, the amount of Te required was 189 t, or 38 % of total production. George [27] gives 40 %. Other uses include thermoelectrics (30 %), alloying (15 %) and vulcanisation (5 %). Of all five rare metals considered in this Section it is only tellurium for which solar cell manufacture consumes a very significant part of annual production! Reserves of 24 kt correspond to a reserves-to-primary production ratio of 50 years.

	cadmium	tellurium	indium	gallium	selenium
crustal abundance (ppm)	0.2	0.001	0.1	15	0.05
“host” element	Zn	mainly Cu	Zn	mainly Al	mainly Cu
reserves, resources (Mt)	0.64, 5.0*	0.024, 0.1*	0.011** (2008)	1.0***	0.092**
annual production (kt)	28	≈ 0.5	1.8	0.31	3.5
% thereof for solar	0.6	38	1	2	1

*Table 1. Rare elements for thin film solar cells. \* estimated, \*\* reserves, resources unknown, \*\*\* resources, reserves proprietary information. Note that, where appropriate, the figures refer to the year 2011, unless otherwise stated. Annual production includes secondary material. Sources: Refs. [17, 26-33]*

*Indium*, like cadmium, is mainly obtained from zinc deposits, where it substitutes for zinc in sphalerite (ZnS), but at the most to the extent of 0.01 %. The largest producer of primary indium is China, which maintains an export quota. Substantial quantities of indium derive from recycling the material which is left over from the rather inefficient process of sputtering ITO (indium tin oxide) layers [28]. Substantially more than 50 % of indium produced is used for the thin layers of ITO required for liquid crystal displays (LCDs), plasma displays, touch panels, organic light-emitting diodes (LEDs) and solar cells. Other uses include solders and alloys, as well as III-V semiconductors for LEDs and laser diodes. To a current (2011) indium requirement of 16 t for CIGS cells we have to add about 6 t for (thinner) TCO layers in all three thin film solar cells. Presumably because of the difficulty of obtaining reliable data, the USGS currently does not quote the global reserves; in 2008 a figure of 11 kt was given. *Gallium* is extracted almost exclusively from the aluminium ore bauxite, but with a very small amount coming from sphalerite. Gallium production increased by 19 % in 2011. Since the majority of gallium is used for the manufacture of

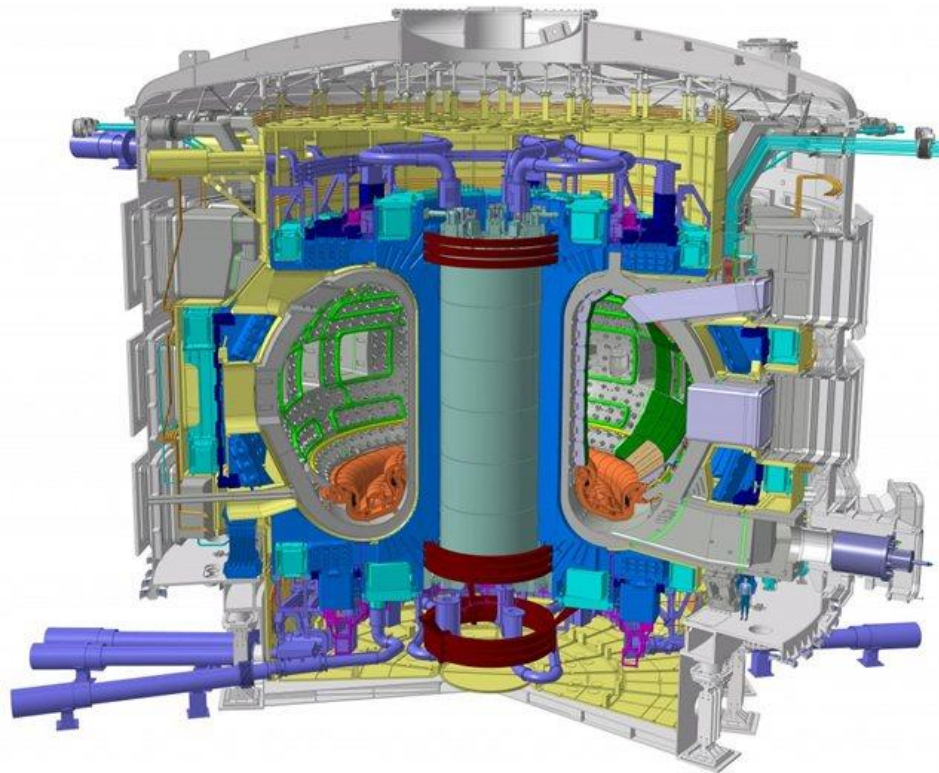
GaAs, and to a lesser extent, GaN devices, this reflects the currently expanding market for “smart” phones [30]. In an analogous way to indium we estimate the amount of gallium required for the manufacture of CIGS solar modules in 2011 as 5 t, corresponding to 1 – 2 % of annual production. The USGS [17] makes no attempt to estimate the gallium reserves, pointing out that only a certain proportion of the gallium in bauxite and sphalerite are extractable, but the details are proprietary. The world resources of gallium in bauxite are estimated to be 1 Mt. The situation with regard to *selenium*, a non-metal, is very similar to that of tellurium: not only does it come between sulphur and tellurium in the same group of the periodic table, but it is also an important by-product in copper mining and extraction. With a crustal abundance of 0.05 ppm it is, however, not quite so rare. Note that the concentration of by-product - selenium, tellurium, gold and antimony, etc. - depends on the copper ore. The main uses of selenium are alloying (40 %), glass (25 %) and agriculture (10 %); we estimate that solar cell manufacture required only 32 t, or about 1 %. Reserves are given as 92 kt [17], assuming that copper remains virtually the only source, which corresponds to a reserves-to-production ratio of about 30 years. As in the case of tellurium, the USGS gives no figure for the selenium resources. Note that nickel also contains selenium, as does coal (between 0.5 and 12 ppm). The latter is probably a potentially large-scale, if at present uneconomical, source [17].

As in the case of wind power, we can – using similar assumptions – make an order of magnitude estimate of the amounts of these five elements that could be required by 2050 as a consequence of the energy transformation process. We assume that there is a 60 % market penetration by renewables, giving a total of 150 000 TWh, and that wind, solar thermal and PV will have equal shares, besides 10 % for various other renewable energy forms. This gives a figure of 45 000 TWh for PV. Very arbitrarily, we give CdTe and CIGS a one third share of the PV market each. After converting to power and assuming a 25 % capacity factor, 7 TWp for each type of module is obtained. Using literature values for the amounts of the five elements required per TWp [26, 32], the resulting material requirements for the “in-use stock” in 2050 would be  $6 \times 10^5$  t,  $7 \times 10^5$  t,  $2 \times 10^5$  t,  $5 \times 10^4$  t and  $3 \times 10^5$  t for cadmium, tellurium, indium (including ITO), gallium and selenium, respectively. It is unlikely that there will be availability problems for cadmium due to geochemical scarcity, but the figure of  $6 \times 10^5$  t for tellurium, for example, is a factor 20 higher than the reserves (USGS), and probably greater than the resources. It may be possible to reduce the amounts of the elements required relative to the power rating by increasing the module efficiency, but this would probably not be more than a few percent. More promising would be the manufacture of modules with substantially reduced film thicknesses, which is thought to be technically possible [26].

#### 4. Materials for nuclear fusion

Figure 5 shows a schematic of the international ITER experiment currently under construction in Cadarache, France. The aim of ITER is to demonstrate the viability of producing energy from nuclear fusion for commercial purposes. Future fusion power plants may make a substantial contribution to electricity supply in the second half of this century. The fuels required are lithium, actually lithium-6, from which the necessary tritium will be bred *in situ* using the fusion neutrons, and deuterium. Neutrons will, however, be lost through parasitic absorption in the structural materials of the reactor. To achieve tritium self-sufficiency, it will be necessary to employ a neutron multiplier, such as beryllium or lead, producing further neutrons via (n, 2n) reactions in the so-called blanket of the reactor. In a previous publication [15] we have shown that, as expected, deuterium will never

become a problem from the supply point of view. It is present to the extent of 1 part in 6,400 (156 ppm) in naturally occurring hydrogen and for fusion purposes would probably be extracted by electrolysis of heavy water obtained via isotopic exchange. Lead is not considered to be a serious problem either, since the identified resources lie in the Giga-ton range. The supply situation for lithium could become difficult, however, depending to what extent the metal will be used in future for lithium-ion batteries, in particular for electric vehicles. Beryllium is also a potential problem. In the next paragraph we examine the availability of lithium and beryllium and try to assess future requirements of lithium for electric vehicles. The lithium and beryllium requirements for fusion are then summarised, assuming that this energy carrier will make a substantial contribution to energy supply sometime in the second half of this century. We note here that lithium-6, deuterium, beryllium and lead are actually “fuels” and are consumed in the nuclear fusion reactor. Subsequently, helium and niobium, which are materials required for fusion reactors rather than “fuels”, will be examined.



*Figure 5: The international ITER fusion experiment currently under construction. Source: ITER Organisation, Cadarache*

The USGS gives global *lithium* reserves and resources as 13 Mt and ca. 40 Mt, respectively [17]; the crustal abundance is 20 ppm [20]. In 2010 the USGS increased its estimate of reserves largely as a result of a re-assessment of the potential of the salt brines under the salars in South America and China. Lithium reserves are divided up approximately 2:1 between brines and minerals, mainly spodumene, a lithium aluminium silicate. In seawater the lithium concentration is on average 0.17 ppm, or 0.17 g per ton. Multiplying by the total volume of seawater gives a lithium content of 226 000 Mt. Annual production in 2012 was 37,000 t (recycling is insignificant); the ceramics and glass industry remains the major user with 30 %, followed by batteries, 22 %. *Beryllium* is significantly rarer with a crustal

abundance of 2.8 ppm, but neither metal is as rare as, for instance, tellurium (see above) or platinum [20]. Despite its presence in over 90 known minerals, only beryl (a beryllium aluminium silicate) and bertrandite (a beryllium sorosilicate hydroxide) occur in minable concentrations. The USGS does not give a figure for the reserves, but estimates the resources as 80 kt, although it is not clear from where this value comes. Annual mine production was 230 t in 2012, with a further 70 t probably coming from recycling. Craig et al [20] note “The restriction on production is two-fold. First, deposits are small and quite expensive to work. Second, the separation of beryllium is a very expensive and exacting process.”

How much lithium will be needed for non-fusion purposes in coming years? It is currently accepted that batteries, for both full battery electric vehicles (BEV) and hybrid electric vehicles (HEV), will lead to a massive increase in demand, and this will dominate the market in the next few decades. We deliberately present a “worst case” scenario: If we assume that (i) the whole global vehicle fleet of approx.  $10^9$  units is “electrified” over the next 40 years linearly in time, (ii) plug-in hybrids with 16 kWh batteries are the system of choice (completely electric vehicles will require larger batteries), (iii) 400 g Li are required per kWh [34] and (iv) recycling takes place every ten years with 80 % efficiency, then approximately 10 Mt lithium will be required by 2050. This figure is almost as high as the present known reserves, but smaller than the resources. If lithium-ion batteries also find large-scale application in electricity storage for industrial and domestic purposes, then there is some cause for concern.

How much lithium and beryllium would be required if fusion were to make a substantial contribution to electricity supply? Here, we use data from the European DEMO reactor study [35] as well as the results of calculations reported in ref. [15]. In one of the two reactor concepts the blanket consists of lithium ceramic pebbles as breeder material and beryllium pebbles as multiplier (He-cooled pebble bed - HCPB) with 2.4 GW fusion power and 1 GWe. Using the same figure as for wind and PV above, namely 45,000 TWh, we arrive at a total of 5,140 power stations that will be required globally. (In our previous paper we made similar estimates but for a lower contribution of fusion to global electricity supply [15].) These would consume 1.5 kt lithium-6, for which 18.7 kt of natural, non-enriched lithium would be required annually (the so-called burn up). Thus, the present lithium reserves of 13 Mt (see above) would correspond to a reserves-to-production ratio of 695 years, if used *only* for fusion. The sum of the lithium inventories for all power plants would be 18.5 kt lithium-6, corresponding to 231 kt natural lithium and representing one tenth of the reserves. This situation looks rather critical, particularly in the light of the possible demand for electric vehicles. On the other hand, if we consider the potential of seawater, then there is enough lithium, at least theoretically, for the operation of 5,140 power plants for 12 million years! The beryllium burn-up in 5,140 HCPB power plants would be 524 t annually and the initial loading 616 kt, probably exceeding considerably the putative resources. Whereas it is conceivable that the first generation of fusion power plants would use a beryllium multiplier, a scarcity of beryllium due to mineral depletion, might encourage the development of a breeding blanket with a Pb-Li eutectic acting both as breeder and nuclear multiplier, as in the DEMO-HCLL concept [35].

Two further elements will probably be required in large quantities in future fusion reactors, but not as “fuels”. *Helium*, on the assumption that “high temperature” superconductors will not be available, will be needed for the cryogenic system and, also, as coolant in the power conversion system. *Niobium* is an important constituent of the superconducting material comprising the magnetic field coils. Nuclear fusion actually produces helium, not only in

the breeding and fusion reactions but also in the beryllium multiplier. However, it is unlikely that the losses – even with efficient recovery systems – would be compensated by the helium produced. After briefly describing the origin of terrestrial helium and the current supply situation, we estimate possible helium requirements for fusion, before turning our attention, very briefly, to niobium.

Although helium is the second most abundant element in the universe, the average concentration in the Earth's crust is probably not even in the ppb range, and in the atmosphere it is only 5.2 ppm by volume [36, 37]. The majority derives from the nuclear decay of uranium and thorium. Most of the helium thus created has diffused to the surface and escaped into the atmosphere over the last 4 billion years, but a small fraction has been trapped by impermeable layers of rock. Natural gas, consisting mainly of methane, also collects in such geological constellations, so that helium for commercial use is normally produced from natural gas, where it is a minor component in concentrations up to, but vary rarely exceeding, about one per cent [38]. It can be calculated that about  $1 \times 10^{14}$  t helium has passed into the Earth's atmosphere since the formation of the planet. Yet the concentration of helium in the Earth's atmosphere (5.2 ppm) corresponds to a total of only  $3.5 \times 10^9$  t, and is presumed to have remained more or less constant on the geological time scale. This means that about  $10^{14}$  t must also have been lost from the upper atmosphere during this period. The reason is that the magnetosphere contains a very dilute helium-hydrogen plasma, the ions of which spiral along the Earth's magnetic field lines. Whereas the latter normally remain closed, the interaction with the solar wind above the poles causes magnetic reconnection to take place, so that the field lines open up and the plasma can escape along them into interplanetary space (the polar wind) [39]. We note, firstly, that only a very small fraction, less than  $10^{-7}$ , of the total amount of the radiogenic helium formed in the Earth's crust in the last four billion years has accumulated, fortuitously and fortunately, in appropriate geological strata. Secondly, despite this huge amount of helium that has passed through the Earth's atmosphere, the annual rate of production in the crust is only about  $3 \times 10^3$  t per year. There is no prospect of tapping into this supply, because of the high degree of dispersion of the sources, i.e. the radioactive nuclei in various minerals.

The total helium reserves and the identified resources as of 2006 are given by the USGS [17] as 8.8 Mt. (i.e. a factor of several hundred less than the amount of helium in the atmosphere.) The US, Qatar, Algeria and Russia have the largest resources at their disposal. Current global production is 31 kt per year. New helium plants in conjunction with liquid natural gas production will shortly come online in Algeria and Qatar. Global production of helium was 31 kt, in 2011; 78 % of this was produced in the United States [17]. Reliable figures for usage are only available for the US, but are not expected to be vastly different globally. For the year 2011 the figures were: Cryogenics (in particular magnetic resonance imaging, but also research in the physical sciences) 32 %, pressurising and purging 18 %, welding (as protective gas) 13 %, leak detection 4 %, breathing mixtures 2 % and others (including party balloons!) 13 % [37]. Helium supply in the last few years has been characterised by shortages and by price rises [40]. The latter, however, have been moderate because there is not a free market in helium. The price is essentially determined by the price at which the US Bureau of Land Management (BLM) sells off the helium from the federal helium reserve. In the next few years, the supply situation will undoubtedly change due to the new helium production facilities outside the US described above, but also – in the opposite sense – by the recommendation of the National Academies of Science in the 2010 report not to run down the federal reserve as originally envisaged by the US Congress. This is a complicated issue, but it suffices here to note that there is *at present* no scarcity of

helium due to depletion. However, the quantity of helium stored in natural gas deposits is finite: the danger exists that natural gas will be exhausted in the next 100 years or so without the helium being extracted and perhaps conserved for future generations.

Following Ref. [16], and taking into account the paper of Clarke and Cai [41], we estimate the helium losses in a future fusion power station. Based on the planning for ITER [42], it would appear that the cryogenic system for DEMO, including the on-site infrastructure, would require about 34 t helium. The necessary helium inventory in the power conversion system of DEMO has been estimated as about 23 t [43], giving a total helium inventory of about 60 t. The existing evidence (other large systems such as CERN, the planning for ITER, design optimisation) suggests that annual losses could be about 2 t per year. On the plus side, the combined helium production in DEMO from the breeding reaction, the fusion reaction and, in the case of the HCPB, the multiplier would be about 0.6 t. Since a lead multiplier does not produce  $\alpha$ -particles, the figure for the HCLL variant is lower at about 0.4 t. A current global helium production rate from natural gas and the US reserve of 31 kt p. a. (see above) corresponds to a reserves/resources-to-production ratio, or “static lifetime”, of 280 years. What difference would fusion make? We use the scenario above: 5,140 power plants (similar to DEMO HCPB or HCLL), which would provide 45,000 TWh p. a. some time in the second half of the century. The total helium inventory of all power plants is 0.3 Mt, which is about 3 % of the identified global resources. Annual losses would be 10 kt, decreasing the “static lifetime” to 210 years. Fusion as a non-sustainable consumer of helium would thus exacerbate an already difficult situation. Potentially more serious is the effective exhaustion of helium in the Earth’s crust as a result of mankind’s unslakeable thirst for “cheap” fossil fuel. We can only emphasise again, as have Nuttal et al [37] in their recent *Nature* article, that natural gas will soon be drastically depleted without the helium being extracted and conserved. Mankind would then only have recourse to the expensive and logistically complicated production of helium from the atmosphere [44].

Finally, we turn to niobium which is required in fusion for the superconducting magnetic field coils consisting of  $\text{Nb}_3\text{Sn}$  and/or  $\text{NbTi}$ . This rare metal with a crustal abundance of 10-20 ppm is mainly extracted from the mineral pyrochlore  $(\text{Na,Ca})_2\text{Nb}_2\text{O}_6$  in Brazil. It also occurs together with tantalum (same group of the periodic table) in the mineral columbite-tantalite,  $(\text{FeMn})(\text{Ta,Nb})_2\text{O}_6$ , which is mined mainly in Australia for its tantalum content and sometimes referred to as “coltan” [20]. The USGS gives the current global niobium production as 69 kt; the reserves are estimated to be at least 4 Mt [17], resulting in a reserves-to-production ratio of at least 60 years. The extent of the resources is unknown. Main uses at present are for special steels and superalloys; the amount of metal required at present for manufacturing Nb-based superconductor appears to be very small in comparison, but no exact figures are available. The ITER experiment requires about 175 t niobium for its toroidal and poloidal field coils [45]. Assuming DEMO will be similar and rounding up to 200 t per reactor, the 45,000 TWh scenario for fusion above would require an in-use stock of 1 Mt niobium, i.e. about a quarter of the currently identified reserves. Lack of information concerning the resources and, on the fusion side, concerning end-of-life recycling prevent us from drawing any conclusions about the niobium situation at present.

## 5. Mineral depletion and scarcity

From this account of the rare elements that may be required for advanced energy technologies, we can conclude that in the next few decades helium may soon become geochemically scarce due to the depletion of the element in the Earth’s crust. The supply

situation with regard to beryllium, dysprosium, indium and tellurium may also become serious during the course of the century. With regard to scarcity in general, this “state” can only be defined in economic terms. It is due to limited, or decreased, availability of a particular resource, 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, as we have noted above, is referred to as “substitution”. The consumption of *exhaustible* natural resources is somewhat different because the so-called Hotelling rent [46] will also contribute theoretically to the costs and thus to the market price. Space does not permit us to discuss Hotelling theory here. Even for effectively inexhaustible raw materials, however, other factors can cause scarcity and lead to the designation “critical” discussed in Section 1. Such factors, both on the supply and demand sides, are sudden strong economic growth in a country or region, new applications following the rapid introduction of new technologies, monopolistic situations, speculation, politically motivated embargos (the “security of supply” issue) and the fact that many important rare elements are mined as by-products, as we have also noted above.

When production costs increase because mining companies are forced to use ores of increasingly lower grade, it may happen that these costs are not, or are not fully, counterbalanced by the introduction of new, innovative techniques for prospecting, mining and processing. This could be taken as a sign that geochemical scarcity pertains. On the other hand, real (inflation-adjusted) prices for mineral commodities in general fell steadily for most of the 20th century. This indication of technological progress has allowed – in the course of time – resources to be re-classified as reserves and undiscovered resources to be re-classified as identified resources. Copper is an interesting example [17]: In 1970, identified and undiscovered world copper resources were estimated to consist of 1.6 Gt; the reserves were 0.3 Gt. Since then, the world has produced 0.4 Gt copper and the reserves are now estimated to be 0.7 Gt and the global resources possibly 3 Gt! Interestingly, this downward trend in price has reversed in the last ten years, despite financial crises and zero economic growth in many countries. The copper price, for instance, is now about five times higher than it was in 2003. Do the specific examples given in Section 2-4 above, taken together with this general observation that inflation-adjusted commodity prices have risen steeply since the turn of the century, mean that mineral depletion is *already* contributing to scarcity and influencing the market? This is a difficult question to answer. All we can say is that mineral depletion/geochemical scarcity could be affecting the market. However, the figures for beryllium, indium, dysprosium and tellurium do not indicate that there will be exhaustion of resources in the next few decades, or even in the next one to two centuries. The possibility exists for helium, but this is not a normal mineral commodity, but rather the by-product of a fossil fuel energy carrier.

In fact, complete exhaustion of a particular mineral will never occur. If uninhibited usage were to continue, a situation would be reached, 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 would automatically cease. Our society, or world economy, would switch to a cheaper, more readily available, but for the purpose, less appropriate substitute. This non-sustainable process of “unlimited substitution” could in principle go on indefinitely, but with disastrous consequences for future generations. Or will there be some kind of saturation point as far as consumption is

concerned? Due to the development of world population and concomitant increases in average standards of living, demand for raw materials will presumably continue to increase until a maximum in the level of in-use stock is reached. Under such conditions, improved recycling could in principle then supply the majority of global materials needs. However, although elements are never destroyed (except in the case of nuclear reactions) and thus remain potentially available, recycling can never be 100 % efficient. Due to the loss of material at very high dilution in the environment (dispersion) and in the recycling processes themselves, fresh ore will always be necessary. For this reason, effective exhaustion is probably inevitable, but the timescale on which this will happen is completely unknown.

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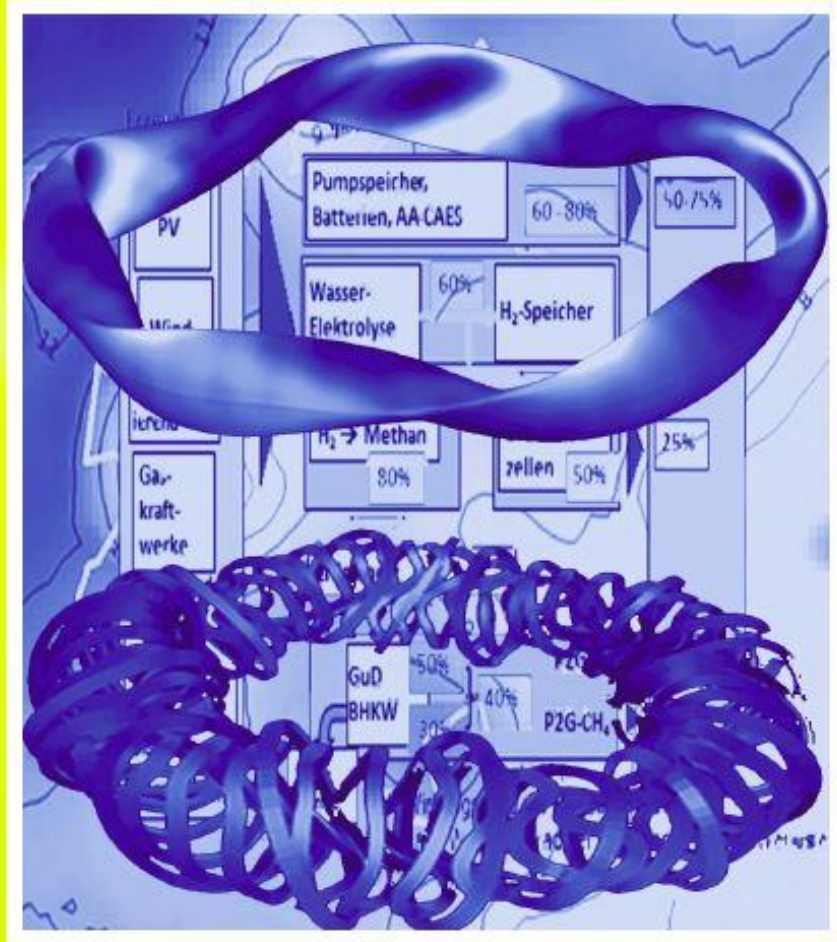
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## Energie

### Technologien und Energiewirtschaft

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# Energie

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Haupt- und Plenarvorträge

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